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Validation of solar irradiation forecasting from a numerical weather predictor model and weather stations observational data on three regions of Sonora-Mexico

Validación de la predicción de la irradiación solar a partir de un modelo numérico de predicción meteorológica y datos observacionales de estaciones meteorológicas en tres regiones de Sonora-México

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Abstract

Lately continuous usage of fossil fuels has become a significant problem due to environmental pollution coming from the usage of these energy sources. Therefore, this has caught attention around the world, looking to stop getting a worse environmental situation. One energy source that has become popular in the last few years is solar energy which can effectively be utilized as renewable and clean energy. However, reliable is a big problem for this kind of energy due to high intermittency by solar radiation. On this paper, we aim to analyze three regions from Sonora in Mexico to evaluate how good is our numerical weather predictor (WRF-Solar) to forecast solar radiation for a year on semi-arid regions and valley-like region. We used WRF-Solar and weather stations observational data to contrast and evaluate accuracy from our model. This looks to help to get a better focus on solar radiation forecasting on northwestern region in Mexico due to high capability to produce solar photovoltaic energy.

Solar energy, Energy forecasting, Energy resource, Renewable energies

Resumen

Últimamente, el uso continuo de combustibles fósiles se ha convertido en un problema importante debido a la contaminación ambiental proveniente del uso de estas fuentes de energía. Por ello, esto ha llamado la atención en todo el mundo, buscando que deje de empeorar la situación ambiental. Una fuente de energía que se ha vuelto popular en los últimos años es la energía solar, que puede utilizarse efectivamente como energía limpia y renovable. Sin embargo, la confiabilidad es un gran problema para este tipo de energía debido a la alta intermitencia de la radiación solar. En este artículo, nuestro objetivo es analizar tres regiones de Sonora en México para evaluar qué tan bueno es nuestro predictor meteorológico numérico (WRF-Solar) para pronosticar la radiación solar durante un año en regiones semiáridas y regiones tipo valle. Utilizamos datos de observación de estaciones meteorológicas y WRF-Solar para contrastar y evaluar la precisión de nuestro modelo. Esto busca ayudar a enfocar mejor el pronóstico de radiación solar en la región noroeste de México debido a la alta capacidad para producir energía solar fotovoltaica.

Energía solar, Predicción de energía, Fuente de energía, Energías renovables

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I. Introduction

On the last few years, renewable energy integration on power systems has gained a lot of interest due to climate changes effects and the necessity to reduce CO2 emissions from usage of fossil fuels. However, most of the renewable energies that have been developed has some major problems considering how uncertain and intermittent they are. For example, solar energy depends on many parameters as cloudiness, dust, location, etc. (Alrashidi, Alrashidi, & Rahman, 2021; Agbulut, 2021).

In this case, solar energy continues to be one of the most resourceful ways to produce energy, but as mentioned before intermittency can be unreliable for continuous production. Given the high demand on this kind of technology to integrate to the traditional power grid, prediction or forecast has become one of the most important keys to a transition from traditional to a smart grid environment, where uncertainty is as low as possible and let electricity suppliers to adapt and distribute energy with quality and assurance (Cannizzaro, *et al.*, 2021).

As a remainder, several countries (Patsalides, Makrides, Stavrou, & Georghiou, 2016) around the world are finding challenging to allow residential customers to install photovoltaic systems due to impacts on the network capacity, this derived for possible effects on the network as noise, unbalanced lines, electrical values changes, etc.

As claimed by (Ochoa, 2021), several barriers must be removed to allow new energy sources penetration on the traditional network, as well distribution companies should increase photovoltaic hosting capacity for low and medium voltage networks for a better understand on how intermittent energies can behave on a robust network. On Mexico, solar photovoltaic systems have become a trend along the whole country, which has helped to reduce costs on these systems and help to increase the diversification of our electrical network. According to the last United Nations Framework Convention on Climate Change (COP27), Mexico has compromised to reduce on a 35% pollution gas emissions and double renewable energies production by 2030, which at 2021 was around 26.8 GW installed capacity.

