INTER-COMPARISON AND VALIDATION AGAINST *IN-SITU* MEASUREMENTS OF SATELLITE ESTIMATES OF INCOMING SOLAR RADIATION AT REUNION BSRN SITE

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Abstract: In Reunion, where the objective is a 100% renewable electricity mix by 2030, climate variability and complex topography make it difficult to integrate solar energy into the electricity grid. This study aims to compare satellite (SARAH-3) and *in-situ* (IOS-net) data of global horizontal irradiance (GHI) and direct normal irradiance (DNI). First, the entire methodology was applied to the Reunion BSRN site, then extended to all stations in the IOS-net network. The BSRN site was selected for its different sensors, which measure the three components of solar radiation using SPN1 pyranometers (GHI and diffuse horizontal irradiance, DHI) and CHP1 pyrheliometers (DNI). The BSRN site serves as a reference to assess the accuracy of the SARAH-3 satellite estimates for other IOS-net stations, which are only equipped with SPN1 sensors. This comparison allows us to assess the reliability of satellite data because *in-situ* data are very accurate but often incomplete. In contrast, satellite data are more systematically available but less accurate due to their dependence on estimation models and a lower spatial and temporal resolution. The study covers data from December 1, 2008 to April 1, 2024, focusing on DNI (2017-2024) for concentrated solar systems and GHI (2008-2024) for PV systems. *In-situ* data from Reunion are imported from IOS-net, quality-checked according to BSRN criteria, and matched with corresponding satellite data. High-quality measurements, at one-minute resolution, collected since 2008 are used to establish correlations between ground-based and satellite data, potentially filling data gaps and improving solar irradiance predictions. This approach could help estimate GHI and DNI in areas without meteorological stations, thereby identifying new regions with high solar potential.

Keywords: GHI ; DNI ; BSRN ; solar irradiance ; SARAH-3 ; in-situ measurements.

1. Introduction

Solar radiation plays a key role in regulating the Earth's climate, and its uneven distribution over the Earth's surface leads to climate variations that influence atmospheric currents, hydrological cycles, global temperatures, and the availability of terrestrial solar energy. It is therefore crucial to accurately assess local renewable energy sources, such as solar energy, to optimize the management of energy production, consumption, and storage ([1]–[4]).

The transition to a low-carbon energy mix is essential for island regions, however, the variability of the most abundant renewable energy sources complexify this transition, which is why the study of solar irradiance variability is a crucial issue. The analysis of the comparison of *in-situ* and satellite data allows us to validate the satellite estimate and possibly improve it. For energy production purposes, it is crucial to examine variations in global horizontal irradiance (GHI) and direct normal irradiance (DNI) [5]. Many studies have shown the relationship between climate variability and surface solar radiation variability at different time scales, particularly in Reunion and the southwest Indian Ocean [6,7,17,18,19].

This study contributes to some of the 17 Sustainable Development Goals (SDGs) of the 2030 Agenda, adopted by the UN in 2015 to eliminate poverty and inequality while promoting an ecological transition. SDG 7 aims to ensure universal access to sustainable and affordable energy services, by increasing the share of renewable energy in the global mix. [21].

The study of solar resources is strategic and economic, especially for island territories such as the tropical islands of the South West Indian Ocean. These islands, dependent on imported fossil fuels, are vulnerable to the volatility of oil and gas prices, as well as to energy security risks. Solar energy offers a local and renewable alternative, reducing this dependence while stabilizing energy cost in the face of fluctuations in the global market [8]. In addition, solar energy offers tropical islands an opportunity to diversify their energy mix and boost their economic development. By making the most of their abundant sunshine, these islands can reduce their long-term energy costs, create jobs in the renewable energy sector and encourage technological innovation [9]. The transition to renewable energies is therefore crucial for the development of island territories, energy security and the reduction of greenhouse gases. It also improves public health by reducing air pollution and its impact on human health [10].

