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EVALUATION OF SOLAR RADIATION ESTIMATED FROM HIMAWARI-8 SATELLITE OVER VIET NAM REGION

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Abstract. Data for the characterization of short-term and inter-annual variability of solar radiation availability are becoming highly valuable for renewable energy deployment. Satellite imagery provides an ability to monitor the surface radiation over large areas at high spatial and temporal resolution as alternatives at low cost. Observations from the latest Japanese geostationary satellite Himawari-8 produced imagery covering Asia-Pacific region permitting estimations of Global Horizontal Irradiance (GHI) and Direct Normal Irradiation (DNI) over Viet Nam at 10-minute temporal resolution. However, accurate comparisons with ground observations are essential to understand their uncertainty. In this study, we evaluated the Himawari-8 radiation product, named AMATERASS, provided by solar radiation consortium under Japan Science and Technology Agency (JST), Strategic Creation Research Promotion Project/Terrestrial Energy Estimation and Demand Data Analyzes (CREST/TEEDDA) using observations recorded at 5 stations in different regions of Viet Nam. The result showed good agreement between satellite estimation and observed data with high correlation of range 0.92-0.94, and better in clear-sky episodes. We compared GHI estimates of EMATERASS with ERA-Interim reanalysis in the spatial scale. The comparison was made separately for 7 climate zones and 4 seasons. The results showed that ERA-Interim products were well associated with satellite-based estimates in seasonal trends, but with different biases. The difference between two products was particularly pronounced in the months of DJF periods and in the north part of Viet Nam because of unresolved cloud in the ERA reanalysis. Thus, satellite estimation of Solar irradiation could be used for producing reliable solar radiation maps for Viet Nam in condition of limited surface network of observations.

Keywords: solar energy, satellite-based solar radiation, Himawari-8.

Classification numbers: 3.4.1, 3.7.1, 3.8.1.

1. INTRODUCTION

Exploiting renewable energy sources, such us wind and solar energy, is one of the important plans in the global energy security as well as in the sustainable development strategy for reducing greenhouse gas emissions not only for developed countries but also for Viet Nam [1]. By the encouragement of the Viet Nam Government, a development of solar energy system has rapidly grown in recent years. Accurate knowledge of the solar radiation reaching the surface plays an essential role in the successful deployment of solar photovoltaic plants. Solar energy on the Earth's surface is far different from that at the top of atmosphere due to interaction of solar radiation when passing through the atmosphere through scattering and absorption processes with gas molecules, aerosol and clouds. Clearly, the solar energy will be significantly reduced during periods of cloud cover and there will be fluctuations in space and time. Therefore, only direct measurements on the ground can accurately evaluate the solar radiation at the surface. However, the density of global stations is very limited, and is often not available in locations where solar system installations can be planned. With outstanding advantages in spatial coverage, resolution and monitoring frequency, geostationary satellites have become useful alternative tools to extract solar radiation components at surface over a large area, especially for areas where there are no measuring stations with hourly frequencies [2].

The goal of satellite-based radiation estimation models is to use solar radiation at the top of the atmospheric and albedo to calculate Global Horizontal Irradiation (GHI) and Direct Normal Irradiation (DNI) at the ground. Over the last decades, there have been different algorithms developed to estimate solar radiation at the earth's surface from satellite images [3-6] and they are mainly divided into three approaches [7]: empirical, physical, and semi-empirical models. With their maturity in the methodology, satellite-based methods have become the most widely option to evaluate solar radiation over the globe [8]. Up to date, surface global solar radiation estimates are routinely performed by using the images recorded from geostationary satellites, such as the Meteosat Second Generation (MSG) over Europe and Africa and the Geostationary Operational Environmental Satellites (GOES) over America and South America, and GMS/Himawari-8 (Geostationary Meteorological Satellite) over Asia Pacific. From those, different datasets of solar radiation are available to provide long term record data over the globe or specific focused regions, such as Europe and Africa with the coverage of MSG satellite [9].