That being the case, renewable energies as photovoltaic and wind will have a huge increase on capacity (CULLELL, 2022). Hence, the northwestern region of Mexico, according to IRENA (International Renewable Energy Agency for its acronym in English), has values of irradiation that can go up to 7 to 8 kWh/m2d, which becomes a very attractive region for energy production coming from solar technologies (Agency, 2018; J. A. Rosas-Flores, 2019). On this paper we will show the progress on a doctoral project focused on solar radiation prediction on the northwestern region of Mexico by the name of “Simulation of the availability, generation and distribution of electricity with photovoltaic systems in northwestern Mexico”.

As main purpose of this research is to corroborate how our model ensemble for forecasting works using observational data from weather stations and how accurate it is.

This paper is divided in five chapters, starting by chapter one were introduction and objectives are shown.

Chapter two where literature review and antecedents according to our theme have been worked.

Chapter three where materials and methodology that emphasize on our numerical model for radiation forecasting and resource maps.

Chapter four where our results show a one year analysis for Sonora region for solar radiation through a three zones (North, Center and South) and a comparative to database from several weather stations.

Chapter five consists on our conclusion on how our system work and how we evaluate it considering a forecast prediction skill score considering data obtained

II. Literature review

Solar radiation forecasting has taken interest on diverse places around the world especially in countries which have transitioned into a more diversified energy network. A few authors have tried to increase accuracy on forecast methods using multiple procedures as data-based forecast, artificial intelligent, machine learning, etc. Some of this authors are our base to apply some of these methods to get a better forecast.

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According to (Lara-Fanego, Ruiz-Arias, Pozo-Vazquez, Santos-Alamillos, & Tovar-Pescador, 2012) an evaluation was done for a three days ahead forecast focusing on variables as global horizontal irradiance (GHI) and direct normal irradiance (DNI) for Andalusia, Spain. On this evaluation, values as MBE (median bias error) and RMSE (root median square error) were used to compare how accurate WRF can be in opposition to a trivial persistence model.

It showed that both errors have high dependence on sky conditions (presumably on cloudy conditions and overcast) and season of the year. Values for MBE on GHI and DNI show that from a clear sky to an overcast situation can go from 10% up to 75% and RMSE from 10% to 50% respectively.

On (Sosa-Tinoco, *et al*., 2016) a methodology to generate a high resolution global solar irradiance assessment was done on south Sonora, using WRF downscaling as a validation on the output and observation taken from different weather stations on this region. It is shown that WRF it's less accurate when an annual simulation is run, this can be concluded from values taken for RMSE in consideration of observable data which responds as values around 6.4% up to 9.91%.

Considering that each time a forecast is made up, there are several factors that has to be considered to make it valid, (Blaga, *et al*., 2019) demonstrated that in literature there was a tendency to avoid reporting model performance assessment in places or on time horizons, where was known that each model might be suspicious of low performance.

Therefore, a complete research on each method of modeling as persistence, classical statistic, machine learning, cloud motion tracking, numerical weather prediction and hybrid models. For that, the usage of normalized values for MBE and RMSE were taken in consideration as a standard value for performance on forecast models, additionally, this study, mentioned that hybrid models tend to have the best performance among all others in any climate and place.

Values on accuracy and capacity of each forecast ensemble might be ambiguous depending on how each author manages parameters and comparison with observable data, however, (Yang, et al., 2020) managed to standardize a new concept for accuracy on solar forecast considering quality, value and consistency called Skill Score, which is based on uncertainty and variability considering factors as RMSE on clear sky persistence index. On contrast with any other actual development on enhancing accuracy and updates which WRF have taken, (Yang, *et al*., 2021) examined an extension on WRF specialized on solar radiation forecast by name of WRF-Solar, this was done by using a tangent linear model (TLM) to analyze individual input variables and initial conditions and achieve knowledge on uncertainty values in outputs values. Therefore, this study indicated that 14 input variables can be highly sensitive to uncertainty and this method by TLM usage can identify physical modules on WRF-Solar that can be stochastically perturbed and modify ensemble based on probabilistic.

Most recently, a study considering input variables as sunlight hours and a model study using Angstromm-Prescott and polynomial regression to quantify solar radiation in a semi-desert region as Ciudad Juarez, Mexico was done, according to (Mejia, *et al*., 2022) they obtained values for RMSE up to 91.36 W/m2, as stated by them this kind of model for solar radiation quantification can be applied to almost any semi-arid region with extreme weather changes.