Similar to the work of Igihozo et al. (2023), SARAH-3 data are used, this time over a wider time range (2008-2024), with a larger number of stations (24 stations) considering the DNI in addition to the GHI. This study will be conducted exclusively in the South-West Indian Ocean (SWIO) region. However, due to the limited coverage of meteorological stations in this area, where the ocean presence is predominant, it is difficult to properly assess the solar resource across the entire area. Reliable and high-quality measurements are essential for effective planning and operation. The aim of this study is therefore to assess the consistency and accuracy of satellite estimates of solar radiation (SARAH-3) compared with measurements made by meteorological stations in the IOS-net project [11, 12], while analyzing their spatial and temporal variations, ranging from diurnal to seasonal cycles, over the SWIO territories, including Reunion, Mauritius, Rodrigues, the Seychelles, Madagascar, the Comoros and South Africa (Durban). It should be noted that of the 39 solar measurement stations, only the " BSRN " station at the University of Reunion has the sensors required to measure the DNI. Section 2 of this article is devoted to the description of the data sets, section 3 to the methodology, section 4 to the analysis of the results, section 5 to the discussion, and section 6 to the conclusions.

2. Data

The variables to be used in this study are the global component of solar radiation incident on a horizontal surface, i.e. Global Horizontal Irradiance (GHI), expressed in W/m², and the direct component of solar radiation incident perpendicular to the surface, i.e. Direct Normal Irradiance (DNI), also expressed in W/m².

2.1. IOS-net in-situ measurements

The *in-situ* measurements of GHI come from SPN1 pyranometers at all the stations of the Indian Ocean network (IOS-net, [12]) including Reunion BSRN site at the north of the island (Figure 1). The *in-situ* measurements of DNI are performed with a CHP1 pyrheliometer at Reunion BSRN site only. For this study, all the data available on the https://galilee.univ-Reunion.fr/ website was retrieved in order to extend the research carried out by Igihozo *et al.* [20]. As a result, the data analyzed covers the period from 1 December 2008 at 00:00 to 1 April 2024 at 23:30, for different locations in the SWIO region where data is available (Figure 1).

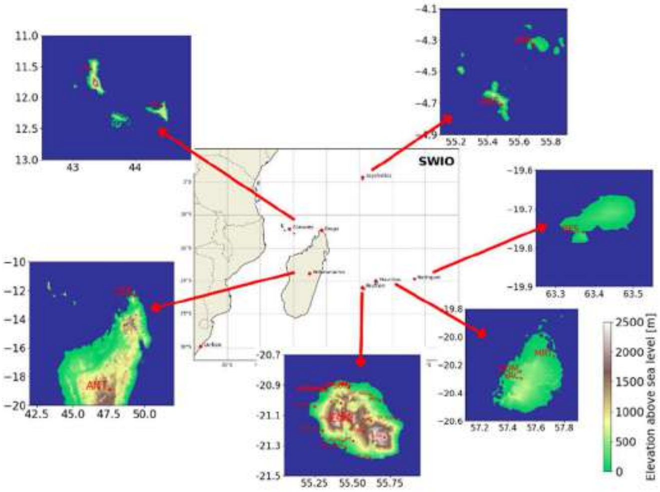

Figure 1 : Location of the IOS-net stations in SWIO used in the study with their elevation

2.2. CMSAF SARAH-3 satellite estimates

The EUMETSAT Climate Monitoring Satellite Applications Centre (CM-SAF, [13]) generates and distributes high-quality long-term climate data records (CDRs) on energy and water cycle parameters, which are available free of charge via the CMSAF Web user interface https://wui.cmsaf.eu/safira/action/viewHome. CM-SAF is a consortium involving several European meteorological services and research institutes (FMI, KNMI, MeteoSwiss, RMIB, SMHI, Met Office, CNRS) with Deutscher Wetterdienst (DWD, Germany) as the lead entity. The latest version of the "Surface Solar Radiation Data Set - Heliosat - Edition 3" (SARAH-3) has recently been published [14]. Based on the first and second generation METEOSAT satellite observations, the SARAH-3 climate data provide a range of surface radiation parameters, such as global radiation, direct radiation, sunshine duration, photosynthetically active radiation, etc. Covering the period from 1983 to 2024, the SARAH-3 data are based on the first generation of METEOSAT satellite observations. SARAH-3 provides 30-minute instantaneous SSR (Solar surface radiation) data as well as daily and monthly averages on a regular grid of

±65° longitude / ±65° latitude with an accuracy of 0.05° x 0.05° lon/lat. Because of the wide temporal range of the study, the approach adopted was to work down the temporal scale. Monthly data were used first, then, for greater accuracy, daily and 30-minute instantaneous SSR data were exploited.

