# SUB-HOUR EVALUATION OF GLOBAL HORIZONTAL IRRADIANCE FROM THE PHYSICAL SOLAR MODEL (PSM) INCLUDING LATITUDES BELOW 20°S

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**Abstract**

Since 2018 the Physical Solar Model (PSM) used for generating solar irradiance estimates in the National Solar Radiation Database (NSRDB) provides estimates for the Americas with a maximum time resolution of 10 minutes and approximate spatial resolution of 4 x 4 km (latitude, longitude). The performance of this model at hour and sub-hour time intervals has not been evaluated beyond 20°S. This work provides performance indicators at the 10 and 60 min timescales for the Global Horizontal Irradiance (GHI) component of the model, using 4 years (2020-2023) of controlled quality 1 min data from four ground stations in Uruguay, located in latitudes between 30 and 35°S. Three sites of similar latitudes in the northern hemisphere from the SURFRAD network (United States) have also been included for comparative purposes. The results show small positive mean biases below 4% (for both time scales) at all but one site, and relative RMSD in the ranges 15 - 28% and 10-16% at the 10 minute and 60 minute timescales, respectively. These preliminary results confirm PSM as a useful tool for solar irradiance estimations at southern latitudes between 30 and 35°S.

*Keywords*: Solar radiation, PSM, National Solar Radiation Database, Global Horizontal Irradiance, South America

## 1. Introduction

The Physical Solar Model (PSM), used for generating solar irradiance estimates by the National Solar Radiation Database (NSRDB) across the Americas, results from a joint effort between the University of Wisconsin, the National Renewable Energy Laboratory (NREL), and the National Oceanic and Atmospheric Administration (NOAA). The model is reviewed in Sengupta et al. (2018). Estimates for Global Horizontal Irradiance (GHI) and its components, Direct Normal (DNI) and Diffuse Horizontal (DHI) irradiances, are generated from GOES (East and West) cloud information, for both, clear-sky and all-sky conditions, with a spatial resolution of 4 km x 4 km. From 1998 to 2017, the time resolution was 30 minutes, covering the region from 60°N to 20°S. Since 2018, the time resolution has increased to 5 minutes for the continental U.S. and 10 minutes for the rest of Central and South America, now extending the coverage to 60°S. These products are publicly available through NREL (https://nsrdb.nrel.gov/data-viewer). The availability of high-resolution, long-term datasets makes NSRDB products a valuable resource for solar irradiance assessment, project design, and grid integration studies.

PSM relies on data from the GOES-East and GOES-West satellites for cloud information over the Americas. GOES-East (GOES-16) is positioned at approximately 75.2°W, providing coverage of the eastern United States, the Caribbean, and much of South America, while GOES-West (GOES-17/18) is located near 137.2°W, covering the western United States and the Pacific region. This configuration ensures continuous monitoring across the Americas. This is particularly relevant for South America, where other solar radiation products, such as the Copernicus Atmospheric Monitoring Service (CAMS), based on the Heliosat-4 model

(Qu et al., 2017), rely on the Meteosat Second Generation (MSG) satellite positioned at 0° longitude over Africa, resulting in limited coverage due to its high viewing angle over the continent.

The PSM is based on fast parametrizations of radiative transfer calculations, Fast All-sky Radiation Model for Solar applications (FARMS) (Xie et al., 2017), with inputs from the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Modern Era Retrospective analysis for Research and Applications, version 2 (MERRA-2, Gelaro et al, 2017) database for global atmospheric information. Several assessments for PSM estimates have been reported at hourly and daily timescales, using ground data from several sites in the Surface Radiation Budget Network (SURFRAD) (Sengupta et al., 2015; Habte et al., 2017; Yang 2018). Since 2018, the PSM coverage was extended to southern latitudes beyond 20° S. To the best of our knowledge, there are no sub-hour validations of PSM for this region that include South American countries. Recently, a first assessment using daily values has been made for several models, including PSM, using controlled quality data from seven sites in Uruguay (Sarazola et al., 2023). Furthermore, the early validation results of PSM against SURFRAD sites have been recently challenged claiming methodological issues (Yang, 2018).

