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Assessment of the Solar Resource in Andean Regions by Comparison between Satellite Estimation and Ground Measurements: Study Case of Ecuador

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Abstract

To develop and implement solar technologies, it is necessary to know accurately the solar resource on the place. Consequently, several institutions working in renewable energy have made efforts to both measure solar radiation and develop models to estimate solar radiation. The main drawback with estimations is their lack of accuracy. Recently, the NREL (NSRDB) has update its meteorological database based in satellite estimations. Some validations have been reported, however, no studies about its validity for the Andean region have been done. In this work, measurements of global horizontal irradiation (GHI) from 53 stations placed along the Ecuadorian territory were compared with satellite estimation data from NSRDB. Statistical descriptive indicators of dispersion (RMSE, MBE) and goodness of fit (KS test) were used. The data were grouped in hourly, daily, weekly and monthly basis, as well as in clear and cloudy basis. Results show that monthly grouping may be used with confidence, since close to 95% of comparisons have a good fit. Also, results show that both, clear sky and cloudy models tend to overestimate solar radiation in such a region. Solar resource seems to be high in Ecuador since more than 75% of the territory has values over 3.8 kWh/m^{2}day.

Keywords: Andean solar resource, satellite estimated solar radiation validation, ground-based measurements

Abbreviations

NREL National Renewable Energy Laboratory (USA)

NSRDB National Solar Radiation Data Base

INER National Institute of Renewable Energy and Energy Efficiency (Ecuador)

INAMHI National Institute of Meteorology and Hydrology (Ecuador)

DMQ Environmental Secretary of Quito Municipality (Ecuador)

CONELEC Electrical Regulation Agency of Ecuador

GHI Global Horizontal Irradiation [W/m^2]

DNI Direct Normal Irradiation [W/m^2]

MBE Mean Bias Error

RMSE Root Mean Square Error

KS test Kolmogorov-Smirnov test

CSR Climatological Solar Radiation Model

PSM Physical Solar Model

NOAA National Oceanic and Atmospheric Administration

FARMS Fast All-sky Radiation Model for Solar applications

REST2 Reference Evaluation of Solar Transmittance, 2 bands model

ESPOCH Polytechnic School of Chimborazo

UPS Salesian Polytechnic University of Cuenca

1. Introduction

The world primary energy consumption is continuously growing. For instance, the increment of this consumption was 0.9% and 1% in 2015 and 2016, respectively, being fossil fuels the main primary energy source (Dudley & Dale, 2017). In 2016, the percentages of fossil fuels consumption in the world energy matrix were of 33.6% for oil, 28.4% for coal and 24.3% for natural gas (Dudley & Dale, 2017). However, a decline of fossil fuels production is expected due to their high levels of exploitation and the shortage of new oil, gas and coal reserve discoveries (Aleklett & Campbell, 2003). Moreover, the IPCC climate change SR15 report calls for urgent actions to phase out fossil fuels and avoid catastrophic environmental breakdown (IPCC, 2018). In this context, renewable energies are called to play a major role in the world energy matrix in future years. Wind turbines, tidal power stations, hydropower stations, biomass for energy use are indirect technologies to collect solar energy, while, solar thermal collectors, concentrated solar technologies, photovoltaic panels are technologies of harnessing directly solar energy. Concentrated solar power, solar thermal and photovoltaic technologies are promising options for supplying an important part of the global energy demand, helping with the gradual replacement of fossil fuels (IEA, 2015). In that sense, it is essential to know the quantity and quality of the solar resource in order to evaluate the technical and financial feasibility of solar projects (Sengupta et al., 2015). Since the Andean region is located over the equatorial line, it gives some advantages for using solar energy (Ordóñez, Morales, López-Villada, & Vaca, 2018). One of them is the mostly constant solar radiation received throughout the year, while another one is its good solar irradiance levels, especially in some elevated areas of Colombia, Ecuador, eastern Peru and Bolivia and northern Chile. For instance, the mean daily global horizontal irradiance (GHI) for Ecuador's capital (Quito) is approximately 4.8 kWh/m^2 day (Global Solar Atlas, 2018).