III. Materials and methods

3.1 Geographical selection

As stated on previous chapters, our objective is to focus on the northwestern region of Mexico, which is known as a geographic place with high irradiation values along the whole year; this region consists on the following states Sinaloa, Sonora, Baja California and Baja California Sur. Therefore, on this paper we chose to start with Sonora as our first geographical location to work with, which can be compared to (Sosa Tinoco, 2015) as which is stated as an analysis on the southern part of Sonora for solar resource. For this study, Sonora was selected due to weather and agro-weather station density, alongside typical climatological characteristics.

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This state considers 72 municipalities, for this was decided to divide by three major zones (Southern, Northern and Centre) where most of the population it's concentrated.

3.2 Observational data

Sonora has at least two weather station network, Automated Weather Station Network of Sonora (REMAS for its acronym in Spanish) (SIAFESON, 2021) and National Institute for Forest and Agricultural Research (INIFAP for its acronym in Spanish) (Remotos, 2022). These networks offers several weather stations historical data as well as real time data including solar radiation, temperature, wind speed, precipitation, humidity, etc. on a time set given of 10 min. Therefore 34 weather stations were selected from 116 allocated all over Sonora state, this is due to highly concentrated on agricultural places and help to verify each region taken in consideration on our simulation, these were divided by 6 for the northern, 11 for the center and 17 for the southern part of Sonora, all of them taken from Automated Weather Station Network of Sonora.

3.3 Typical meteorogical year

According to (Sosa Tinoco, 2015), there are several methods to reduce stress on computational cost when using WRF-model, though a typical meteorological year consisting of at the minimum six days per month for 2021 got selected for this case of study considering mean global horizontal irradiation for each month and season, as well this allows us to analyze a complete region instead of a certain location by one-by-one weather station. However, other authors may consider a typical meteorological year for more days and more years of data, this study only considered one year to reproduce values and correct our numerical weather prediction model.

3.4 Model and set up

In this study, Weather Research Forecast (WRF) model v4.3.3 was used along with WRF Pre-Processing System v4.3.1. Our model run on a local server provided by Instituto Tecnologico de Sonora considering that we didn't take in consideration the very first six hours of each day, due to WRF needs time to prepare and stabilize. Domain and physics set up are described as below.

3.5 Domain set up

As stated before, we chose three different zones on the most populated places of Sonora. For each of these zones three domains were selected being 9 x 9 km, 3 x 3 km and 1 x 1 km of resolution by a grid of 100 x 100 points for these three places which are shown on figure 3 to 5.

Figure 1 Weather station selected on North Sonora

Figure 2 Weather station selected on Center and South Sonora

3.6 Physics schemes

Our physics schemes were taken from (Sosa-Tinoco, Prosper, & Miguez-Macho, 2022), which allowed us to activate WRF-Solar scheme for a better solar energy applications forecast, this specific configuration improves solar tracking algorithm for deviation associated with Earth's orbit, moreover, it represent direct normal irradiance and diffuse irradiance components on account for radiation parametrization.

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As it reduces errors in simulation of clear sky irradiances and surface irradiance biases in all sky conditions (Jimenez, *et al*., 2016). On table 1, physics schemes to activate WRF-Solar, as well as simulation parameters, are shown.

Simulation parameters	
Simulation period	Three days per month (36 days total)
Model version	WRF-Solar 4.3.3
Domains	3
Horizontal resolution	9, 3 and 1 km
Time step	30 s
Physics scheme	
Cumulus Parameterization	Kain-Fritsch scheme (Kain, 2004)
Longwave radiation physics	RRTMG Longwave (Iacono, *et al*., 2008)
Shortwave radiation physics	RRTMG Shortwave (Iacono, *et al*., 2008)
Planetary boundary layer	MYNN 2.5 level TKE (Nakanishi & Niino, 2006)
Surface layer option	MYNN Monin-Obukhov (Nakanish, 2001)
Land-surface physics	Noah-MP land-surface model (Tewari., *et al*., 2004)
Microphysics	Thompson aerosol-aware (Morrison., Thompson, & Tatarskii, 2009)
Fast All-sky Radiation Model (FARMS)	Activated (Xie, Sengupta, & Dudhia, 2016)