3. Methodology

3.1. Estimation of DNI at the IOS-net stations

DNI needs to be estimated for all IOS-net stations, except the BSRN site. Therefore, for all the other stations, the DNI is estimated using the GHI and diffuse horizontal irradiance DHI values from the SPN1 available for each station using equation (1) :

$$DNI = \frac{1}{\mu_0}(GHI - DHI) \quad (1)$$

With μ_0 the cosine of the sun's zenith angle (SZA).

DNI can be estimated using a Python function https://github.com/GRerwan/code_stage_M1_v2.git which requires as input a DataFrame containing irradiance data (GHI and DHI), as well as a DataFrame containing geographical data (longitude, latitude, altitude), the name of the station and the time zone.

3.2. Data quality control of the IOS-net data

The quality of the data at the one-minute time step is checked using the BSRN criteria adapted to the BSRN site in Reunion [15]. The physical limit equations for GHI, DHI and DNI were recovered, with S_a being the extraterrestrial solar irradiance depending on geographical position and season, making it possible to see which sites in IOS-net dataset have good quality and also to see which sites have many errors. This is the first approach to post-processing raw data.

$$QC1 - GHI : S_a * 1.5 * \mu_0^{1.2} + 100 \quad (2)$$

$$QC2 - DHI : S_a * 0.95 * \mu_0^{1.2} + 50 \quad (3)$$

$$QC3 - DNI : S_a \quad (4)$$

An example of the results for two stations is shown in Figures 2 and 3. It was found that the GHI values for the ‘amitie’ station in Seychelles (Figure 3) comply with the physical limits of the QC1 criterion, suggesting good data quality. However, for the ‘leportmairie’ station in Reunion (Figure 2), many values exceeded this criterion, requiring them to be removed, which could affect the reliability of the averaged data. The scatter plot provides probabilistic information, with the darker areas indicating a greater density of measurement points and therefore a higher probability of the data exceeding the criterion.

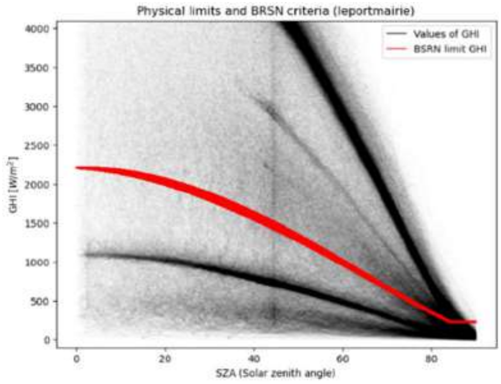

Figure 2: GHI (in black) as a function of SZA at "leportmairie" station as compared with the physical limit QC1 (in red) defined in Eq. (2) over the time period 2015 to 2017

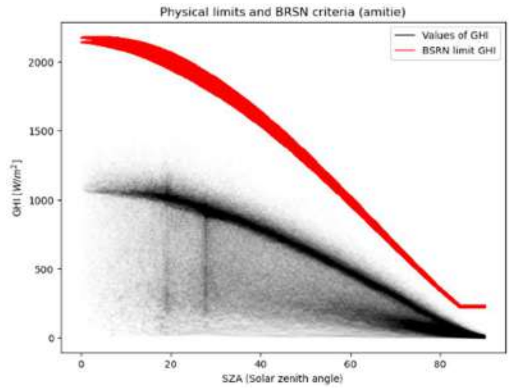

Figure 3: Same as Figure 2 but for the "amitie" station over the period 2020 to 2023

3.3. Data pre-processing

The analysis was carried out at different time scales, from annual to hourly averages. A classification of hourly irradiance profiles was carried out using the Caelus method [16] (see Section 3.4) to facilitate the analysis at the hourly time scale. Because this classification method requires 1-minute irradiance data, the method was applied to the IOS-net data only, as the SARAH-3 irradiance data is available with a 30-minute time step. The classification was applied on the filtered data. In addition, as the SWIO region covers several time zones, UTC time was retained in the analysis of the IOS-net and SARAH-3 data.