In this study, we perform the first assessment of GHI from the PSM model at the 10 minute and 60 minute timescale for latitudes between 30°S and 35°S, using four years of 1-minute controlled quality ground data from four sites in Uruguay. Three sites from SURFRAD in the U.S. are also included to provide context for these results using the same methodology.

## 2. Data

The GHI measurements used in this works are from four sites in Uruguay and three in United States, listed in Table 1, including their geographical details and code. The four sites of Uruguay belong of the Red de Medida Continua de Irradiancia Solar (RMCIS, Solar Irradiance Continous Measurement Network) (http://les.edu.uy/rmcis/). They are maintained by the Solar Energy Laboratory (LES, Uruguay). In these sites, data is registered every 1 minute as an average of 6 instantaneous measurements taken every 10 second by class A pyranometers with periodic two-year calibrations with traceability to the World Radiometric Reference (WRR). For comparison purposes, 1-minute GHI data from three mid-latitude sites from the SURFRAD network were also included. These sites are located at latitudes similar to Uruguay's stations but in the northern hemisphere (United States). The quality of instruments and maintenance practices at SURFRAD sites are at least as good as those from RMCIS. All data was processed and aggregated at 10-minute level, filtering out those values outside the recommended bounds from the Baseline Surface Radiation Network (BSRN, Long & Shi, 2008) and excluding records with solar altitudes below 7°, which are associated to larger measurement errors due to cosine effect. A 10-minute interval is considered valid only if seven or more of its minutes are valid.

**Table. 1: Site details for the 1 minute ground data used for the assessment. Data for the period 2020-2023 was considered for all sites, except TBL for which 2021-2023 was used. The Climate zone columns refers to the updated Köppen-Geiger classification**

| Site and Country | Code | Latitude (°) | Longitude (°) | Altitude (m asl) | Climate zone | Measurement Network |
|---|---|---|---|---|---|---|
| Salto, UY | LES | -31.29 | 57.92 | 56 | Cfa | RMCIS-LES |
| Treinta y Tres, UY | PPP | -33.26 | -54.48 | 26 | Cfa | RMCIS-LES |
| Artigas, UY | ART | -30.40 | -56.51 | 136 | Cfa | RMCIS-LES |
| Tacuarembó, UY | TAC | -31.71 | -55.83 | 142 | Cfa | RMCIS-LES |
| Goodwin Creek, US | GWN | +34.25 | -89.87 | 98 | Cfa | SURFRAD |
| Table Mountain, US | TBL | +40.13 | -105.24 | 1689 | Dfb | SURFRAD |
| Desert Rock, US | DRA | +36.62 | -116.02 | 1007 | BWh | SURFRAD |

The geographical distribution of the seven measurement sites, along with their Köppen climate classification, is illustrated in Figure 1. The figure highlights the distinct climatic regimes covered, ranging from the humid subtropical zone (e.g., LES, PPP) to the continental and oceanic climates (e.g., TBL, DRA) used for comparative analysis.

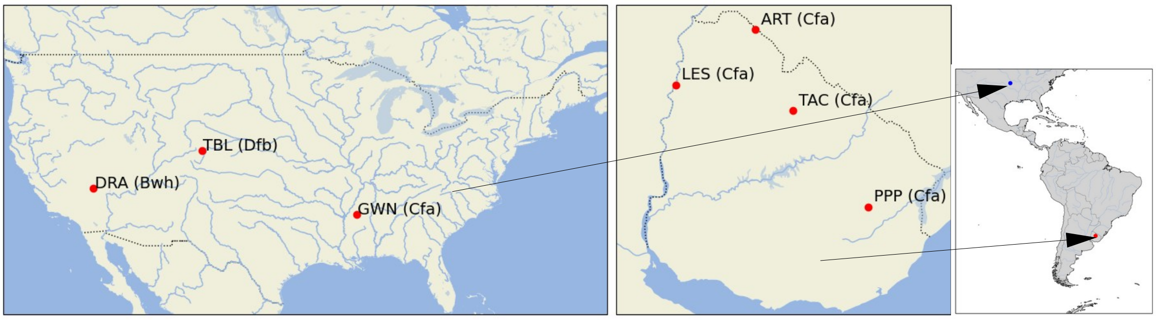


**Figure 1. Location of measurement stations. The map shows the distribution of stations in Uruguay (left) and the United States (right) used in this study.**