Despite Ecuador's solar potential, the participation of this kind of energy in the matrix is minimal. As example, in the Ecuadorian electricity matrix, the energy generated by solar photovoltaic technology covered only 0.14% of the national demand in 2016 (Ministerio de Electricidad y Energía Renovable, 2017). Few studies have been devoted to analyze the solar resource, nor the potential of solar technologies in Ecuador (Cevallos-Sierra & Ramos-Martin, 2018). Moreover, in this kind of studies estimated solar radiation was used, due to the lack of available measured data. Hence, to promote the introduction of solar technologies, it is necessary to know accurately the solar resource. In 2008, the Electrical Regulation Agency of Ecuador (CONELEC) published a solar atlas (CONELEC, 2008). It was built using the monthly and annual averages of satellite solar radiation data from the National Solar Radiation Data Base (NSRDB), which was computed with the Climatological Solar Radiation Model (CSR) (CONELEC, 2008). Since the mesh of such estimations is very large (40x40 km), an algorithm to interpolate data at a low mesh was developed (CONELEC, 2008). Other available solar radiation data includes estimations made by the National Aeronautics and Space Agency (NASA) (NASA, n.d.), by the National Renewable Energy Laboratory (NREL) (NREL, 2018) and by Solargis (Global Solar Atlas, 2018). No validation with ground measurements of those data base have been reported for Ecuadorian or Andean regions. Currently, NREL refined its models and obtained solar radiation data every half hour with a spatial resolution of 4x4 km. The new database, which have a considerably higher geographical resolution and an improved two step physical model, promises more reliable estimates of solar radiation. Moreover, this model will be capable to adapt to next generation satellite datasets coming from the Geostationary Operational Environmental Satellite (GOES) (Sengupta et al., 2018). However, Ecuador's solar map has not been yet updated and validated, so its data could be more reliable when using the new NREL database. On the other hand, some governmental institutions have implemented stations to measure meteorological variables in Ecuador. Among others, the National Institute of Meteorology and Hydrology (INAMHI), which is the office in charge to monitoring and forecasting climate in Ecuador, the Secretary of Environment of Quito municipality (DMQ) and the National Institute of Renewable Energy and Energy Efficiency (INER) measure global horizontal irradiation (GHI). No record exists that those measured data have been used to analyze the potential of solar resource for energy projects. This work aims to compare satellite estimated (NREL) and measured (INAMHI, DMQ and INER) solar radiation data to quantify the confidence to use data coming from NREL. This comparison may be useful to update the solar map of Ecuador and to have a more reliable estimation of the solar potential to use this resource.

2. Methodology

Measurements of global horizontal irradiance (GHI) from stations distributed along the country were used to validate satellite estimated data coming from the National Solar Radiation Data Base (NSRDB) of the National Renewable Energy Laboratory (NREL). Those stations belong to three public institutions: the Secretary of Environment of Quito municipality (DMQ), the National Institute of Meteorology and Hydrology (INAMHI) and the National Institute of Renewable Energy and Energy Efficiency (INER). The data were grouped in hourly, daily, weekly and monthly basis to analyze their confidence in such basis. Also, since the NSRDB model uses two scenarios (cloudy sky and clear sky), the data were grouped accordingly. The root mean square error (RMSE), the mean bias error (MBE) and the Kolmogorov-Smirnov test (KS test) were used to compare the data. With validated data, the Ecuadorian solar map was updated and a preliminary analysis of solar potential was made.

2.1 Estimated and Ground-Based Measurement Data

On one hand, the estimated solar radiation data from NREL was used. These estimations utilize a two step Physical Solar Model (PSM) (Sengupta et al., 2014, 2018), which was developed by National Renewable Energy Laboratory (NREL) in collaboration with the University of Wisconsin and the National Oceanic and Atmospheric Administration (NOAA). This model takes images collected by the GOES-EAST and GOES-WEST satellites, which are located on the equatorial line at 75 º W and 135 º W, respectively. Due to their position, the range of NREL data covers the area between the longitudes 25 º W and 175 º W, and between the latitudes -20 º S and 60 º N. The satellite images are taken in 5 different wavelength bands, which are: visible band (0.64 µm) with 1 km resolution and infrared bands (3.9 µm, 6.5 µm, 10.7 µm and 12 µm) with 4 km resolution. These images are input for the Advanced Very High Resolution Radiometer (AVHRR) Pathfinder Atmospheres-Extended algorithms (PATMO-x) adapted for the GOES data in order to find cloud properties (NOAA, 2016). On the other hand, the model computes aerosol properties combining MODIS data with MERRA-2 dataset. Other properties are computed using water vapor, pressure and temperature profiles data from MERRA-2 project, snow albedo data from the National Snow and Ice Data Center and surface albedo from MISR, TOMS and OMI satellites (Sengupta et al., 2014). The PSM uses all these data to numerically solve the radiative transfer equation for solar radiation through the Earth's atmosphere. This model namely Fast All-sky Radiation Model for Solar applications (FARMS) subdivides it into two scenarios: cloudy and clear skies. For the cloudy sky scenario, the global horizontal irradiance is calculated taking as input the cloud properties, optical depth of aerosol and precipitable water vapor. For the clear sky scenario, global horizontal irradiance and direct normal irradiance are obtained with the REST2 model (Gueymard, 2008; Sengupta et al., 2018). This model was validated using ground-based meteorological measurements from seven stations located along the USA, showing that the model has a bias of approximately ± 5% (Habte, Sengupta, Lopez, Xie, & Maclaurin, 2018).

On the other hand, for ground-based measurements, fifty-three stations that belong to the Secretary of Environment of Quito municipality (DMQ), the National Institute of Meteorology and Hydrology (INAMHI) and the National Institute of Renewable Energy and Energy Efficiency (INER) were used. In Figure 1. Available solar stations network in Ecuador. Colorless stations were removed of the study since they data was very inaccurate or limited to very few values the locations of the fifty-three stations on the Ecuadorian map are shown.

