Calibration of selected pyranometers and satellite derived solar radiation in Puerto Rico

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Abstract: Knowledge of solar radiation at the ground surface is valuable for many disciplines. In this study, ground-based sensors at Fortuna and Mayaguez, Puerto Rico, were used to calibrate daily-integrated satellite-derived solar radiation. The calibration equations yielded R^2 values of 0.88 and 0.83 at Fortuna and Mayaguez, respectively. A regression equation was also derived based on the combined data from the two locations with an R^2 of 0.87. The calibration equations for Fortuna and UPRM were validated using 283 and 227 days of solar radiation data from 2010, respectively. The combined data equation (intended as an island-wide equation) worked well at UPRM but not at Fortuna. We recommend, for locations other than the study areas, that the uncorrected remotely sensed data be used. At the study sites, the uncorrected data produced reasonably accurate results with a maximum 6.22% error between the mean estimated and measured solar radiation.

Keywords: solar radiation; pyranometer; remote sensing; GOES; Puerto Rico; Caribbean; calibration; satellite; renewable energy technology.

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1 Introduction

Knowledge of the solar radiation flux at the ground surface is valuable for many disciplines. For example, in agriculture, solar radiation is necessary for estimating crop water requirements and for performing irrigation scheduling (Allen et al., 2005). Solar radiation in combination with energy balance techniques is also important for estimating photosynthetic activity of vegetation (Merva, 1995), and relationships have been developed for estimating photosynthetically active radiation (PAR) from solar radiation data (e.g., Finch et al., 2004; Xia et al., 2008). Long-term records of solar radiation are essential for evaluating solar as a potential energy source at specific locations (Irizarry-Rivera et al., 2009), and for conducting health related studies (e.g., skin cancer; Johnson, 1973).

Data from ground-based solar radiation sensors (pyranometers), though valuable near the sensor, may not be representative of areas several kilometers away, especially in areas like Puerto Rico where cloudiness tends to be highly variable (Rojas González, 2012), thereby rendering interpolation techniques unreliable. To overcome this problem, solar radiation data can be estimated from the National Oceanic and Atmospheric Administration's (NOAA's) Geostationary Operational Environmental Satellite (GOES). The GOES Surface and Insolation Products (GSIP) is an example of a remote sensing product that produces hourly full disk and hemispheric solar radiation at a 4 km × 4 km spatial resolution (Laszlo et al., 2008). Because of the relatively small land area and high cloud spatial variability of Puerto Rico, in this study, remotely sensed solar radiation data with a 1 km × 1 km spatial resolution are derived from the radiative transfer model originally developed by Gautier et al. (1980) using hourly data from the visible channel of NOAA's GOES satellite (referred to here as the GDM method after the authors' names Gautier, Diak, and Masse).

Over the years, improvements to the method have been made by Diak and Gautier (1983), Gautier et al. (1984) and Diak et al. (1996). Calibration and validation studies of the high-resolution GDM method have been performed in southern Ontario (Gautier et al., 1980) and in Florida (Sumner et al., 2008; Paech et al., 2009); and Otkin et al. (2005), using a coarse resolution (20 km), evaluated the GDM model over the Continental US. In these studies, in general the method performed well, with daily integrated solar radiation results within 5 to 15% of the observed mean in comparison to ground-based pyranometers.

Otkin et al. (2005) discuss potential sources of uncertainty in satellite remote sensing of solar radiation and issues related to its comparison with pyranometer data. Sources of error in the remote sensing instrumentation may include directional or cosine response errors, a slightly non-linear instrument response function, long-term instrument stability, and satellite navigational errors. Navigational errors tend to be more significant for high resolution products. Another source of error relates to the different scales associated with the satellite measurement (in this study 1 km) and the pyranometer, which is a point measurement.

Remote sensing of solar radiation has several important advantages over the use of pyranometers networks including relatively high spatial resolution, large spatial coverage, and availability of data in remote inaccessible regions and countries that may not have the means to install a pyranometer network (Paech et al., 2009). If the remote sensing solar radiation data are of high quality (i.e., comparable to pyranometer data), its use is more or less equivalent to adding thousands of pyranometers to a region. For example, Puerto Rico has a land area of approximately 9,000 km^2, and therefore, by employing the 1 km GDM product for Puerto Rico, it is as if 9,000 pyranometers exist, giving hourly and daily integrated solar insolation data. The remote sensing products for Puerto Rico and the northern Caribbean are available to the public each day shortly after midnight, and the compressed data file contains the previous 24 hours of data.