Viet Nam region is covered by the GMS-series satellites of Japan Meteorological Agency (JMA). Before the year of 2016, the only clear sky radiance from these images has been provided by JMA for different national hydro-meteorological agencies. This product is useful for assimilating into regional numerical weather models but not sufficient for energy application as it does not account for cloud condition, which significantly reduces the radiation by reflection and absorption of cloud. Since the launch of the latest satellite Himawari-8, the Advanced Himawari Imagers (AHIs) have acquired full-disk observations in 16 bands every 10 min with a spatial resolution ranging from 0.5 to 2 km [10]. Recently, new surface downwelling solar radiation estimates from Himawari-8 observations made by applying the EXtreme speed and Approximation Module (EXAM) multiple drive system algorithm [11] have been released for wider applications, particularly in energy sector. The product is also available for Viet Nam region, therefor we evaluated it by using surface observations.

Another approach to assess surface solar irradiation is re-analysis tool, where numerical weather models for forecast are used in re-analysis mode to re-produce Earth-atmosphere states over the globe in combination with ground observations and satellite data [12]. Although, the accuracy of irradiance estimates from re-analysis seems generally lower than that of satellite-based products [9, 13], re-analysis products are comparable with satellite-based products in terms of spatial and temporal coverages and free availability. There are two types of reanalysis, global and regional, depending on their spatial extent. Global reanalysis is common type and two widely used datasets are ERA-Interim [14, 15] from the European Centre for Medium-range

Weather Forecast (ECMWF) and MERRA-2 from NASA's Global Modeling and Assimilation Office (NASA's GMAO) [15]. Recently, a comprehensive comparison between re-analyses of solar irradiation from ERA-Interim and MERRA and measurements at surface in Europe, Africa and Atlantic Ocean has been carried out in a study of Boilley and Wald [12]. Their results revealed the overestimation trend in both re-analysis datasets, however, they found better correlations and less bias within an irradiation homogeneous area of North Africa.

Located in the tropical region, Viet Nam has a great potential advantage in solar energy development with a large number of sunny hours along the country. However, the limited reference solar radiation network is a possible barrier for investors. There have been only 12 pyranometers operated by the Hydro-meteorological agency since 2014. Recently, with the support from the World Bank, 5 more pyranometers have been installed from 2017. Satellite-based and re-analysis estimates of solar irradiation could become a substitution of ground measurement only with proper understanding of their limitations and uncertainties. Therefore, this study focuses on assessing the quality of satellite-based and re-analyses products when compared to qualified ground measurements of recently installed stations in Viet Nam. To understand better the difference between satellite and re-analysis estimates, a comparison is also performed between them for different climate regions. The rest of this paper is organized as follows. Section 2 presents descriptions of satellite-based AMATERASS and ERA-interim solar irradiance products as well as surface-observed data used in this analysis. The assessment of the error and its spatial variations are investigated in Section 3. Results of evaluations and discussion on different climate regions depending on seasons are also presented in this section. Conclusions are provided in the Section 4.

2. MATERIALS AND METHODS

2.1. Solar radiation products

2.1.1 AMATERASS data

The estimation of surface downwelling global shortwave (SW) radiation from new generation satellite Himawari-8 using the EXAM algorithm [11] produces solar radiation products, named AMATERASS [16]. This algorithm was based on a fast neural network, accurately reproducing the radiative transfer model using the Comprehensive Analysis Program for Cloud Optical Measurement (CAPCOM; [17, 18]) method to retrieve cloud optical thickness and cloud-particle effective radius from Himawari-8 observations by a lookup table (LUT) approach under a homogeneous plane-parallel and single-layer cloud model. Additional input information included in EXAM, such as water vapor and ozone, was acquired from external sources (e.g., the Japanese Reanalysis JRA-55 [19] and OMI/Aura [20] satellite), and surface albedo was computed from Himawari-8 observations using a statistical method [19].

AMATERASS 30-min data with spatial resolutions of 4 × 4 km was downloaded from ftp.amaterass.org of solar radiation consortium (JST/CREST TEEDDA) with permission for a research purpose. From 30-min data we computed daily products and interpolated them into sites of surface observations by bilinear interpolation method or the nearest point method if less than 4 points available.