The total number of valid data pairs (N) remaining after quality control filtering and temporal aggregation is presented in Table 2. At the 10-minute resolution, most stations (LES, PPP, ART, TAC, GWN, DRA) retain over 90,000 valid pairs, while the TBL station shows the lowest availability with approximately 66,500 pairs.

The aggregation of the 10-minute data to the hourly timescale was performed only when 2/3 or more of the component 10-minute intervals within that hour were deemed valid. At this resolution, N values are naturally reduced due to aggregation, falling to ~1/6 of the original amount of data, that is around 15,000 for most sites and 10,826 for TBL. The high data availability across the network ensures a robust statistical basis for the subsequent performance evaluation.

GHI values from the PSM model (GHIpsm) where downloaded at 10-minute time steps from the NSRDB server (https://nsrdb.nrel.gov/data-viewer) for each of the 7 locations. Only complete records (GHI, $GHI_{psm}$) where selected for the analysis. The period of avaliability in this case is 2020-2023, which determines the period assessed in this study.

Figure 2 presents the mean values of GHI measurements and GHIpsm estimates across all stations and both resolution. The overall mean GHI values range from approximately 400 W/m$^2$ (GWN) to over 520 W/m$^2$ (DRA), reflecting the different climatic regions and altitudes of the sites. The mean GHIpsm values show a slight positive bias relative to the GHI measurements across most stations and both resolutions.

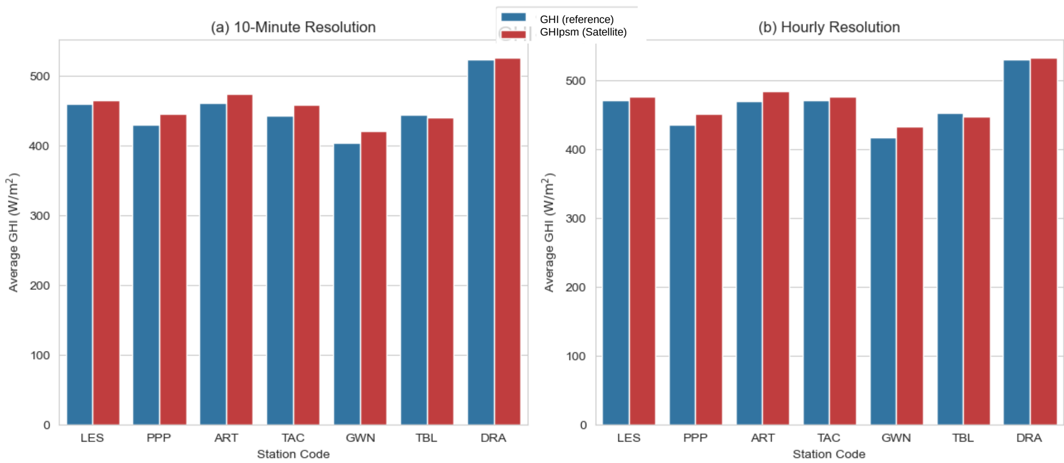


**Figure 2. Mean Global Horizontal Irradiance (GHI) across Sites. GHI values derived from the ground measurements (blue) and PSM model (GHIpsm) estimates (red). (a) 10-Minute Resolution and (b) Hourly Resolution.**