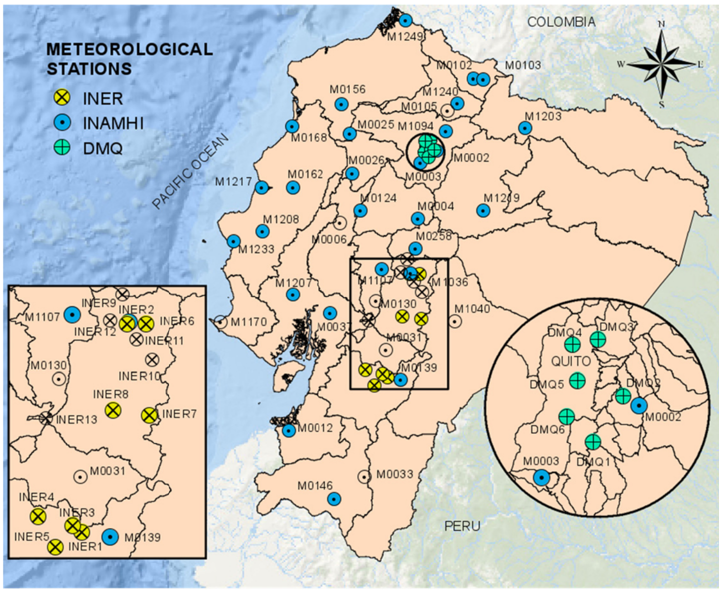


Figure 1. Available solar stations network in Ecuador. Colorless stations were removed of the study since they data was very inaccurate or limited to very few values

The DMQ measures, among other meteorological variables, global horizontal irradiation (GHI) since 2004 in six stations distributed in Quito city. The actual administration grouped the data from 2004 to 2006 and from 2007 to 2015, following the confidence of data. In this work the second group of data was used. The DMQ uses those data to monitor the quality of the environmental variables in Quito. In Table 1. Name and location of the meteorological stations belonging to the DMQ these stations are listed.

Table 1. Name and location of the meteorological stations belonging to the DMQ

Station name	Code	Measured years	Latitude	Longitude	Elevation (m)
Los Chillos	DMQ1	2007-2015	-0.30	-78.46	2453
Tumbaco	DMQ2	2007-2015	-0.21	-78.40	2485
Carapungo	DMQ3	2007-2015	-0.10	-78.45	2660
Cotocollao	DMQ4	2007-2015	-0.11	-78.50	2739
Belisario	DMQ5	2007-2015	-0.18	-78.49	2835
El Camal	DMQ6	2007-2014	-0.25	-78.51	2840

Also, INAMHI accounts with several meteorological stations distributed along the country. This office works for more than fifty years, however regarding solar radiation measurements, until 2014 they recorded only heliophany. Recently, this office implemented new solar radiation measurement equipment, consisting in 34 pyranometers distributed into their stations. Therefore, GHI measurements coming from this institution are available only for 2015. In Table 2 the stations belonging to the INAMHI are listed.

Table 2. Name and location of the meteorological stations belonging to the INAMHI

Station name	Code	Measured year	Latitude	Longitude	Elevation (m)
La Tola	M0002	2015	-0.23	-78.37	2480
La Cuca	M0012	2015	-3.49	-80.08	32
Rumipamba	M0004	2015	-1.02	-78.59	2685
Riobamba-ESPOCH	M1036	2015	-1.65	-78.67	2850
Laguacoto-Guaranda	M1107	2015	-1.61	-79.00	2608
Tena-Chaupishungo	M1219	2015	-0.92	-77.82	665
La Concordia	M0025	2015	-0.03	-79.38	379
Tomalón	M1094	2015	0.01	-78.26	2790
La Teodómira	M1208	2015	-1.17	-80.39	60
Palesema-San Lorenzo	M1249	2015	1.30	-78.73	45
Chone-U.Católica	M0162	2015	-0.66	-80.04	36
Izobamba	M0003	2015	-0.37	-78.56	3058
Ibarra-INAMHI	M1240	2015	0.33	-78.13	2256
San Juan la Maná	M0124	2015	-0.92	-79.25	215
Milagro	M0037	2015	-2.12	-79.60	13
Quinindé	M0156	2015	0.32	-79.47	115
Gualaceo	M0139	2015	-2.90	-78.78	2230
PUCE-Bahía de Caráquez	M1217	2015	-0.65	-80.40	55
Ángel	M0102	2015	0.62	-77.94	3000
Querochaca	M0258	2015	-1.36	-78.614	2865
Cariamanga	M0146	2015	-4.30	-79.55	1950
Cantagallo-Granja UN	M1233	2015	-1.28	-80.73	64
Nobol	M1207	2015	-1.90	-80.04	7
Lumbaqui	M1203	2015	0.04	-77.34	580
Pedernales	M0168	2015	0.06	-80.05	33
San Gabriel	M0103	2015	0.60	-77.82	2860
Puerto Ila	M0026	2015	-0.49	-79.35	319
Chillanes	M0130	2015	-1.98	-79.07	2320
Otavalo	M0105	2015	0.24	-78.25	2550
Macas	M1040	2015	-2.21	-78.16	1110
Cañar	M0031	2015	-2.55	-78.95	3083
La Argelia-Loja	M0033	2015	-4.04	-79.20	2160
Santa Elena	M1170	2015	-2.23	-80.88	13
Pichilingue	M0006	2015	-1.07	-79.49	120

Finally, in recent years, the INER implemented 13 stations for measuring solar radiation (GHI and DHI). It was done in collaboration with the Polytechnic School of Chimborazo (ESPOCH) and the Salesian Polytechnic University of Cuenca (UPS). Those stations are located close to Riobamba city (ESPOCH) and Cuenca city (UPS), and were implemented in 2013. Available data from this institute exist for 2014 in nine stations and for 2015 in four stations. In Table 3 the stations belonging to the INER are listed.