2.1.2 Reanalysis data (ERA-interim)

ERA-Interim is the 4th generation of reanalysis products from the European Centre for Medium-Range Weather Forecasts ECMWF [14]. This dataset has a spatial resolution of 0.125 × 0.125 degree and 60 vertical levels from ground to level of 0.1 hPa. The radiative transfer model in ERA-Interim uses climatological values for aerosols, carbon dioxide, trace gases and ozone, while it takes prognostic information from the forecasting model for the water vapor. In addition, the irradiance at the top of the atmosphere is higher of 2 W/m^2 [14]. The variable used for this study is the surface solar radiation downwards (SSRD) [J/m2]. We retrieved data at the steps 3, 6, 9 and 12 hours from the two daily forecasts performed at 00:00 and at 12:00 for 1-year period, which corresponds to that of satellite products from November 2017 to October 2018. ERA-Interim data was downscaled to AMATERASS resolution of 4×4 km by bilinear interpolation for comparison and also bi-linearly interpolated to the measurement stations for validation. Daily irradiation is computed by summing the eight available GHI estimates after multiplying them by the number of seconds in 3 hours and converted to W/m^2.

2.2. Surface radiation data

For validating satellite-based and re-analysis solar irradiance, in this study we used highly qualified data of 5 First-class stations installed under the World Bank project for 1-year continuous period. This data is freely available on the website of the WB at https://energydata.info/dataset/esmap-solar-measurements-in-vietnam. These stations automatically measure 3 components of solar radiation at surface including GHI, HNI, and DNI together with temperature, pressure, and wind at every 1 minute. Monthly data of 1-min measurement and of hourly average with daily report on the measurement quality is available on the web after data screening. The reason we used data from these stations is because of their availability and continuous consistency during the study period chosen.

The locations of these 5 ground stations and the topography are shown in Fig. 1. Detail description of station name, height, latitude and longitude are given in Table 1.

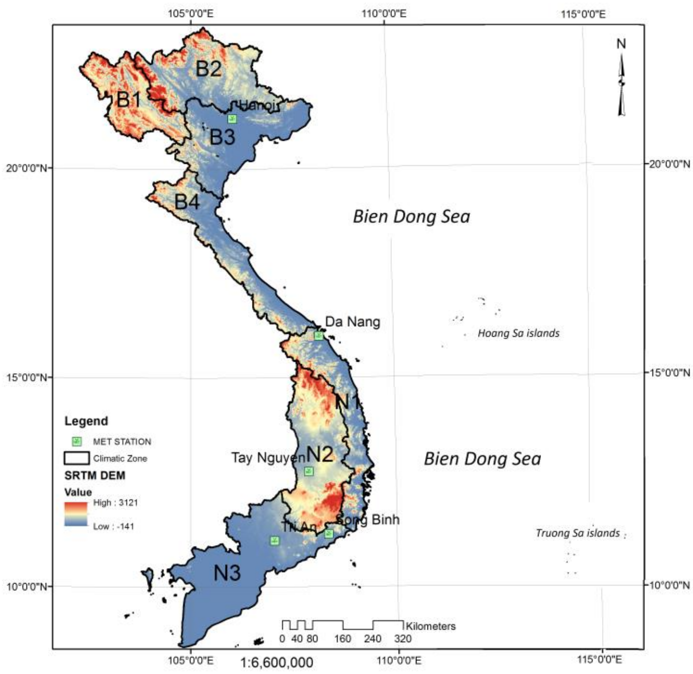

Figure 1. Locations of World Bank ground stations in Viet Nam and division of 5 climate zones (B1, B2, B3, B4, N1, N2, N3).

Table 1. Description of 5 pyranometer stations used for evaluations.

Station Name	Code	Height	Latitude	Longtitude
Ha Noi	VNHAN	40 m	21.2015°N	106.0630°E
Da Nang	VNDAN	20 m	1 6.01257°N	107.18649°E
Tay Nguyen	VNCEH	275 m	12.7534°N	107.8763°E
Song Binh	VNSOB	59 m	11.2640°N	108.3452°E
Tri An	VNTRA	57 m	11.1024°N	107.0378°E

2.3. Method for evaluation

AMATERASS and ERA-Interim GHI data were bi-linearly interpolated to above mentioned 5 station positions after processing to daily products. The deviations of estimates from ground-true data were computed by subtracting measurements from satellite-based and re-analyses estimations. These deviations of daily and hourly variables are characterized by the mean bias error (MBE), mean absolute error (MAE), root mean square error (RMSE), and the correlation coefficient. Following Bojanowski *et al*. [13], we also computed relative bias and RMSE by dividing the bias and the RMSE by the average value of all observations for each station.