## 3. Methodology

To quantitatively evaluate the performance of PSM estimate, namely GHIpsm, relative to the ground-based GHI, a set of widely accepted statistical metrics was utilized. These metrics are all based on the residual ($r_i$) for each measurement pair (i), as defined by:

$$r_i = GHI_{psm} - GHI \quad \text{(eq.1)}$$

For a sample size of N valid data pairs, the primary indicators chosen were the Mean Bias Deviation (MBD), the Mean Absolute Deviation (MAD), and the Root Mean Squared Deviation (RMSD), as shown in Equations 2 to 4:

$$MBD = \frac{1}{N}\sum_{i=1}^{N} r_i \quad \text{(eq. 2)}$$

$$MAD = \frac{1}{N}|r_i| \quad \text{(eq. 3)}$$

$$RMSD = \sqrt{\left(\frac{1}{N}\sum_{i=1}^{n} r_i^2\right)} \quad \text{(eq.4)}$$

To facilitate comparison across sites with inherently different mean irradiance levels (as seen in Figure 3), these metrics are expressed in relative terms: rMBD, rMAD, and rRMSD. The use of relative metrics, presented as a percentage of the average GHI ground measurement at each site, effectively normalizes the error, ensuring that performance differences are attributed to model accuracy rather than the site's absolute solar resource potential.

## 4. Results

Results of the performance metrics are summarized for all seven stations and both temporal resolutions (10-minute and hourly) in Table 2 and visually represented in Figure 3.

The rMBD values indicate a positive bias in most of the stations (ranging from +0.6% to +4.1%), showing a slight overestimation by the satellite model across the majority of the RMCIS and SURFRAD sites. The only underestimation is noticed for TBL station at both resolutions. The largest positive bias is observed at GWN where the rMBD is +4.1% at the10-minute scale.

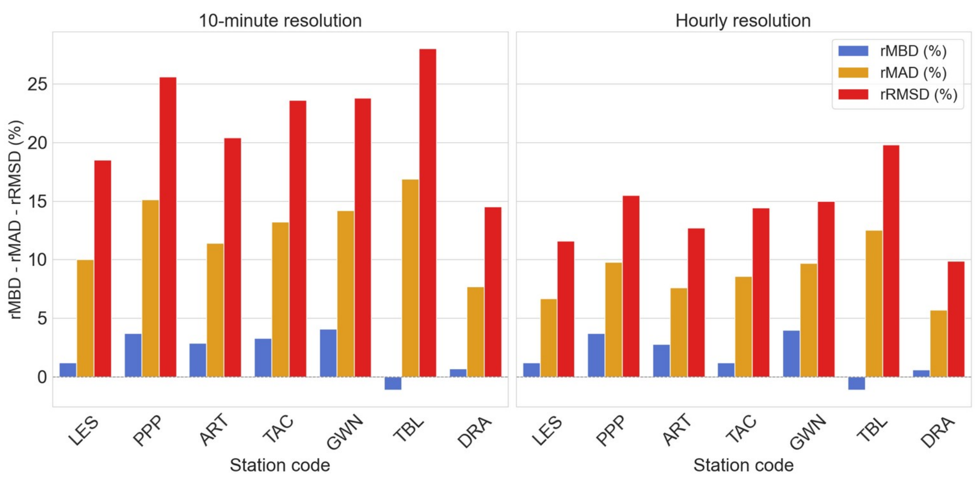


**Figure 3. Comparison of Relative Performance Metrics by Site and Temporal Resolution. (a) 10-minute scale (left panel) and the (b) Hourly scale (right panel).**

**Table 2. Number of selected records from each site, average values of GHI and GHIpsm, and the performance indicators at the 10-minute and hourly scale.**