3.4. Classification of sky types

3.4.1. Savitzky-Golay filter

To improve the comparison of hourly ground data, the use of a daily cycle classification is useful and can be optimized by applying the Savitzky-Golay filter. This filter is particularly effective at smoothing irradiance data while preserving the essential characteristics of the signal, unlike moving averages, which can alter important details. It reduces the noise present in the measurements, which improves the accuracy of the classification of daily cycles. In addition, this linear filter preserves the shape of the signals without distortion, making it easier to recognise patterns. It is easy to implement and can be adjusted to suit specific needs, making it an excellent choice for pre-processing data in the classification of daily cycles.

3.4.2.Caelus method

After applying the Savitzky-Golay filter [23], and following the Caelus method [16], it is possible to classify the days into 6 distinct categories according to the type of sky, thus improving the relevance of the results. This classification is essential to more rigorously compare data from land stations. Grouping similar days, simplifies the analysis and facilitates the interpretation of variations in the solar resource. This makes it possible to identify whether the estimation errors are constant or specific to certain types of days. The Caleus classification has not yet been used with satellite data because the existing program is not compatible.

3.4.3. Study considerations

It is also important to point out that, to improve the comparison of data sets, it was decided to consider only the irradiance measured between 02:00 and 14:00 UTC to limit ourselves to the daylight period. This approach was chosen to avoid working with many missing values during the night, when irradiance is naturally zero or non-existent. By concentrating on this time period, it is possible to obtain more consistent and comparable data, which facilitates the analysis and reliability of the results.

3.5. Measures of accuracy

A set of statistical measures, including mean bias error (MBE), root mean square error (RMSE), and mean absolute error (MAE), were used to assess the reliability of SARAH-3 solar irradiance estimates compared with *in-situ* data. These indicators make it possible to assess the trend in deviations, the overall dispersion of errors, and the average precision of estimates. By combining these measurements, it is possible to assess the performance and adequacy of SARAH-3 estimates in relation to data observed on the ground.

4. Results

4.1. Comparison of estimated and measured DNI at Reunion BSRN site

Several results were obtained for the DNI data at Reunion BSRN site. Firstly, as the BSRN station hosts a CHP1 pyrheliometer to measure DNI, it was possible to compare the measured DNI with the DNI estimated from the GHI and DHI measurements performed with a SPN1 pyranometer (Eq. 1). Figure 4, showing the scatter plot at different timescales, shows that the two DNI values are very close (from 21.23 W/m² to 75.49W/m² for RSME). It can therefore be said that the estimated DNI represents the measured DNI relatively well.

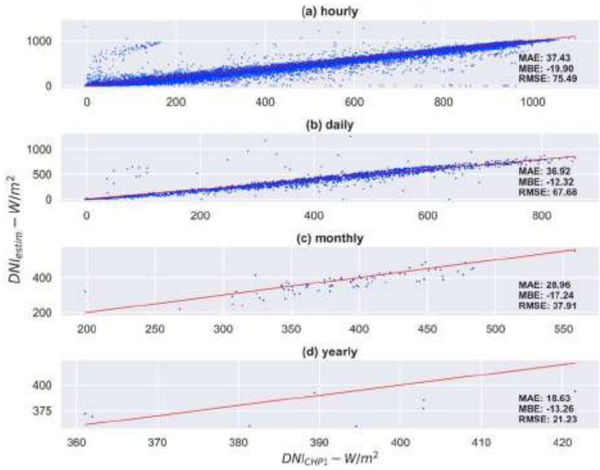

Figure 4: Scatter plots of measured DNI (CHP1) with estimated DNI (SPN1) at the BSRN site in Reunion from the hourly (top) to the yearly (bottom) time scales and associated values of the statistical metrics (MAE, MBE and RMSE, in W/m^2). Data which are taken over the whole range of available DNI measurements from the CHP1, covers the period from 2016-08-01 to 2024-04-01.