In order to overcome the limitations of small number of ground stations and validating gridded products against point records, a spatial validation was also performed by calculating the difference between ERA-Interim and AMATERASS at grid scale. Comparisons were carried out separately for 7 different climate regions, namely the Northwest (B1), Northeast (B2), North Delta (B3), North Central (B4), South Central (N1), Central Highlands (N2), and the South (N3) (Fig. 1) and divided by 4 seasons (winter - DJF, spring - MAM, summer- JJA, and autumn - SON).

3. VALIDATION RESULTS AND DISCUSSION

3.1. Satellite –based and re-analysis estimate evaluation by ground measurement

Firstly, we compared daily products of GHI estimated by Himawari-based AMATERASS and ERA-Interim re-analysis with surface daily accumulation by pyranometer at 5 stations. Figure 2 shows scatter plots of these comparisons between ground observations with AMATERASS and ERA-interim estimates. As clearly seen, AMTERASS estimates incline to positive bias in comparison to ground observed solar radiation at 5 locations, while ERA products are in wider disturbance with inclining to negative bias at 4 stations, except Hanoi. The AMATERASS estimates reproduced the observations agreeably at all stations with correlation coefficients comparable (0.91 to 0.94) at all stations (Table 2). This trend is similar to that reported in the study of Dimiani [21] at 4 stations in Japan.

In contrast to Himawari-based products, ERA-Interim solar irradiance estimates found considerably less correlated with surface observations at all stations. Their daily products only have correlation coefficients in range of 0.6 - 0.7 (Table 2). The lower correlation of re-analysis estimates with ground observations compared to that of satellite-based estimates is highly consistent with previous studies, because of the superior quality in satellite estimates [22]. Table 2 indicated larger values of MAE and RMSE of ERA-interim with observations than those of Amaterass with observations. In addition to different methods of their estimates, both re-analysis and satellite products representative for an average of solar irradiance over a cell, were interpolated to points estimates, hence larger errors are associated with higher spatial variability and coarser grids [23]. By mentioning the impact of aerosol on surface solar radiation in many previous studies, authors explained that due to an absence of aerosol effect in the EXAM algorithm for AMATERASS products, under cloudless conditions, the model could result in an overestimate of surface solar radiation, depending on the actual aerosol load at locations. And their results concluded that the total mean bias was approximately 10–15 W m-2 under clear-sky conditions, mainly because of overall instantaneous direct aerosol forcing efficiency in the range of 120–150 W m^{-2} per unit of aerosol optical depth, however, cloud variability was the main source of uncertainty in the satellite estimates, followed by direct effects of aerosols and bright albedo. Therefore, the total mean bias was found in the range of 20–30 W m^{-2} under all-sky conditions [21].