Because of the lack of solar radiation data in Puerto Rico and because of the need for reliable data that can be used for a wide range of applications, a calibration/validation study was conducted. The objectives of this study are:

1 re-calibrate the pyranometers at the Fortuna Agricultural Experimental Station and the Agricultural and Biosystems Engineering Building on the UPRM Campus

2 develop calibration equations for improving solar radiation estimates from a GOES-based GDM model at the two locations and for the entire island of Puerto Rico.

2 Technical approach

In March of 2009, the hourly and daily-integrated solar radiation GDM product became available for Puerto Rico at 1 km spatial resolution, and in March 2010, the 2 km spatial resolution product became available for the northern Caribbean Region. Data for Puerto Rico and the northern Caribbean Region are available on a daily basis to the public via the website http://pragwater.com/solar-radiation-data-for-pr-dr-and-haiti. Although the authors' intended use of the data was for hydrologic and agriculture applications, the majority of website visitors downloading the data are using it for solar energy design and analysis studies.

The GDM satellite remote sensing methodology involves performing a radiation energy balance on the atmosphere at the location of each pixel. The surface albedo (a GOES product) is taken as the minimum albedo obtained during a running two week period. If the measured digital brightness, determined from albedo and sun angle at the location, are at or below a clear sky threshold, then the surface insolation is estimated using a clear sky model based on Reyleigh scattering, water vapour absorption and ozone absorption. If digital brightness is above the clear sky threshold, then a cloudy model is used, in which Rayleigh scattering, ozone absorption and water vapour absorption above and below the cloud is used to estimate ground level insolation. Plane parallel clouds are assumed in the analysis (Otkin et al., 2005).

Calibrating remotely sensed solar radiation requires the use of ground-based pyranometers, however, over time, these sensors are subject to drift and require re-calibration. In this study we used a pyranometer maintained by the US Department of Agriculture Natural Resource Conservation Service (NRCS) and another maintained by the Agricultural and Biosystems Engineering Department, UPRM. Figure 1 shows the locations of the two sensors and Table 1 provides the site characteristics. The first step of this study involved re-calibration of the two pyranometers at their respective locations. The sensor used at Fortuna is a Licor 200 Pyranometer,[1] having a spectral response range from 400 to 1,100 nm. The sensor used at UPRM is a WatchDog Silicon Pyranometer attached to a Model 2900ET Weather Station (UPRM), having a spectral response from 300 to 1,100 nm. The calibration of these sensors was performed using a WatchDog Silicon Pyranometer and Series 1000 Data Logger purchased from Spectrum Technology, Inc. in December 2010. At the time of the study, this sensor was approximately six months old (i.e., relatively new), whereas the sensors at the study sites were approximately five years in age.

Table 1 Study site characteristics

Site	*Latitude (degrees)*	*Longitude (degrees)*	*Elevation (m)*	*NOAA climate division**
Fortuna	18.02 N	66.53 W	21	2
UPRM	18.21 N	67.14 W	7	4

Notes: *NOAA climate divisions: 1: North Coastal; 2: South Coastal; 3: Northern Slopes; 4: Southern Slopes; 5: Eastern Interior; 6: Western Interior.

Figure 1 Locations of NRCS soil climate analysis network (SCAN) weather stations in Puerto Rico (see online version for colours)

Note: Red star represent stations used in this study (UPRM and Fortuna).

The next step was to compare the re-calibrated pyranometers with the remotely sensed solar radiation data, which are archived on a publicly accessible server at the UPRM (http://academic.uprm.edu/hdc/solar). Using the geographical coordinates of the two study locations (Table 1), the corresponding satellite pixels were identified and the appropriate hourly and daily integrated solar radiation data were extracted from the files for comparison. Data covering the period April 3 to June 17, 2011 for UPRM and June 21 to August 26, 2011 for Fortuna, were used for the calibration. After the calibration was completed, a validation was conducted using archived daily integrated solar radiation data from 2010. The validation datasets for UPRM and Fortuna consisted of 227 and 283 days of data, respectively.