| Site code | Time interval | Data pairs N | Mean GHI ($W/m^2$) | Mean $GHI_{psm}$ ($W/m^2$) | rMBD (%) | rMAD (%) | rRMSD (%) |
|---|---|---|---|---|---|---|---|
| LES | 10 min | 93623 | 459.4 | 465.0 | +1.2 | 10.0 | 18.5 |
| | hourly | 15187 | 471.1 | 476.5 | +1.2 | 6.7 | 11.6 |
| PPP | 10 min | 91588 | 429.6 | 445.6 | +3.7 | 15.1 | 25.6 |
| | hourly | 15073 | 435.1 | 451.1 | +3.7 | 9.8 | 15.5 |
| ART | 10 min | 92136 | 461.3 | 474.6 | +2.9 | 11.4 | 20.4 |
| | hourly | 15074 | 470.0 | 483.4 | +2.8 | 7.6 | 12.7 |
| TAC | 10 min | 92943 | 443.4 | 458.0 | +3.3 | 13.2 | 23.6 |
| | hourly | 14841 | 471.1 | 476.5 | +1.2 | 8.6 | 14.4 |
| GWN | 10 min | 93413 | 404.3 | 420.8 | +4.1 | 14.2 | 23.8 |
| | hourly | 15055 | 416.3 | 432.8 | +4.0 | 9.7 | 15.0 |
| TBL | 10 min | 66508 | 444.5 | 439.7 | -1.1 | 16.9 | 28.0 |
| | hourly | 10826 | 452.6 | 447.6 | -1.1 | 12.5 | 19.8 |
| DRA | 10 min | 93579 | 522.9 | 526.4 | +0.7 | 7.7 | 14.5 |
| | hourly | 15410 | 530.2 | 533.0 | +0.6 | 5.7 | 9.9 |

Regarding the overall accuracy, the rRMSD values are significantly influenced by the temporal resolution. For the high-frequency 10-minute data, rRMSD is generally high, ranging from 14.5% (DRA) to 28% (TBL). As expected, when aggregating to the hourly resolution, the random component of the error is minimized, resulting in substantial improvements in rRMSD across all sites, dropping to values between 9.9% (DRA) and 19.8% (TBL). The sites with the most stable and accurate performance are DRA and LES, consistently showing the lowest rRMSD values at both scales. The rMAD values confirm these trends, with the largest errors concentrated at TBL (rMAD=16.9% at 10-minute scale) and the lowest at DRA (rMAD=5.7% at hourly scale).

Figure 4 shows scatter plot of measured GHI versus GHIpsm for ART station, as an example, for the 10-minute and hourly scales. Figure 5 shows the same results for the GWN station. The inclusion of the 1:1 reference line in each plot facilitates a direct visual assessment of the model's bias and the dispersion of its estimations relative to the ground-based measurements.

## 5. Conclusions

This work presents the first sub-hourly evaluation of the PSM model in South America using ground truth data from the southeast of the continent, and provides evidence of its suitability for GHI estimation at mid-southern latitudes.

Results obtained show that PSM maintains a small positive relative bias, generally under 4%, without significant variation across timescales. Dispersions measured by rRMSD range from 18% to 26% at the 10-minute level and from 12% to 16% at the hourly level for the southern sites. These values are comparable to those obtained at the well-characterized SURFRAD sites, suggesting consistent model performance. Similarly, rMAD values range from 10% to 16% at 10-minute intervals and from 7% to 17% hourly, again consistent with SURFRAD benchmarks. As expected, sites dominated by clear-sky conditions (e.g., DRA) exhibit lower dispersion, highlighting the sensitivity of model accuracy to local climatic variability.

These preliminary results, based on four years (2020–2023) of high-quality ground-based measurements, confirm PSM as a promising tool for solar resource assessment at low-altitude, temperate-climate sites up to 35°S. A broader validation effort, including additional models and sites with desert climates, mountainous terrain, or seasonal snow cover, remains pending.