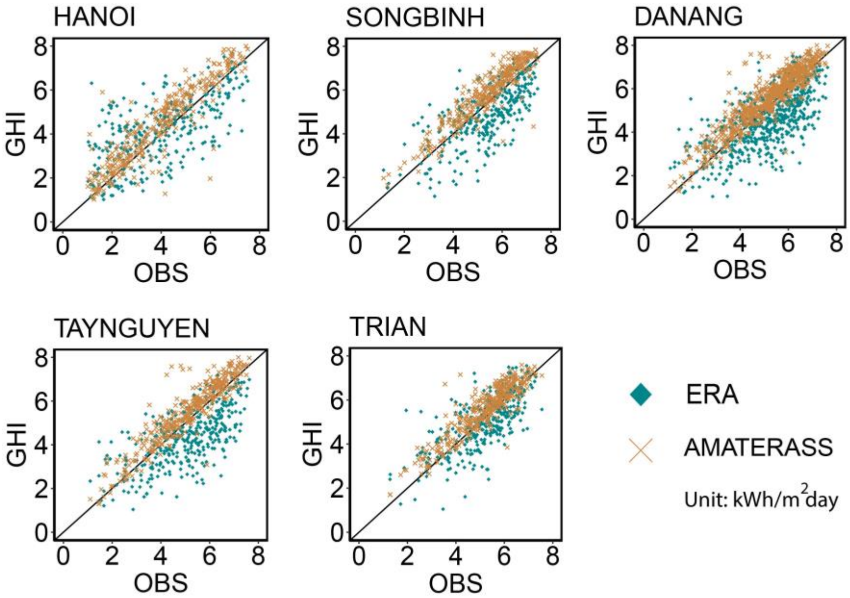

Figure 2. Scatter plot of ground observations and Amaterass estimates of daily GHI at 5 stations during 10/2017-9/2018.

Table 2. Statistic comparison between AMATERASS, ERA-Interim and ground measurements. Relative values are expressed relatively to the mean observed value.

Station	HA NOI		DA NANG		TAY NGUYEN		SONG BINH		TRI AN	
	AMA	ERA	AMA	ERA	AMA	ERA	AMA	ERA	AMA	ERA
r	0.91	0.67	0.92	0.69	0.93	0.68	0.93	0.72	0.91	0.72
MBE (kWh/m^2)	0.48	0.17	0.4	-0.52	0.4	-0.75	0.47	-0.44	0.38	-0.15
MAE (kWh/m^2)	0.66	1.04	0.51	0.93	0.5	1.08	0.56	0.87	0.48	0.72
RMSE (kWh/m^2)	0.89	1.33	0.68	1.17	0.68	1.32	0.69	1.08	0.64	0.92

Apparently, the AMATERASS and ERA showed opposite bias in comparison with ground observations at 4 stations, except Hanoi station. Although these stations are located at 5 different regions, it is hard to interpret the performance of AMATERASS and ERA-interim in spatial variation. Therefore, it is worth to compare directly the ERA-Interim with satellite-based estimates assuming the latter as an approximation of ground observations because of its outperforming the former.

Table 3. Correlation between AMATERASS and ground measurements by hourly data.

Station	Ha Noi	Da Nang	Tay Nguyen	Song Binh	Tri An
r (hourly)	0.9283	0.9124	0.9479	0.9515	0.9550
r (hourly/ clear sky)	0.9810	0.9027	0.9702	0.9836	0.9782

For AMATERASS product, we also evaluated hourly data separately for all-sky conditions and for clear-sky episodes. The clear-sky condition was defined by clear sky index KT greater than 0.7 following Boilley and Ward [12]. An improvement of correlation coefficients in clear sky conditions was noted in 4 stations with the best one at Hanoi station, except Da Nang station with slight declination as in Table 3. Although aerosol was not explicitly solved in the algorithm producing AMATERASS [11], the performance of its solar estimates was improved in clear-sky conditions indicating the larger obstruction of cloud on the surface solar radiation. Divergent mean bias and root mean square errors were also found for different stations depending on their location and cloud variability conditions.

3.2. Spatial comparison of ERA-Interim with satellite products

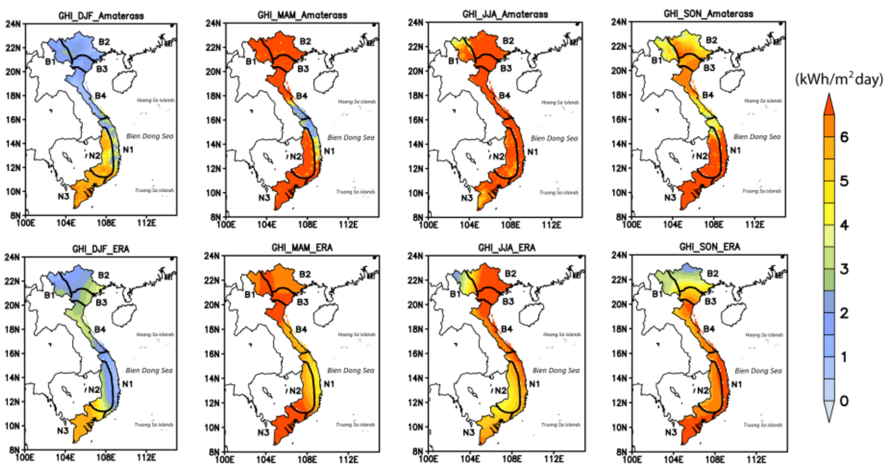

Figure 3. Mean daily GHI of AMATERASS estimates (above line) and ERA-Interim (below line) divided by seasons (Winter – DJF; Spring – MAM; Summer –JJA; Autumn – SON).