Statistical analyses were performed to evaluate calibration and validation data with respect to the pyranometer data. In this study, we used the coefficient of determination (R^2), mean bias error (MBE), root mean squared error (RMSE) and the percent error (% error), statistics which have been used in previous calibration/validation studies (e.g., Otkin et al., 2005). The R^2 values were determined as part of the linear regression analysis. The MBE is the difference between the mean remotely sensed and mean pyranometer solar radiation data. The RMSE is defined as the square root of the sum of the squared errors divided by the number of samples (n). The % error is defined as the error divided by the mean observed solar radiation times 100. Error here is defined as the difference between the remote sensing and the pyranometer values (the latter assumed to be the 'true' value).

3 Results

3.1 Pyranometer re-calibration

Figure 2 shows the *hourly* solar radiation data from the silicon pyranometer versus the pyranometers at Fortuna and UPRM, respectively. Relatively little scatter is observed in the hourly data ($R^2 = 0.9738$ and 0.9786, for Fortuna and UPRM, respectively), however, increasing error (relative to the 1:1 Line) is evident with increasing magnitude of solar radiation for Fortuna. The slope in the Fortuna equation was 1.2153. Table 2 summarises the calibration equations for the two locations.

Figure 2 Hourly solar radiation for silicon pyranometer vs. pyranometers at Fortuna and UPRM

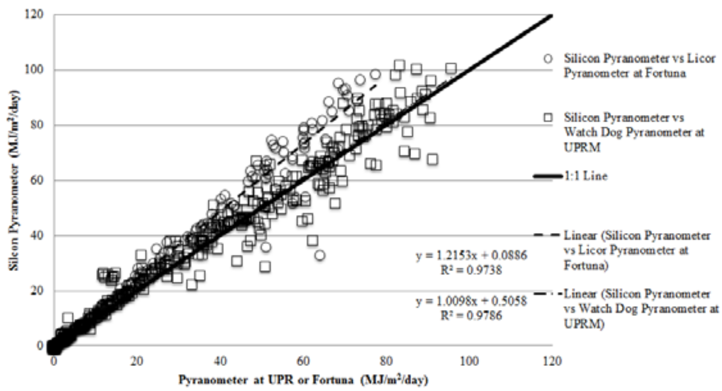


Table 2 Summary of the calibration equations for the hourly solar radiation for Fortuna and UPRM pyranometers

Location	*Pyranometer*	*Equation**	R^2	*Equation no.*
Fortuna	Licor 200	$y = 1.2153x + 0.0886$	0.97	1
UPRM	WatchDog	$y = 1.0098x + 0.5058$	0.98	2

Figure 3 shows the regression results for the *daily* integrated analysis for the two sites. The Fortuna error increases with increasing solar radiation. At 5 MJ/m^2/day, the error is approximately 1 MJ/m^2/day, but at 25 MJ/m^2/day the error is approximately

4 MJ/m^2/day. In general, the Fortuna pyranometer under-estimates solar radiation. The daily-integrated solar radiation from the UPRM pyranometer shows excellent agreement with the silicon pyranometer. Table 3 summarises the calibration equations for daily integrated solar radiation for the two locations.

Figure 3 Daily-integrated solar radiation for silicon pyranometer vs. pyranometers at Fortuna and UPRM

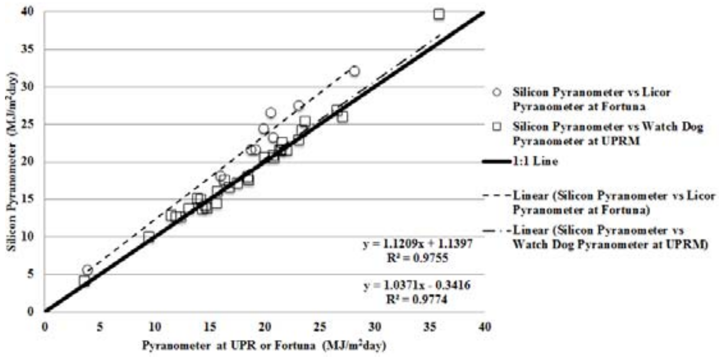


Table 3 Summary of the calibration equations for the daily-integrated solar radiation for Fortuna and UPRM pyranometers

Location	*Pyranometer*	*Equation*	R^2	*Equation no.*
Fortuna	Licor 200	$y = 1.1209x + 1.1397$	0.98	3
UPRM	WatchDog	$y = 1.0371x - 0.3416$	0.98	4

3.2 Remote sensing calibration

Figure 4 shows the daily-integrated remotely sensed solar radiation data versus the pyranometer data at Fortuna and UPRM. The estimated coefficient of determination (R^2) values for Fortuna and UPRM were .88 and 0.83, respectively. *Note that the pyranometer values were obtained using the calibration equations from Table 3*. Figure 5 shows the daily-integrated remotely sensed solar radiation data versus the combined pyranometer data. The overall coefficient of determination was 0.87. It is hoped that the regression equation based on the combined data may be useful as an island-wide calibration equation. Table 4 shows the calibration equations for the remote sensing data for the two locations and the combined data.