Table 1 Set up parameters

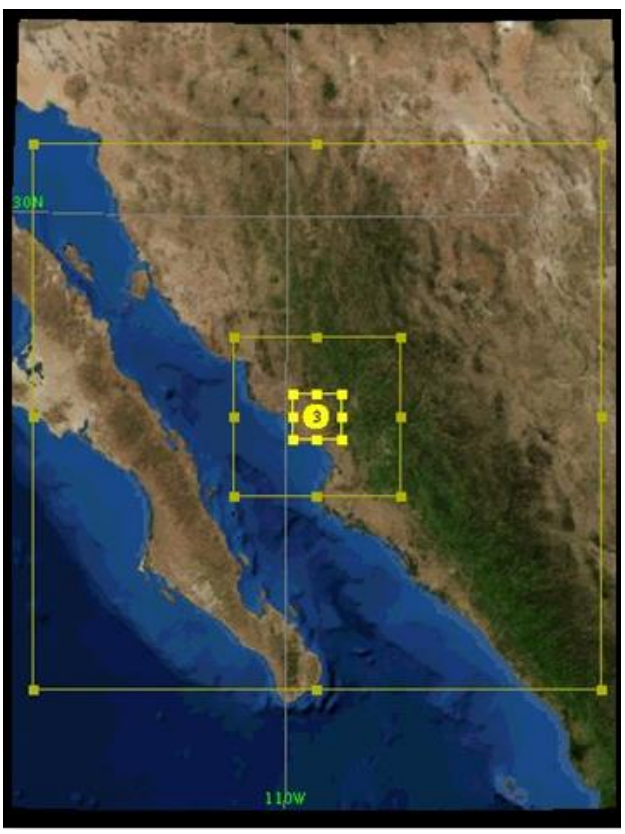

Figure 3 South zone domains

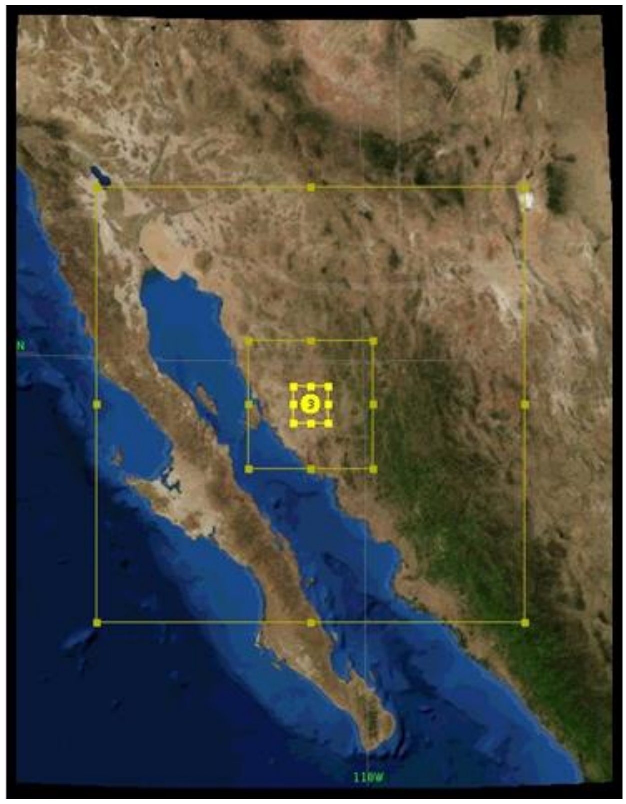

Figure 4 Center zone domains

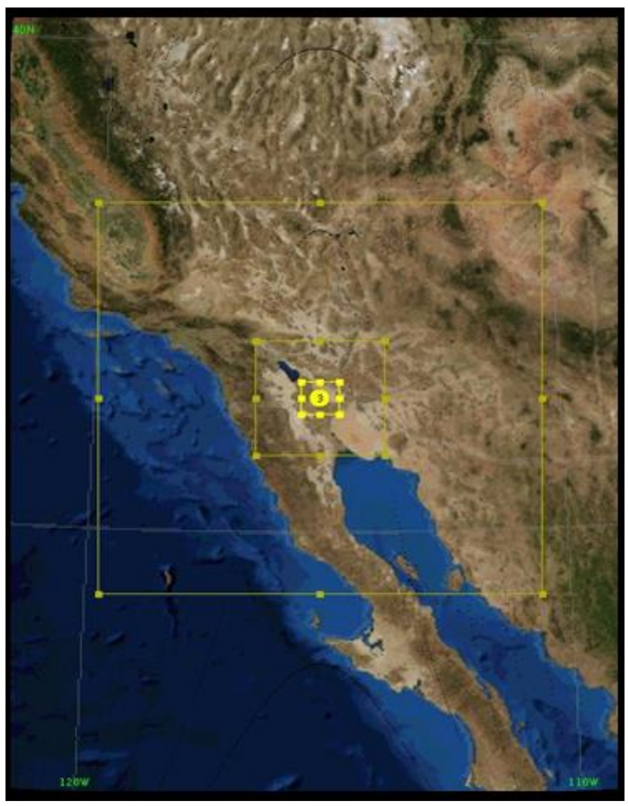

Figure 5 North zone domains

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IV. Results and discussions

4.1 Validation metrics

As said on previous chapter, we evaluated for a representative year model by using a standard of three representative days per month to compare data coming from our forecasting tool and weather stations. These days were selected with weather conditions as cloudy, overcast, sunny days, etc. These are shown on table 2.

Days selected for analysis (YYYY-MM-DD)	
2021-1-3	2021-7-2
2021-1-16	2021-7-12
2021-1-19	2021-7-25
2021-2-10	2021-8-18
2021-2-20	2021-8-23
2021-2-24	2021-8-27
2021-3-8	2021-9-7
2021-3-15	2021-9-18
2021-3-28	2021-9-27
2021-4-1	2021-10-1
2021-4-14	2021-10-11
2021-4-23	2021-10-27
2021-5-1	2021-11-3
2021-5-5	2021-11-7
2021-5-28	2021-11-25
2021-6-16	2021-12-1
2021-6-21	2021-12-9
2021-6-23	2021-12-19

Table 1 Days used for analysis

Therefore, observational data taken from REMAS weather stations were used with exact same days on 10-minute data frame.

4.2 Model results

4.2.1. North region

For our north region (San Luis Rio Colorado), results show that this region is less likely to have changes or weather conditions that can affect along the year. As this region shows high values for solar irradiation especially on spring and summer seasons (from April to September). However, root mean square error (RMSE) shows a lower value on Autumn and Winter seasons, around RMSE=100 and 104 W/m^2 respectively, despite these seasons can have lots of cloudy days, on contrast for Spring and Summer, around 162 and 152 W/m^2 respectively. This can be explained by weather effects on this region on certain seasons as Monsoon.

Therefore, our model shows a highly reduce on accuracy considering certain days can be difficult to simulate due to cloud, dust and other factors that can affect radiation. Results are shown on seasonal values every three months on figures 6 to 9.

As saw on figure 6 to 9, days that have several cloud weather can be pretty hard to analyze for WRF-Solar using only the scheme configuration we used, as well, some values might not look like our observational data can relate directly to values from WRF-Solar, however, if we analyze each under the curve value for each day, they can relate with a low error between them, as shown our RMSE for every season are not more than 150 W/m^2.