Table 3. Name and location of the meteorological stations belonging to the INER

Station name	Code	Measured year	Latitude	Longitude	Elevation (m)
Nulti	INER1	2015	-2.87	-78.94	2623
Espoch	INER2	2014	-1.66	-78.68	2754
Tixan	INER3	2015	-2.83	-78.99	2725
Cajas	INER4	2015	-2.78	-79.19	3646
Baños	INER5	2015	-2.96	-79.09	3062
Quimiag	INER6	2014	-1.66	-78.57	2709
Altillo	INER7	2014	-2.19	-78.55	3442
Tixan Pistilli	INER8	2014	-2.16	-78.76	3546
Urbina	INER9	2014	-1.49	-78.71	3642
Alao	INER10	2014	-1.87	-78.54	3064
Tunshi	INER11	2014	-1.75	-78.63	2840
San Juan	INER12	2014	-1.64	-78.78	3232
Cumandá	INER13	2014	-2.21	-79.15	331

2.2 Protocol of Comparison

The measured (DMQ, INAMHI and INER) and satellite estimated (NSRDB) GHI data were organized in hourly series. Measured data without their correspondent estimated data, and vice versa (outlier data) were filtered. Additionally, nocturnal data were excluded from this validation (values lower than 50 W/m^2). Both series data, were grouped in hourly, daily, weekly and monthly basis. Moreover, on the aim to distinguish the accuracy of the FARMS and REST2 models, these series data were also grouped in clear, cloudy and all sky basis. Several methods to identify clear sky from GHI data have been proposed (Younes & Muneer, 2007). The simplest is to consider clear sky those data that overpass a threshold value of clearness index (k_t), which is defined as the ratio of global horizontal irradiance to the extraterrestrial irradiance on a horizontal plane. A threshold value of 0.7 ($k_t >$ 0.7) was used in this work, following the recommendation of Li and Lam (D. H. Li & Lam, 2001). Likewise, to consider GHI in the cloudy sky basis a threshold of 0.35 was used ($k_t < 0.35$) (D.H. Li & Tang, 2008). Only measured and estimated data that match over the threshold value were considered.

Once the data was classified in the time and sky model basis, a statistical comparison was conducted. Gueymard (Gueymard, 2014) analyzed some statistical metrics to compare solar irradiation. Indicators of dispersion and of distribution similitude are recommended. In this work, the root mean squared error (%RMSE), the mean bias error (%MBE) and the Kolmorogov-Smirnov test (KS test) were used. The RMSE indicates the global error between two series data and the MBE permits to differentiate if the model overestimates or underestimates the phenomenon. Both are indicators of the dispersion between two series and they are defined by equations 1 and 2.

$$\%\boldsymbol{RMSE} = \sqrt{\frac{\frac{1}{n}\sum_{i=1}^{n}\left(x_{e,i}-x_{m,i}\right)^2}{\frac{1}{n}\sum_{i=1}^{n}x_{m.i}^2}} * \mathbf{100} \tag{1}$$

$$\%\boldsymbol{MBE} = \frac{\frac{1}{n}\sum_{i=1}^{n}(x_{e,i}-x_{m,i})}{\frac{1}{n}\sum_{i=1}^{n}x_{m,i}} * \mathbf{100} \tag{2}$$

where n is the number of data, $x_{m,\,i}$ is the i-th measured datum and $x_{e,\,i}$ is the i-th estimated datum. On the other hand, the KS test was used to proof the goodness of fit of both data series. This test has been largely used to validate estimated and measured solar radiation data (Espinar et al., 2009; Raush, Chambers, Russo, & Crump, 2016). It uses a statistic indicator D defined as the maximum of the absolute difference of the cumulative distribution functions of the estimated and measured data $S(x_{e,\,i})$ and $R(x_{m,\,i})$, respectively.

$$\boldsymbol{D} = \boldsymbol{max}\left|\boldsymbol{S}\left(x_{e,i}\right) - \boldsymbol{R}\left(x_{m,i}\right)\right| \tag{3}$$

If the D statistic value is lower than a threshold value V_c (critical value) both data series may be considered statistically similar. The critical value is dependent of the number of data and may be computed with the following equations for a 0.01 significance level (Massey, 1951).

$$\boldsymbol{V_c = 0.45}, \quad \boldsymbol{n = 12} \tag{4}$$

$$\boldsymbol{V_c = \frac{1.63}{\sqrt{n}}}, \quad \boldsymbol{n \geq 35} \tag{5}$$

The critical value for twelve data was used only for monthly comparison, since there are just one-year data for most of the stations.

3. Results

3.1 Quality of Data

To have confidence on the ground-based measurements, the quality of the sensors and their maintenance protocol were assessed. In Table 4, the pyranometer model and its ISO9060 class (ISO, n.d.) are presented for all stations used in this work.