The maps of average solar radiation GHI (kWh/m^2day) during 2017 -2018 in 4 seasons are plotted in Figure 3. Both products showed clear different seasonal variation in the north and in the south. In the north, the lowest GHI occurred in the months of DJF period and reached the maximum during MAM and JJA periods, then declined in SON months, while in the south two periods of maximum GHI were MAM and SON, the months of DJF and JJA had lower GHI, but not as small as that during DJF months in the north. Although, two estimates shared similar patterns in the north and in the south, they also exhibited the deviation in average values in different climate zones. For examples, in the months of DJF, ERA-Interim revealed considerably lower estimates in N1 and N2 zones and slightly higher in the eastern part of B2, B3, and B4 zones, while in the months of MAM, AMATERASS produced lower estimates in the central parts belong to B4 and N3 zones. In the periods of MAM and SON, both estimates are comparable for N3 zone.

We computed statistic correlation between them at grid scale for 4 seasons as shown in Figure 4. It is interesting that the lowest correlation coefficient (below 0.5) was found in N3 zone in the months of MAM and SON. The highest correlation was along the central part of Viet Nam. In the northern part, two products were well correlated in all seasons with coefficients over 0.7.

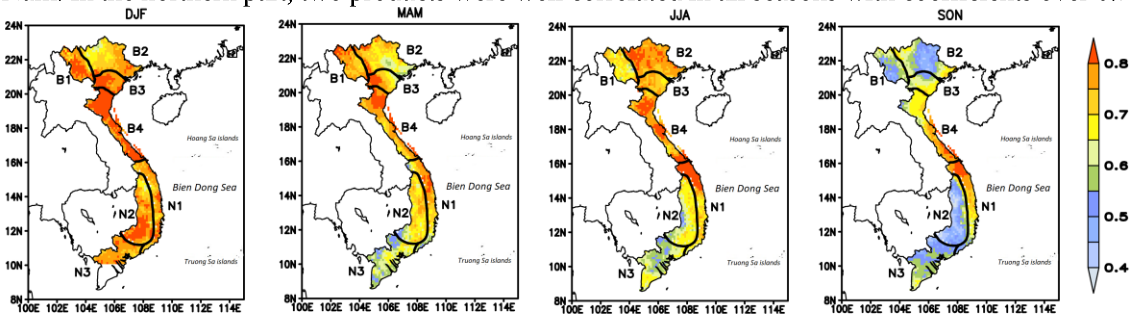

Figure 4. Correlation coefficients between ERA-Interim and AMATERASS estimates of GHI divided by seasons.

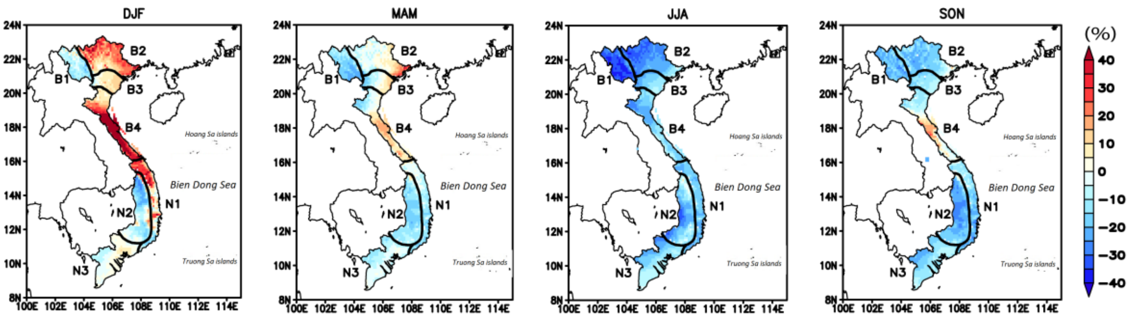

Figure 5. Relative mean bias of GHI estimates between ERA-Interim and AMATERASS divided by seasons.