4.2. Comparison of in-situ and satellite-derived DNI

Secondly, the comparison between *in-situ* and SARAH-3 DNI at Reunion BSRN site shows that the satellite has difficulty estimating the DNI in view of the distribution of the different point clouds (Figure 5). In this case, the scatterplot for the hourly mean does not correspond precisely to the x = y curve, indicating a poor correlation of the DNI values for the hourly mean. This is confirmed by a high RMSE value of 227.59 W/m², suggesting a poor estimate of the hourly satellite data. Satellite estimates for hourly averages are therefore not very reliable (Figure 5). On the other hand, for the daily and monthly averages, the scatter plot more closely follows the x = y curve, and the RMSE and MAE values decrease, indicating reduced errors between the two DNI data sets. This means that the estimates become more accurate at these time scales. Care must therefore be taken when interpreting the results, as the difference between the *in-situ* and SARAH-3 data may differ depending on the time scale considered.

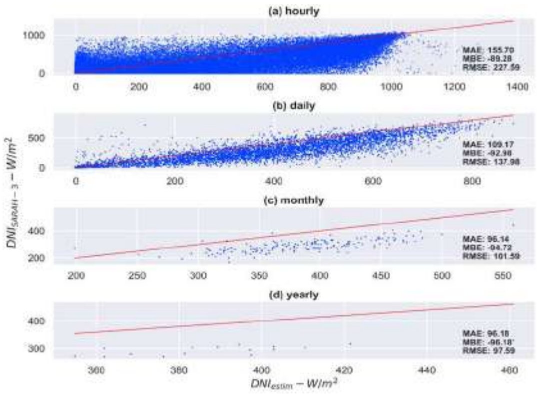

Figure 5: Scatter plots of estimated DNI (SARAH-3) with estimated DNI (SPN1) at the BSRN site in Reunion from the hourly (top) to the yearly (bottom) time scales and associated values of the statistical metrics (MAE, MBE and RMSE, in W/m^2). Data which are taken over the whole range of available DNI measurements from the SPN1, covers the period from 2008-12-19 to 2024-04-01.

4.3. Comparison of estimated and measured GHI at Reunion BSRN site

Figure 6 shows the scattering of points for different time averages, comparing SARAH-3 and SPN1 GHI at Reunion BSRN site. It is to be noted that SARAH-3 estimates GHI better than DNI, as indicated by the trend of points close to the y = x curve. Errors evaluation confirm that SARAH-3 estimate of GHI is twice as accurate as that of DNI, with a RMSE of 69.15 W/m² for GHI compared with 138 W/m² for DNI for daily mean. The MBE, ranging from -23.6 W/m² to -34.9 W/m², also shows an underestimation of the data by SARAH-3.

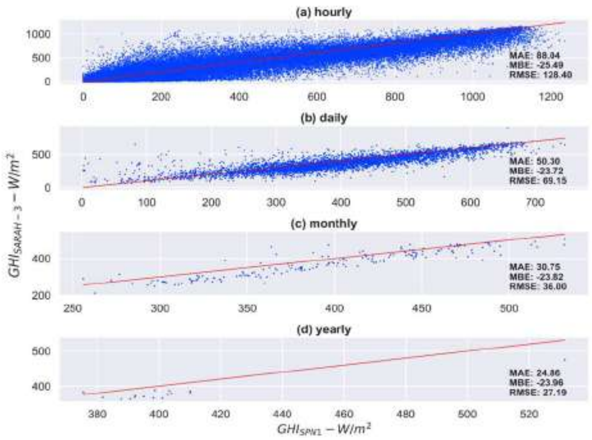

Figure 6: Scatter plots of estimated GHI (SARAH-3) with GHI (SPN1) at the BSRN site in Reunion from the hourly (top) to the yearly (bottom) time scales and associated values of the statistical metrics (MAE, MBE and RMSE, in W/m^2). Data which are taken over the whole range of available GHI measurements from the SPN1, covers the period from 2008-12-19 to 2024-04-01.

4.4. GHI and DNI measures of accuracy for all stations

In this study, it was arbitrarily chosen to keep only stations with data over a time range greater than 2 years with consecutive missing values of less than 3 months.

Table 1 : Mean Absolute Error (MAE), Mean Bias Error (MBE), and the Root Mean Square Error (RMSE) in W/m² of the stations and their corresponding pixel in SARAH-3 daily mean GHI data.