Table 4. Brand, model and ISO9060 class for sensors used

Institution	Number of stations	Brand and model	ISO class
DMQ	6	Kipp&Zonen CM3	Second class
INER	13	Kipp&Zonen CMP6	First class
	31	Hukseflux SR11	First class
INAMHI	2	Kipp&Zonen CM3	Second class
	1	Kipp&Zonen CMP6	First class

Almost all pyranometers are ISO9060 first class, which means they present high confidence of their measurements. Moreover, most of them (INAMHI and INER) were implemented in 2014, that ensure the validity of their calibration for 2015. Regarding the maintenance protocols, for the DMQ stations, an annual calibration of the pyranometer is planned. Additionally, the dome of the pyranometers is cleaned once a month. These stations measure GHI each 5 seconds, however, only a minute average is recorded. Note that since these stations are located in Quito city, the DMQ may ensure the compliance of the maintenance. For the INAMHI stations, the calibration of the pyranometers is expected twice a year using a Kipp&Zonen CMP22 pattern. Also, the dome cleaning is made at the same time of the calibration (twice a year). These stations measure and save GHI every minute. The large time space between the dome cleaning may affect the measurements, because a fine layer of dust is placed on the dome, specially for stations placed in dusty locations. Finally, the operation of the INER stations has been delegated to two universities (Escuela Politécnica del Chimborazo, ESPOCH and Universidad Politécnica Salesiana, UPS). Even in the agreements between these institutions a regular maintenance is expected, because of the far location of those stations, no maintenance was done during 2015. These stations measure GHI and DHI using a shadow ring that need to be adjusted manually. Since the adjustment of the shadow ring was not ensured, the DHI measurements were not confident.

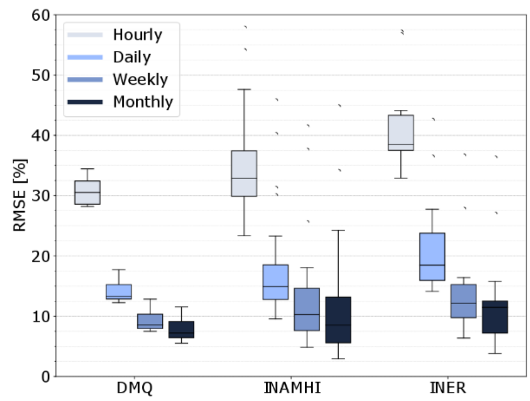


Figure 2. Box plots of the RMSE of the meteorological stations grouped according their owner

Figure 2 shows the box plot of the hourly, daily, weekly and monthly RMSE of the stations grouped according to their owner. Results suggest that the error on the validation may be attributable to the maintenance. For instance, for daily comparison, even the DMQ equipment is not the most accurate, the maintenance compliance ensures a RMSE value in the 10-20% range. For the INAMHI stations, where the cleaning dome is less frequent, seven stations overpass the 20% RMSE threshold, reaching values until 30%. Similarly, may be occur in the INER stations, where the daily RMSE varies in the 14-40% range. These stations did not have any maintenance during the time taken for this study. In this case, six stations overpass the 20% RMSE threshold. Similar trends are noticed for hourly, weekly and monthly comparisons. This fact highlights the huge importance to clean the pyranometer dome regularly and to comply the maintenance protocols. Therefore, in countries with no strong structures of meteorological measurements, it is important to improve concurrently the number of stations and the maintenance observance.

In the following analyses, stations that overpass largely the 20% daily RMSE threshold or have insufficient data (lack of measurements) were removed (seven corresponding to INAMHI and five corresponding to INER), because the error associated to these stations may be attributable to the lack of maintenance compliance. The location of these twelve stations may be noticed as colorless stations in Figure 1, and its name was writen in italics in Table 2. Name and location of the meteorological stations belonging to the INAMHITable 2 and Table 3.

3.2 Hourly, Daily, Weekly and Monthly Comparison

The RMSE for the selected stations is presented in Figure 3. Normalized RMSE for estimated and measured GHI data for EcuadorFigure 3. Note that for the DMQ stations those values were computed for several years, while for the others were for just one year.

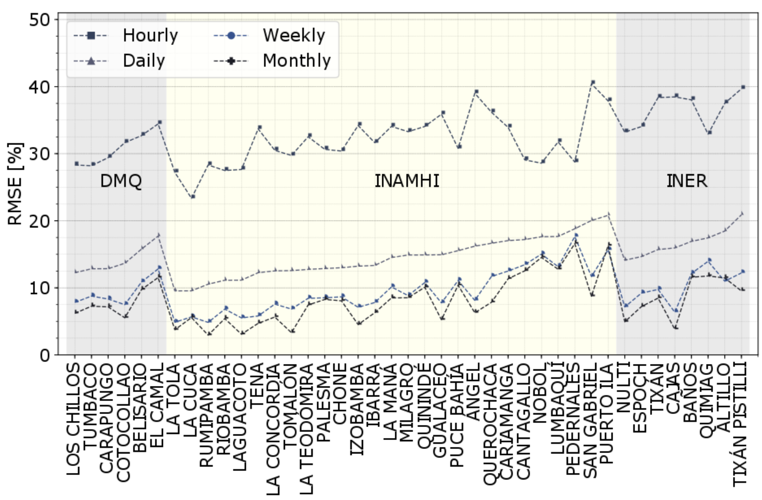


Figure 3. Normalized RMSE for estimated and measured GHI data for Ecuador

For the hourly basis, the RMSE is very high, achieving values in the 30-40% range. It implies a low confidence to use estimations in this basis (e.g. it is not accurate to take as true an estimated value for a specific hour and day). However, in the daily basis, all stations have RMSEs lower or close than 20%. Still low levels of RMSE were found for weekly and monthly basis, most of them lower than 10%.