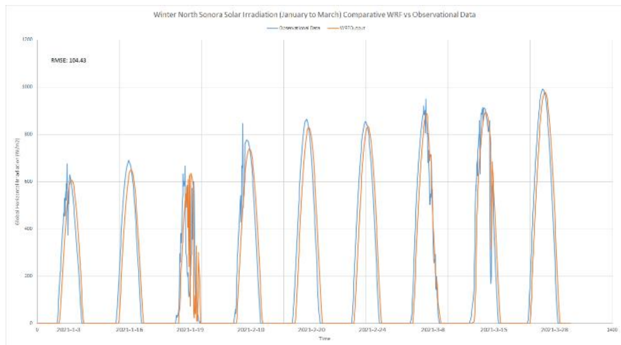

Figure 1 Winter North Sonora Comparative WRF vs Observation

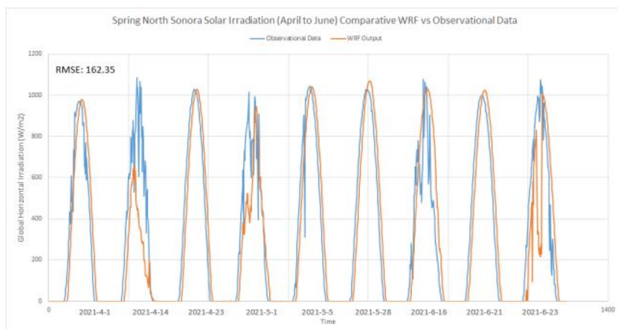

Figure 2 Spring North Sonora Comparative WRF vs Observation

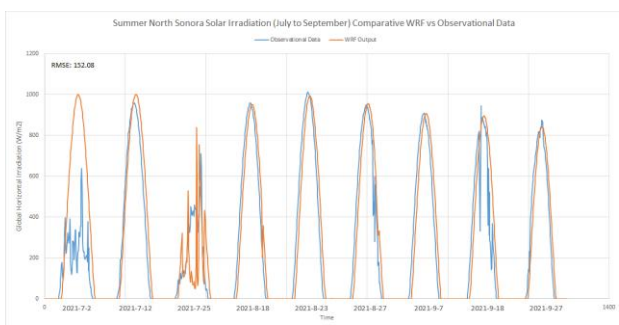

Figure 3 Summer North Sonora Comparative WRF vs Observation

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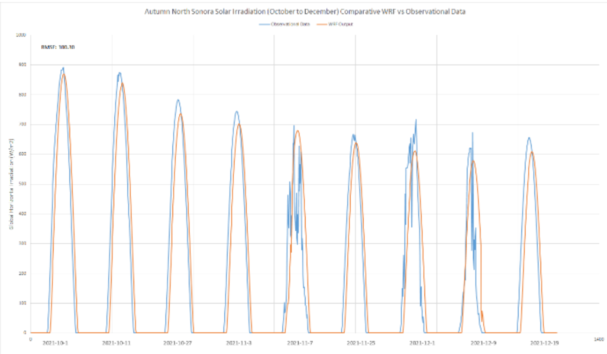

Figure 4 Autumn North Sonora Comparative WRF vs Observation

The dispersion plot in figure 10, show the comparison between forecast and observation values for the whole year on the northern region. The R^2 is high for this case, with a greater density of data close to the trendline, between 70% and 100%, meaning that the model is performing well on most days with clear sky conditions.

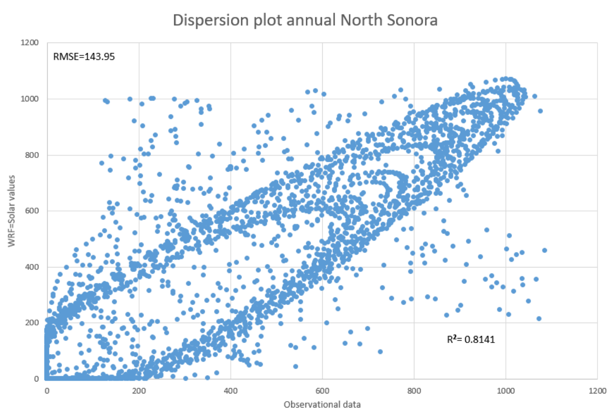

Figure 5 Dispersion plot North Sonora

4.2.2 Center region

Center region or Hermosillo it's known by being a high heat place and lots of sunny days on these region, however lots of variability is shown on seasons that are supposed to be the highest irradiation. Results are shown on figures from 11 to 14, where are possible to observe several days affected by cloudiness specially on summer, although, autumn which is supposed to be a season with high quantities of rain and/or cloudy days show the lowest variability from WRF-Solar values and observational data from weather stations, only with an RMSE value of 107.65 W/m^2.

As well, our dispersion plot, on figure 15, for this region shows a high correlation between observational data and WRF-Solar values as R^2 it's around value of 80%, which means a high efficiency on our model working for this region.