Stations	MAE	MBE	RMSE
Anseboileau(ANS)	76.02	60.11	86.99
Antananarivo(ANT)	99.45	-6.99	205.77
Bras Panon(BRA)	62.34	6.63	81.79
Cilaos Piscine (CIL_PISC)	77.47	-18.76	93.22
Cratère Bory(CRA)	215.57	-176.76	301.13
Diego(DIE)	109.26	-50.20	159.62
Durban(DUR)	190.84	-145.65	239.00
Edf Bois de Nefles(EDF_BOIS)	67.12	7.69	90.69
Edf la Possession(EDF_POSS)	67.57	-14.73	82.41
Edf Saint-André(EDF_AND)	69.95	32.56	89.56
Edf Saint-Leu(EDF_LEU)	69.64	-23.78	84.46
Edf Saint-Pierre(EDF_PIER)	72.80	-44.73	87.03
Hahaya(HAH)	55.76	20.37	68.08
Le Port Barbuse(LEP_BUSS)	73.83	-34.67	90.44
Le Port mairie(LEP_MAIR)	235.49	-222.59	275.45
Mrt Bras d'Eau(MRT)	67.88	47.31	84.04
Ouani(OUA)	61.75	18.42	73.08
Piton des Neiges(PIT)	151.65	-101.05	179.81
Plaine parc national(PLA)	72.94	24.60	89.76
Reserve Tortues(RES)	63.89	-5.91	88.33
Sainte-Rose mairie(ST_ROS)	59.70	20.35	80.06
Saint-Louis Jean Joly(ST_LOUIS)	73.95	-8.82	101.22
UR Moufia(URM)	50.30	-23.72	69.15
Vacaos(VAC)	58.18	21.09	71.14

Table 2 : same as Table 1 but for DNI

Stations	MAE	MBE	RMSE
Anseboileau(ANS)	40.33	8.06	54.47
Antananarivo(ANT)	72.81	-33.16	212.52
Bras Panon(BRA)	46.73	-24.70	71.18
Cilaos Piscine (CIL_PISC)	95.76	-77.35	122.09
Cratère Bory(CRA)	264.89	-246.53	343.96
Diego(DIE)	83.90	-66.57	143.51
Durban(DUR)	151.85	-149.30	195.11
Edf Bois de Nefles(EDF_BOIS)	50.37	-37.66	80.63
Edf la Possession(EDF_POSS)	81.13	-71.78	103.47
Edf Saint-André(EDF_AND)	44.07	0.22	64.99
Edf Saint-Leu(EDF_LEU)	84.68	-75.74	108.12
Edf Saint-Pierre(EDF_PIER)	88.24	-86.41	107.87
Hahaya(HAH)	47.78	-26.41	63.92
Le Port Barbuse(LEP_BUSS)	100.03	-93.08	123.59
Le Port mairie(LEP_MAIR)	278.25	-277.71	311.29
Mrt Bras d'Eau(MRT)	42.66	20.71	59.39
Ouani(OUA)	39.03	-17.66	53.09
Piton des Neiges(PIT)	169.10	-158.55	212.38

Plaine parc national(PLA)	58.08	-45.34	79.67
Reserve Tortues(RES)	47.59	-33.58	74.89
Sainte-Rose mairie(ST_ROS)	35.67	-15.54	58.03
Saint-Louis Jean Joly(ST_LOUIS)	49.32	-34.60	79.74
UR Moufia(URM)	62.75	-54.66	83.87
Vacoas(VAC)	43.05	-33.31	53.84

The data in Tables 1 and 2 are provided for the daily average to facilitate comparison with the findings reported by Igihozo et al. [20]. Unlike DNI estimates, GHI values appear to be overestimated by the SARAH model for some stations (see Table 1). In general, in this study, stations with more precise estimates (MAE less than 70 W/m²), show a tendency to overestimate the GHI values by SARAH-3. Conversely, at stations with a relatively high RMSE, the GHI values are underestimated by SARAH-3. However, regarding the DNI, there is rather a tendency to underestimate the irradiance data by SARAH-3 whatever the MAE value. In particular, the stations of "Cratère Bory" and "Le port mairie" present the least precise estimates, with RMSE and MAE values greater than 200 W/m² for both the GHI and the DNI.