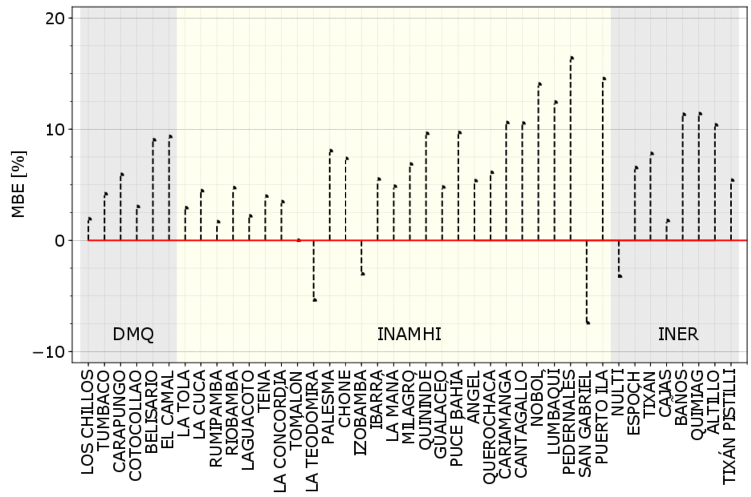


Figure 4. Normalized hourly MBE for estimated and measured GHI data for Ecuador

In Figure 4 the hourly MBE for all stations are presented. The MBE results show that in general, satellite data estimations tend to over-estimate GHI. This result confirms conclusions made by other authors (Raush et al., 2016). Also, for most of studied stations, the MBE values are lower than 10%. These dispersion indicators values suggest a good agreement between measured and satellite estimated data. Finally, to ensure the goodness of such a fit, the KS test was conducted (0.01 significance level). In Figure 5 the percentage of stations that fulfill the null hypothesis of the KS test are shown. As expected, the fit of data in the hourly basis is very low (12%, approximately). However, in the daily, weekly and monthly basis the fit is enough confident to be used in estimations of solar projects (56%, 90% and 96%, in the daily, weekly and monthly basis, respectively). These results confirm the confidence found with the dispersion indicators.

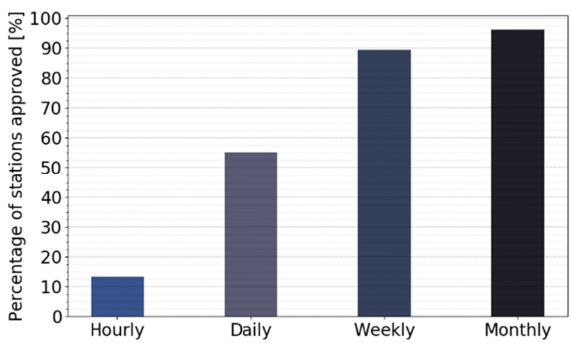
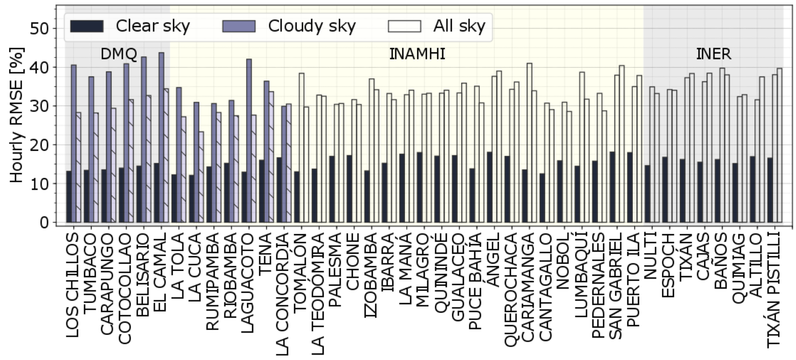


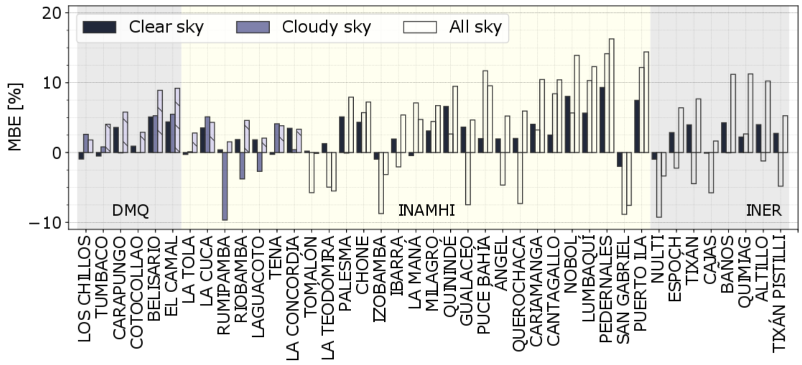
Figure 5. Percentage of null hypothesis in the KS test in hourly, daily, weekly and monthly basis

3.3 Clear and Cloudy Sky Comparisons

The capabilities of the REST2 and FARMS models were tested by splitting and comparing measured and satellite estimated data in clear and cloudy sky basis. As stated before, data with k_t over 0.7 was considered clear sky and data with k_t under 0.35 was considered in cloudy basis. The first group of data may be considered in the REST2 model (clear sky), while the second may be considered in the FARMS model (cloudy sky). In Figure 6 the hourly RMSE and MBE of all stations grouped according the sky basis are shown.