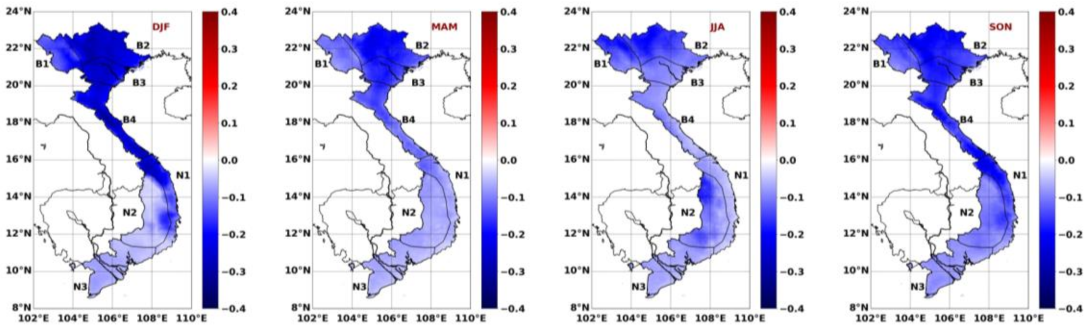

Figure 6. Mean bias of cloud fractions between ERA-Interim and Himawari-8 divided by seasons.

In the month of the winter season, in all climate zones correlation coefficients were approximately greater than 0.7. Spatial variation of relative mean error in Figure 5 revealed that mean positive biases were mainly found in the northern parts of Viet Nam, B1, B2, B3, and B4 regions, particularly in the DJF period, and reached to the highest of 40 % in the B4 region. In contrast to that, only slightly negative biases were found in the N1, N2, and N3 regions all year around and the most comparable estimates of GHI between ERA-interim and AMATERASS were in the N3 region. We anticipated a possible reason for higher estimates of ERA-interim in the northern regions as a difference in cloud fraction simulation by models compared to observations by satellite. The northern part of Viet Nam is strongly affected by cold surge, because of the topographic configuration, it makes enhancement of cloud covers in sub-grid scale of the model, resulted in higher GHI estimation of ERA-interim compared to AMATERASS [24, 25]. This point of view was clear out by comparing cloud fractions between ERA and Himawari-8 estimates as in Figure 6, which showed correspondingly the largest underestimations of in the northern regions in DJF period. In addition, the negative biases of ERA-interim GHI towards AMATERASS were found in the period of JJA in the condition of comparable estimation of cloud fraction over whole country, this was also described in a study of Boilley and Wald under clear-sky conditions [12]. This dependence of the bias on the clear-sky is subjected to limitation of the re-analysis when modeling cloud and it effect on solar radiation [26].

Table 4. Averaged relative RMSE between ERA-Interim and AMATERASS by climate zones and seasons.

RRMSE_ERA_AMATERASS (%)

	B1	B2	B3	B4	N1	N2	N3
YEAR	51.2	49.01	43.53	40.85	34.41	32.95	24.66
SON	45.28	42.35	38.41	37.18	39.33	42.53	31.93
JJA	55.8	38.97	28.46	28.06	26.44	29.72	27.98
MAM	33.69	34.69	32.47	26.09	19.69	20.23	15.41
DJF	49.09	52.27	50.8	56.6	49.51	38.23	24.01