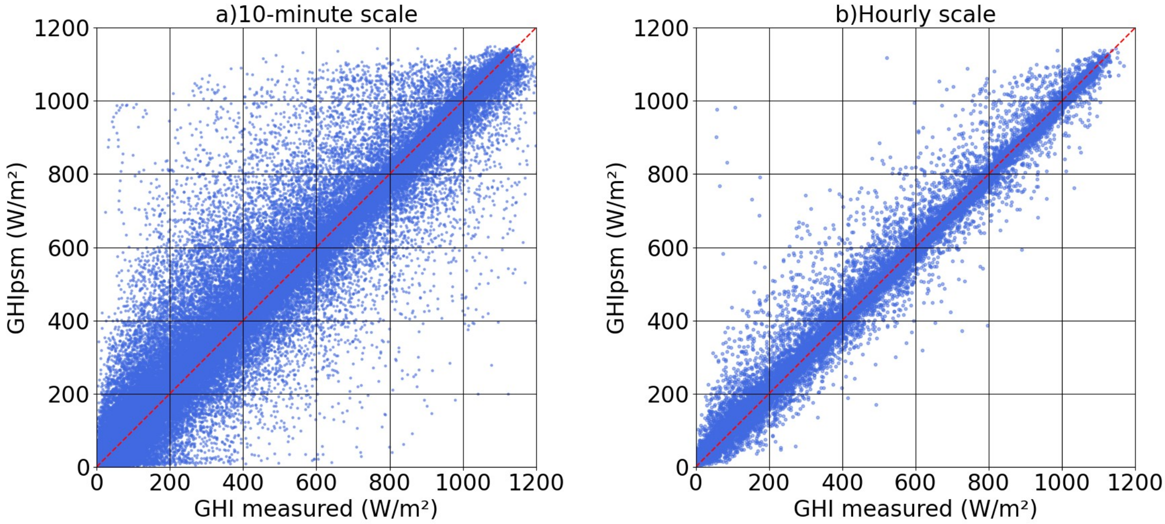


**Figure 4. Scatter plots of the PSM model estimated GHIpsm versus GHI measured at the Artigas (ART) station. (a) Data with 10-minute time resolution, (b) hourly mean data. The red dashed line indicates the 1:1 reference line.**

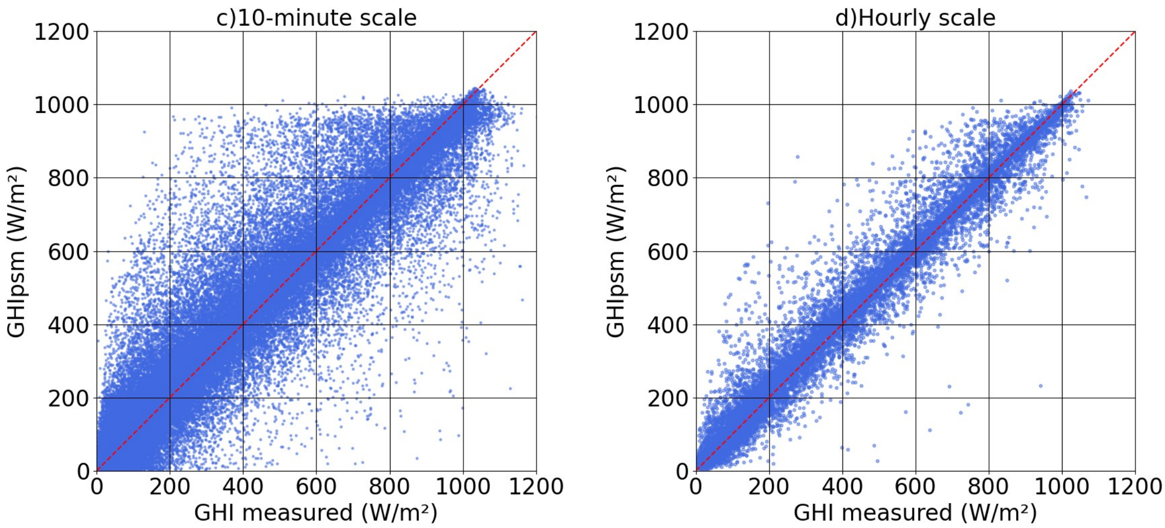


**Figure 5. Scatter plots of the PSM model estimated GHIpsm versus GHI measured at the Goldwin Creek (GWN) station. (a) Data with 10-minute time resolution, (b) hourly mean data. The red dashed line indicates the 1:1 reference line.**

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