4.5. Sky classification

Therefore, the analysis of the distribution of various sky types provides valuable insights into satellite estimation. Without exception, the percentage of scatter clouds on all stations of the IOS-net network exceeds 50%. However, we know that the presence of clouds, especially scattered clouds, impairs the accuracy of satellite estimation, so the presence of clouds could illustrate a divergence between *in-situ* and satellite measurements that would be systematic as can be seen in the study of Pfeifroth *et al.(2024)* [22].

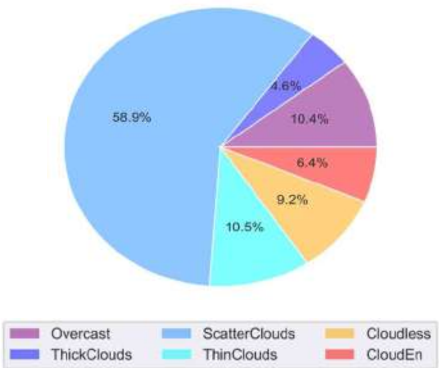

Figure 7: Sky Classification of hourly data at the BSRN site with the Caelus method (https://github.com/jararias/caelus), (CloudEn=Cloud Enhancement).

5. Discussion

To evaluate the performance of SARAH-3 in estimating the SSR (DNI and GHI), satellite data were compared to *in-situ* measurements with analysis at different time scales, ranging from annual means to diurnal cycles. This approach revealed differences with mean errors varying between 20 W/m² and 320 W/m² for the RMSE, up to 280 W/m² for the MAE, and between -280 W/m² and 70 W/m² for the MBE, indicating significant discrepancies between SARAH-3 estimates and ground-based data. Comparing the results of this study with those obtained by the work of Igihozo *et al.(2023)*, we notice that there is a greater difference between satellite and *in-situ* data when considering a larger time range. For example, for the BSRN site (UR Moufia) the RMSE goes from 26.56 W/m² to 69.15 W/m². This shows that one year is not necessarily sufficient to represent a station.

The discrepancies observed between SARAH-3 estimates of SSR and *in-situ* measurements could be due to approximations in the atmospheric parameters used by the GNU-MAGIC/SPEMAGIC algorithm, such as aerosol, water vapour and ozone levels. This difference can also be explained by the proportion of sky types resulting from the Caelus classification. The presence of clouds weakens the viability of satellite estimates, since one of the main input data of the SARAH-3 algorithm concerns the cloud index. SARAH-3 relies on monthly mean data for aerosols, a resolution considered too coarse for such a crucial parameter, which can affect the accuracy of estimates, especially in regions with no ground-based measurements. In addition, the spatial resolution of SARAH-3 (0.05° x 0.05°, or 25 km² per cell) may be insufficient in regions with rugged terrain, where topographical variations can cause significant differences in insolation. A finer resolution would therefore be required for more accurate estimates of solar irradiance, suggesting the need to develop research methods to improve this resolution.

6. Conclusion

The aim of this study was to compare and assess the consistency and accuracy of the SSR estimates provided by CM-SAF SARAH-3 with *in-situ* measurements from the IOS-net radiometric network. In addition, the study aimed to analyse the temporal variability of the solar resource in the territories of the south-west Indian Ocean, including Reunion, Mauritius, Rodrigues, the Seychelles, Madagascar, the Comoros and South Africa.

In order to compare SARAH-3 data with *in-situ* data, hourly, daily, monthly and annual comparisons were carried out for all the data from the 24 stations in the IOS-net network. The results obtained show the variability of the solar resource from a temporal and spatial point of view. SARAH estimates are more or less accurate depending on the stations considered. The main point to emerge from the results is that the DNI data are underestimated by SARAH for 92% of the stations. For GHI, SARAH-3 overestimates irradiance values for around 40% of stations. Moreover, according to the results obtained, the GHI estimates are twice as accurate as the DNI estimates. These variations in estimates are explained by the 5km spatial resolution, which means that significant variations occur within each 25km² pixel.

This study therefore highlights several characteristics of the solar resource. It shows that the SARAH-3 satellite estimation model can be a major asset for characterising the solar resource, especially in areas without observations. Although SARAH-3 tends to underestimate DNI and overestimate GHI, an in-depth analysis, including the classification of stations according to topography and surrounding relief, could improve the accuracy of the results obtained between satellite and *in-situ* data. In addition, the accuracy of the estimates could be improved by increasing the spatial resolution of the satellite data.

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