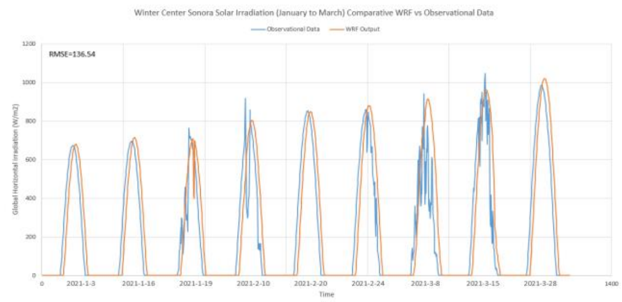

Figure 6 Winter Center Sonora Comparative WRF vs Observation

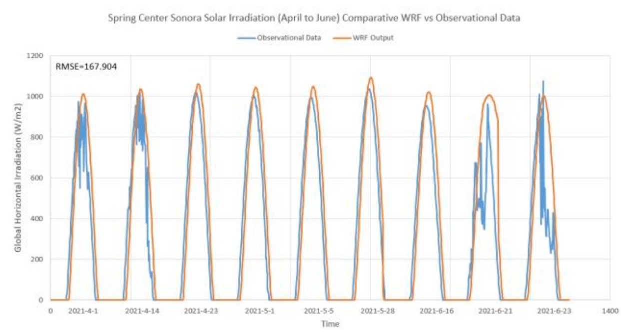

Figure 7 Spring Center Sonora Comparative WRF vs Observation

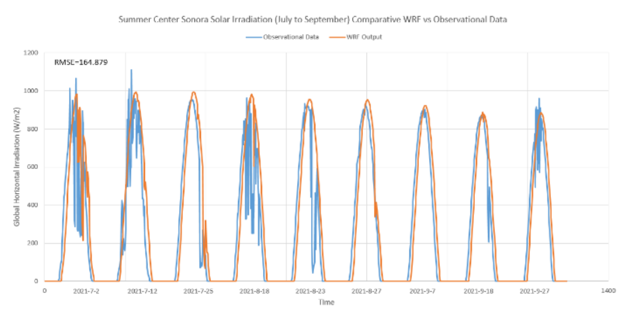

Figure 8 Summer Center Sonora Comparative WRF vs Observation

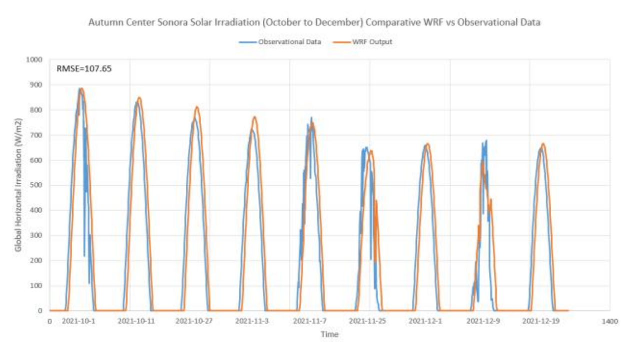

Figure 9 Autumn Center Sonora Comparative WRF vs Observation

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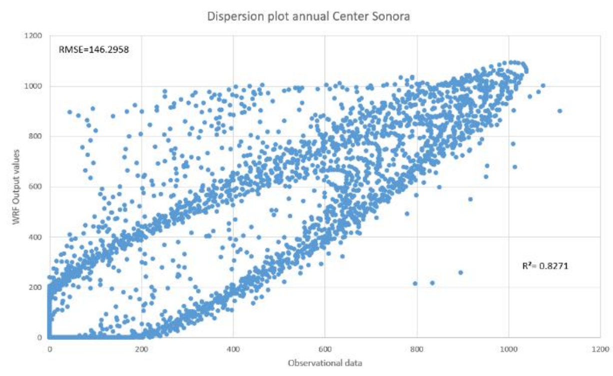

Figure 10 Dispersion plot Center Sonora

4.2.3 South region

Finally, our southern region in Sonora it's one of the most affected by weather conditions along the whole year due to its valley surface. Results are shown on figures from 16 to 19. We can see that our worst season would be summer due to high variability along the whole season, again, this is capable to be due to weather phenomena as Monsoon effect on this region, it reports values of RMSE as high as 160.874 W/m^2 and then again our best season for our forecast would be autumn with the lowest RMSE value of 99.01 W/m^2.