(a) Normalized RMSE for estimated and measured GHI data for Ecuador in clear, cloudy and all sky basis



(b) Normalized hourly MBE for estimated and measured GHI data for Ecuador in clear, cloudy and all sky basis

Figure 6. Statistic indicators for estimated and measured GHI data for Ecuador in clear, cloudy and all sky basis

The RMSE plots show that for the clear sky basis the error is lower than for the cloudy sky basis. It is normal since, the model to estimate the scattering of radiation through clouds is more complicated. The MBE plot shows positive values for the clear sky comparison, while shows positive and negative values for the cloudy sky comparison. It means, that the REST2 model tend to overestimate solar radiation, while the FARMS model both overestimate and underestimate solar radiation. These results are in accord with comparisons made by NREL, where the MBE is always positive for clear sky and positive and negative for cloudy sky (Habte et al., 2018). However, in this work there is a predominance of positive values for cloudy sky, in opposition with the NREL results. This difference may be attributable to the parallax error on the pictures taken by the satellites, which is lower for equatorial latitudes (Habte et al., 2017). Note that the MBE for clear sky is, in general, lower than 5%, while for the cloudy sky is lower than 10%.

4. Discussion: Ecuadorian Solar Resource

Due to the Ecuador geographical location (over the equatorial line), the solar resource along the year is mostly constant. It may be very advantageous for solar projects, since the useful energy coming from these projects may be nearly constant, avoiding to forecast over-sized energy storage or heavy energy support equipment. Even this advantage, the presence of the Andes mountain creates several micro climates, that reduces the solar potential in comparison with other locations (e.g. the annual irradiation for Atacama - Chile is 2500 kWh/m^2 year, while for Quito is 1750 kWh/m^2 year), specially in the coast-mountain inter-region. The mean daily solar irradiation for Ecuador varies from 2.9 kWh/m^2 day to 6.3 kWh/m^2 day. In general, stations located in high altitude have higher solar irradiation levels. Obviously, the lower atmosphere thickness improves the radiation that reach the ground. On the other hand, stations located in the coast-mountain inter-region have the lowest solar irradiation values. In such regions, the atmospheric pressure causes the formation of clouds, that makes these regions highly wet. In Figure 7 box plots of measured annual solar irradiation for all stations (years 2014 or 2015), together with the altitude profile are presented.

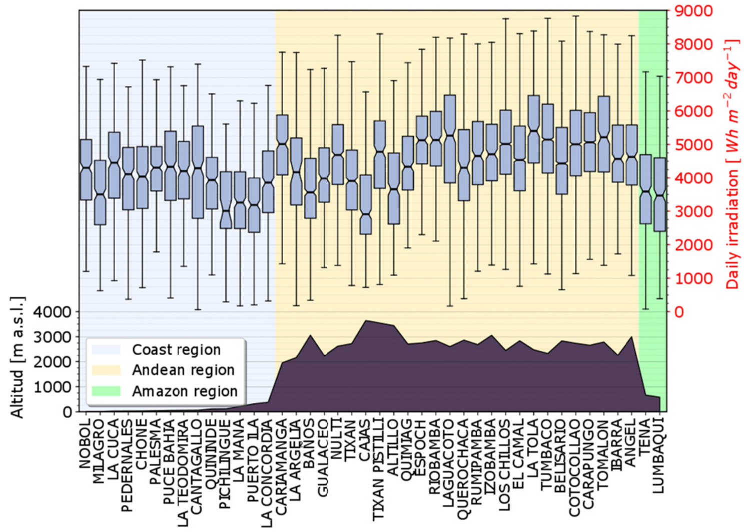


Figure 7. Box plots of measured daily GHI with their corresponding altitude

As seen in the comparison section, the monthly RMSE, for all studied stations, is approximately 6%. Additionally, the dispersion of them on the country, permits to use satellite-estimated data coming from the NSRDB (NREL) with enough confidence to evaluate the solar potential of Ecuador. In that sense, the typical meteorological year (TMY) downloaded from the NSRDB (NREL, 2018) was used to generate an annual solar map for Ecuador. This map may become a powerful tool to study the feasibility to implement solar projects. Figure 8 shows the map of the annual GHI for Ecuador.