Table 4 Summary of the calibration equations for the daily-integrated remotely sensed solar radiation for Fortuna and UPRM pyranometers

Location	*Pyranometer*	*Equation*	R^2	*Equation no.*
Fortuna	Licor 200	$y = 0.9938x - 0.8234$	0.88	5
UPRM	WatchDog	$y = 1.0978x - 3.6159$	0.83	6
Combined data	----	$y = 1.0381x - 2.0654$	0.87	7

Figure 4 Daily-integrated solar radiation for remote sensing vs. pyranometers at Fortuna and UPRM

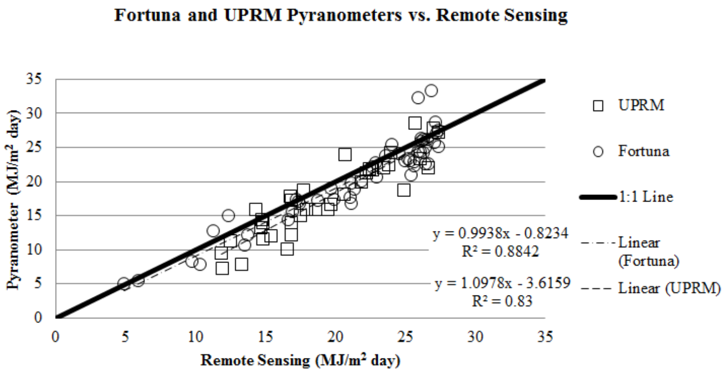


Figure 5 Daily-integrated solar radiation for remote sensed vs. pyranometers (combined data)

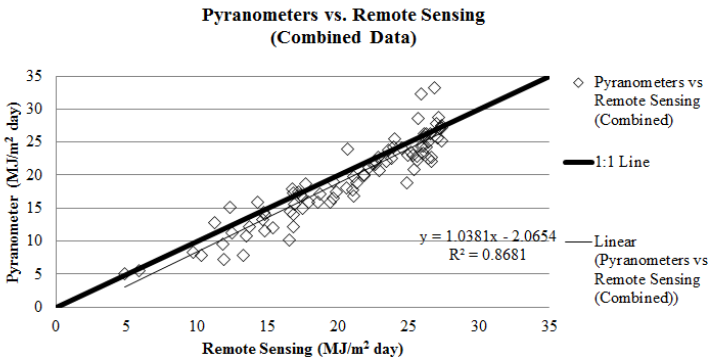
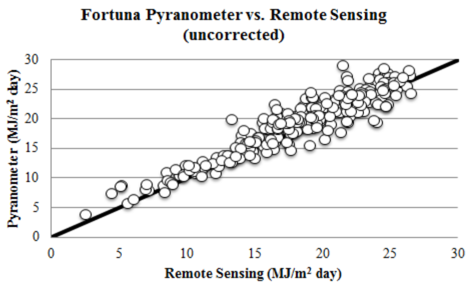
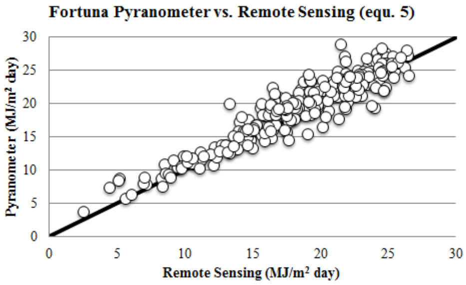


Figure 6 Daily-integrated solar radiation for 283 days in 2010, (a) Fortuna pyranometers vs. uncorrected (b) equation (5) (c) combined equation (7)