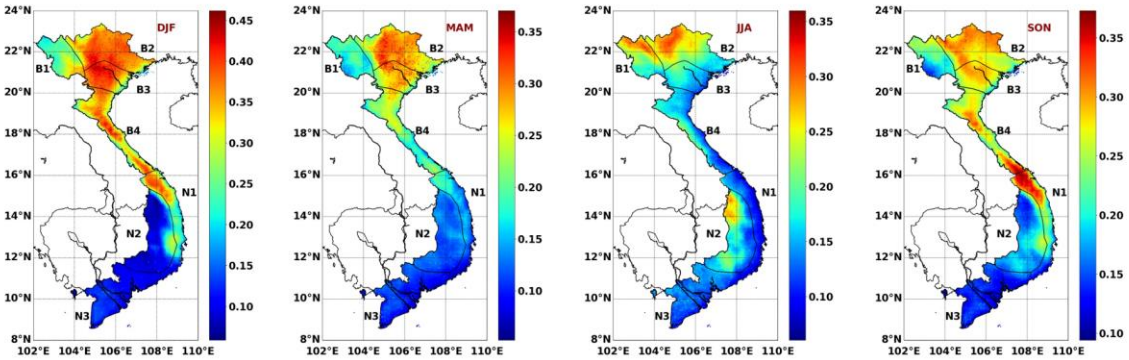

Figure 7. RMSE of ERA-Interim and Himawari-8 cloud fractions by seasons.

We averaged the statistic values by zones and seasons, for example, regional averaged relative RMSE presented in Table 4. The result showed the relatively lower disturbance between reanalysis and satellite-based estimates in the MAM months in all zones, and higher in the DJF months. It is noted that the relative RMSE tends to decrease from the north to the south, where more clear sky conditions predominate, suggesting the improvement of reanalysis in modeling solar irradiance in higher clearness conditions. This result was consistent with previous evaluation reported by Boilley and Ward for ERA-Interim reanalysis over Europe, Africa, and Atlantic Ocean that the uncertainty was less for clearer sky conditions, in cloud conditions ERA reanalysis often predicted as clear sky conditions [10]. Cloud patterns in the north regions of Viet Nam (B1, B2, B3, B4) are complicatedly affected by different synoptic disturbances, while in the south part, particularly N3 region clouds are mainly associated with south-west monsoon. Therefore, the prediction of clouds by the model is expected more biased, resulted in larger RMSE of GHI estimates of ERA compared to AMATERASS in the northern than in the southern regions and higher in the period of DJF than in the period of MAM. Correspondingly, the RMSE of cloud fractions predicted by ERA-interim and observed by Himawari-8 satellite by 4 seasons in Figure 7 depicted the highest differences in the northern (B1, B2, B3, B4) regions in the DJF period and the lowest in the southern, particularly in N3 region in all seasons. Evidently, simulation of cloud presences in the numerical model largely influences on radiation balance on the surface as the higher cloud fraction, the less solar radiation at the surface. In the newest study, Camargo et al. [27] showed the advance of the regional reanalysis over the global reanalysis such as ERA in solar radiation assessment because of increasing horizontal resolution to 2 km to overcome the limitation of unresolved cloud by large grid of global reanalysis.4. Conclusions

The study evaluates AMATERASS product of downwelling global solar radiation estimated from Himawari-8 visible images by EXAM algorithm and ERA-Interim reanalysis against 5 pyranometer stations in Viet Nam for period from October 2017 to September 2018. The results of validation showed the outperform of satellite-based estimates over reanalysis data over Viet Nam in terms of the statistic calculations. Daily AMATERASS solar radiation estimates were outstandingly correlated (order of 0.91 to 0.93) with surface observations in mainly positive biases, while ERA-Interim was correlated with surface observation in lower order of 0.67 - 0.72. The better performance of satellite-based products in clear sky episodes by assessment in hourly resolution confirmed higher uncertainty of solar radiation in cloudy conditions.

For spatial analyses between two datasets, we compared the daily GHI estimated by ERA-Interim and AMATERASS. The comparison was made dividedly for 7 climate zones and 4 seasons. The conclusion is that ERA-Interim was also well correlated with satellite-based estimates but in opposite biases in different regions. Difference between two products was found generally higher in the northern than in the southern of Viet Nam, and this difference was most pronounced in months of the DJF period because of the largest under-prediction of cloud in the ERA-interim reanalysis.

As a summary, in a condition of sparse networks of solar radiation observation in Viet Nam, satellite-based estimates could be a reliable alternative because of its high performance in accuracy and in spatial and temporal resolutions compared to reanalysis products. However, the reanalysis is advantageous in longer time series for climatological studies. Hence, longer period of evaluation for combined use of satellite-based and reanalysis estimates is required for the future work.

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