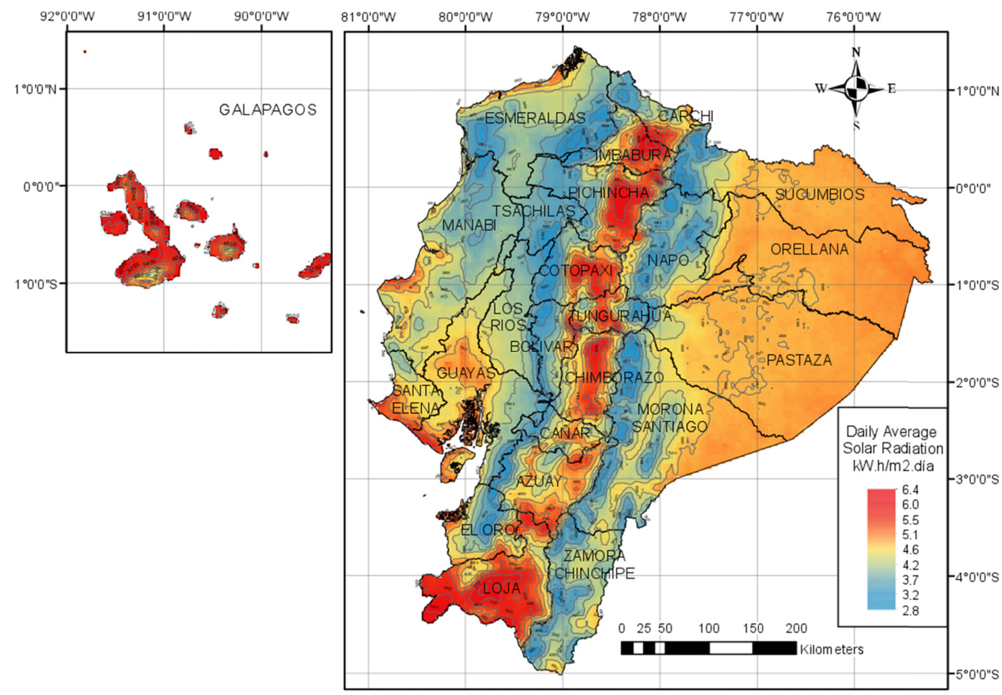


Figure 8. Solar map for Ecuador built from estimated solar radiation data

In general, the GHI levels of radiation are good enough to implement low temperature solar thermal and photovoltaic projects. Cevallos-Sierra and Ramos-Martín (Cevallos-Sierra & Ramos-Martin, 2018) mentioned a value of 3.8 kWh/m^2 day for the mean daily solar irradiation as a good compromise in the low limit for photovoltaic purposes. Using the same criteria for solar thermal projects, fig. Figure 8 shows that approximately the 75% of the Ecuadorian territory has enough potential to implement photovoltaic and thermal (low temperature) solar projects. Moreover, more than 55% of territory has solar radiation levels over 4.1

kWh/m^2 day, that means a very good solar potential. As expected, the 25% of territory with low solar radiation levels is located in the coast-mountain inter-region. Special attention should be done to Pichincha, Ibarra, Loja and Galapagos regions. The high solar potential of Pichincha and Ibarra (4.5 - 5.7 kWh/m^2 day) are important because an important part of the industry and population are placed in these regions. On the other hand, Loja accounts with the larger surface with a very high solar radiation level (4.2 - 5.7 kWh/m^2 day). Since the economic activity of this region is the agriculture, solar projects may help to diversify the productive matrix in such a region. Due to the exceptional location of the Galapagos Islands, the solar radiation levels are the highest in the country, reaching values in the 4.8 - 6.3 kWh/m^{2}day. It suggests a high importance of the solar technology in the diversification of the energy matrix of the Islands. Specially, taken into account the highly sensitivity of the ecological systems of the Islands. Finally, a validated solar map, as that presented here, may be a powerful tool to assess the potential of implementation of solar projects in Ecuador.

5. Conclusions

Global horizontal irradiation (GHI) measurements from fifty-four stations were compared with satellite-estimated data from NSRDB (NREL) in Ecuadorian territory. On this aim, statistical indicators of dispersion (RMSE and MBE) and of goodness of fit (KS test) were used. To accomplish a deep analysis of the comparison, the data was grouped by time (hourly, daily, weekly and monthly) and by isolation condition (clear and cloudy skies). This grouping permitted to quantify the confidence of the estimated data following time series and cloud model (REST2 for clear sky and FARMS for cloudy sky). Twelve stations were removed of the study, since they presented bad behaviors due to low compliance of maintenance and cleaning protocols. For all remained stations, the RMSE was lower than 20% and the MBE was lower than 15% in daily, weekly and monthly basis, that suggest a good fit between estimated and measured data. In average, the forty-one stations had approximately a daily RMSE of 13% and a daily MBE of 4.5%, which are comparable with results reported in the literature. Moreover, the percentage of stations that passed the KS test was of 56%, 90% and 96%, in the daily, weekly and monthly basis, respectively. In hourly basis, all indicators were too bad to be considered. Regarding the models used by NSRDB, the clear sky model (REST2) seems to overestimate solar radiation, while the cloudy sky model (FARMS) overestimate and underestimate solar radiation, with predominance of the first case. The errors associated to the clear sky model are lower than those associated to cloudy sky model. It is normal, since the cloudy sky model must determine cloud properties to apply the radiative transfer equation through these clouds. Finally, using the estimated data from NSRDB, a solar map with the annual GHI was built. In general, the mountain region has the highest solar potential with levels of solar radiation between 4 and 5.9 kWh/m^2 day. Special consideration may be done to the Galapagos Islands region, where the solar potential is extremely high, achieving values of 6.3 kWh/m^2 day. The coast and forest regions have lower solar potential with values between 3.2 and 5.0 kWh/m^2 day. The region with the worst solar potential is the coast-mountain inter-regions, due to the atmospheric pressure. In this region the solar radiation is around 2.5-3.3 kWh/m^2 day. As conclusion, Ecuador has a big potential to implement solar project since almost 75% of the territory has solar radiation levels over 3.8 kWh/m^2 day, as well as 55% of the territory has solar radiation levels over 4.1 kWh/m^2 day.

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Availability of Data and Materials

All data generated during this research is available under request to the corresponding author. Meteorological data from DMQ is public and may be accessed in the DMQ we page (http://www.quitoambiente.gob.ec/ambiente/index.php/). INAMHI and INER data are available by requesting directly these institutions.

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