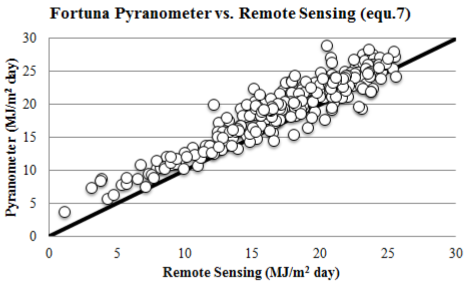


(a)

Figure 6 Daily-integrated solar radiation for 283 days in 2010, (a) Fortuna pyranometers vs. uncorrected (b) equation (5) (c) combined equation (7) (continued)



(b)



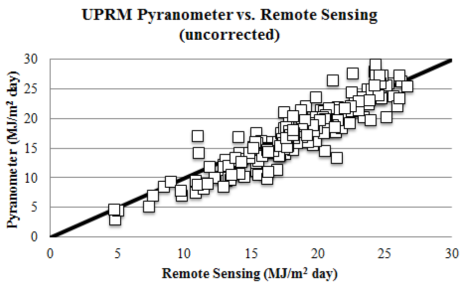
(c)

3.3 Validation of remotely sensed solar radiation

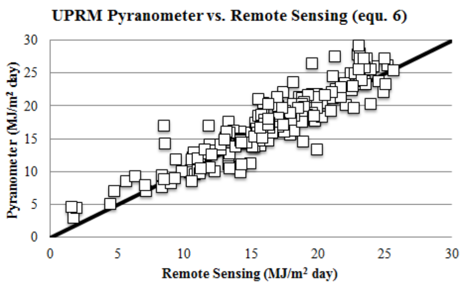
In this section, validation of the calibrated remote sensing data will be presented. Figure 6 shows the daily-integrated solar radiation for 283 days in 2010 at Fortuna. Figure 6 shows the remotely sensed data uncorrected [Figure 6(a)], using equation (5) [Figure 6(b)], and using the combined data equation (7) [Figure 6(c)]. Equation (5) [Figure 6(b)] does a good job of estimating solar radiation at Fortuna. Figure 6(c) is based on the combined data equation (7), and in this case the majority of the data are located above the 1:1 line, indicating that the remote sensing data are underestimating the solar radiation by 1 or 2 $MJ/m^2/day$ on average. The uncorrected data [Figure 6(a)] appears to do a reasonably good job of matching the pyranometer data. The data indicate a good distribution above and below the 1:1 Line (solid black line).

Figure 7 shows the daily-integrated solar radiation for 226 days in 2010 at UPRM. The figure shows the remotely sensed data uncorrected [Figure 7(a)], using equation (6) [Figure 7(b)], and using the combined data equation (7) [Figure 7(c)]. Both equations performed reasonably well for estimating the solar radiation at UPRM. The uncorrected remotely sensed data appears to slightly underestimate daily integrated solar radiation with respect to the pyranometer. Equation (6) slightly overestimates with respect to the pyranometer; while, the combined equation (7), appears to produce the best match to the pyranometer data.

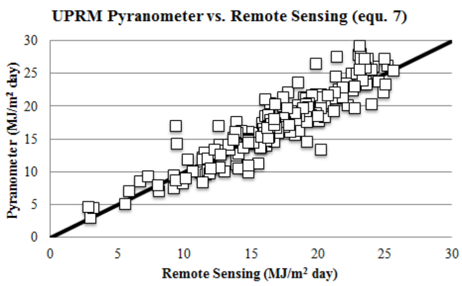
Figure 7 Daily-integrated solar radiation for 226 days in 2010, (a) UPRM pyranometers vs. uncorrected (b) equation (6) (c) combined equation (7)



(a)



(b)



(c)

Table 5 summarises the results of the statistical analyses of the validation data. The table includes the mean value of daily integrated solar radiation (R_s), the MBE, the RMSE and the % error. The best results for the UPRM site were obtained using the combined equation (7) with a MBE of –0.31 MJ/m^{2}day, RMSE of 2.07 MJ/m^{2}day, and a % error of –1.80%. The best result for the Fortuna site is associated with the uncorrected data with a MBE of –0.11 MJ/m^{2}day, RMSE of 1.79 MJ/m^{2}day and % error of –0.56%. The poorest result was found when using the combined equation (7) for Fortuna with a MBE of –2.19 MJ/m^{2}day, RMSE of 2.86 MJ/m^{2}day, and % error of –11.23%.

As mentioned previously, the purpose of developing the combined data equation was to derive a single equation that could be used to estimate the daily integrated solar radiation throughout Puerto Rico. Because of the relatively poor performance of equation (7) at Fortuna, its use is not recommended as an island-wide equation; rather we recommend instead that the *uncorrected* data be used. The uncorrected UPRM results included a MBE of 1.07 MJ/m^{2}day, RMSE of 2.36 MJ/m^{2}day and a % error of 6.22%, an error that is consistent with the error obtained by Diak and Gautier (1983) in a validation study of the GDM conducted in southern Ontario. Most studies evaluating the GDM model obtained percentage errors within 5 to 15% (Diak and Gautier, 1983; Otkin et al., 2005), therefore, we can consider, at least in terms of the percentage error, that the uncorrected remote sensing results are quite good.

Table 5 Results of statistical analyses of the validation data

	UPRM (n = 227)				*Fortuna (n = 283)*			
	Mean R_s	*MBE*	*RMSE*	*% error*	*Mean R_s*	*MBE*	*RMSE*	*% error*
Pyranometer	17.12				19.54			
Uncorrected	18.18	1.07	2.36	6.22	19.43	–0.11	1.79	–0.56
Equation (5) (Fortuna), equation (6) (UPRM)	16.34	–0.77	2.18	–4.52	*18.49*	*–1.05*	*2.07*	*–5.39*
Equation (7) (combined data)	*16.81*	*–0.31*	*2.07*	*–1.80*	17.35	–2.19	2.86	–11.23
Mean	17.11	0.00	2.20	–0.03	18.70	–1.12	2.24	–5.73

Notes: *n* = sample size, mean R_s is the mean daily integrated solar radiation, MBE is the mean bias error (MJ/m^2 day), RMSE is the root mean squared error (MJ/m^2 day) and % error is the percent error in the mean daily integrated solar radiation. The italicised indicates the best result for that location. The calculation of the mean R_s (bottom row) does not include the pyranometer data.

4 Discussion

Previous calibration efforts have been undertaken by the authors of this study, in which six pyranometers were used (e.g., Harmsen et al., 2010). Upon a closer evaluation of the data from several of the pyranometers, some of the sensors were deemed unreliable and therefore, in this study, the most reliable of the sensors (Fortuna and UPRM) were retained and re-calibrated. In this study, significant errors were observed in the NRCS pyranometers at Fortuna. The NRCS SCAN website indicates that the Fortuna solar radiation sensor has been operational since August of 2006. To our knowledge, the sensor has never been re-calibrated since the original factory calibration.

The two study sites cover a range of conditions including coastal/humid (UPRM) and lowland/semi-arid (Fortuna). The two sites account for most of the conditions that might be encountered within the lower elevations of Puerto Rico. A calibration of the remote sensing data was not performed under humid/mountainous conditions, and therefore, future studies should endeavour to evaluate the remote sensing product under these conditions. Based on the results of this study, we recommend that the *uncorrected* remote sensing data be used for all locations within Puerto Rico, except at UPRM (i.e., Mayaguez area) where equation (7) will yield a better result.

5 Summary and conclusions

In this study, pyranometers at Fortuna and UPRM were re-calibrated. Using the re-calibrated pyranometers, solar radiation data from a GDM satellite remote sensing method was calibrated. For the daily-integrated analysis, R^2 values for the linear equations, for Fortuna and UPRM were 0.88 and 0.83, respectively. The R^2 value for the combined data equation was 0.87. A validation was conducted for a 283-day period for Fortuna and a 226-day period for UPRM. The site-specific equations [equations (5) and (6)] performed well, however, when using the combined data equation [equation (9)], solar radiation was underestimated consistently by 1 or 2 MJ/m^2/day on average for Fortuna. On the other hand, the same equation performed well for Mayaguez (MBE = –0.11 MJ/m^{2}day, RMSE = 1.79 MJ/m^{2}day and % error = –0.56). The uncorrected data produced reasonably accurate results at both locations with a maximum % error of 6.22%, which is comparable with estimates obtained in the literature. Therefore, the uncorrected remotely sensed solar radiation data are recommended for use throughout Puerto Rico. This study did not consider areas of the island defined as humid-mountainous, and therefore, future calibration/validation efforts should focus on this environment. This research should be considered preliminary, as ongoing efforts are underway to further improve the accuracy of the remote sensing product in Puerto Rico.

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Notes

1 Reference to commercial products in no way implies endorsement of the product by the authors.