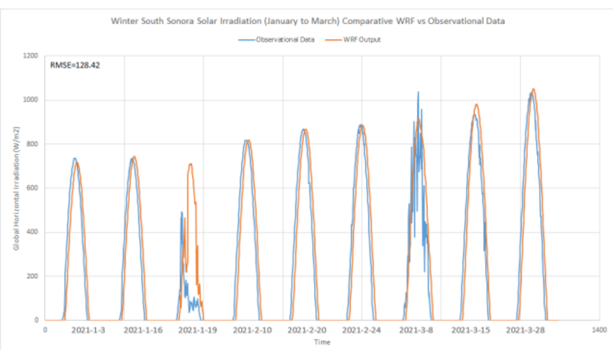

Figure 11 Winter South Sonora Comparative WRF vs Observation

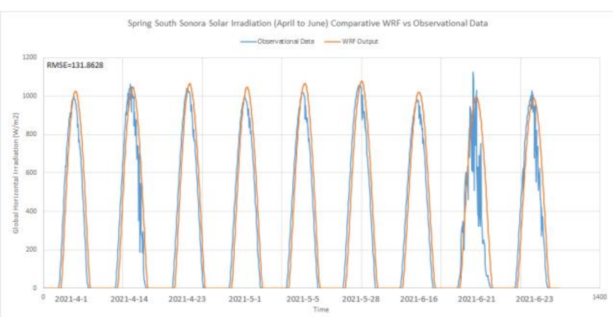

Figure 12 Spring South Sonora Comparative WRF vs Observation

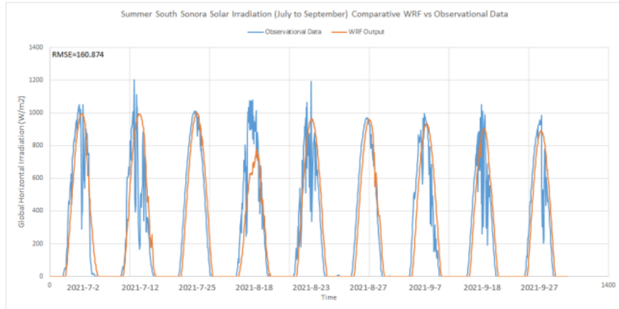

Figure 13 Summer South Sonora Comparative WRF vs Observation

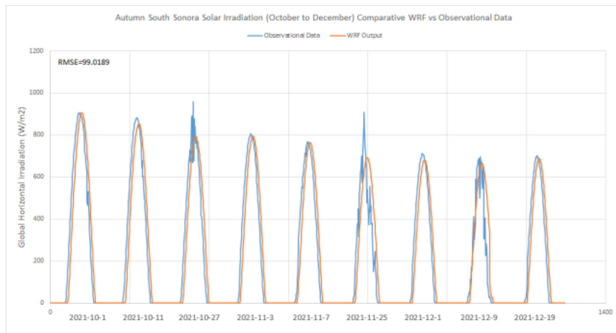

Figure 14 Autumn South Sonora Comparative WRF vs Observation

As our dispersion plot for this region shows a high tendency between values where R^2 can be seen as high as 85%, therefore our model can be performed effectively on this region as well.

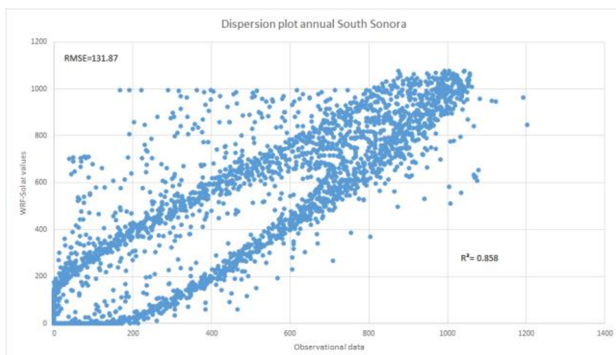

Figure 15 Dispersion plot South Sonora

V. Conclusions

In the present work an analysis for solar energy forecasting based on WRF-Solar and weather stations data in Sonora State was done to inspect how several regions with different weather conditions along the year can affect our model accuracy to forecast solar radiation.

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At first, we evaluated our results directly from WRF-Solar output against weather station observational data for a year by using representative days per month. Subsequently, we look into our data correlation by applying statistics so we can evaluate by RMSE how disperse are our values for the observed values. A low RMSE values indicates that our model has high accuracy to predict real data occurring on the place where weather stations are working.

As we can appreciate on dispersion plots, values from RMSE for northern and center region are almost identical, this can be merely by the semi-arid regions and the tendency on this places to have similar days along the year.

However, southern region analyzed show a low RMSE compared with the others, even though this region is considered as climate changing place due to its valley surface form.

We consider that regions that are semi-arid as northern and center Sonora places, can have effects as high dust concentration that affect somehow solar radiation.

Even though, we obtained RMSE values as high as 160 W/m^2 for some regions, a few adjustments on physics and model schemes as Aerosol Optical Depth add-in might correct these high values on RMSE for semi-arid regions and forced satellite images for cloud modeling for valley-like regions are solutions to get a better accuracy.

Overall, this forecast model has proven to be capable for forecast on semi-arid regions. It presents good accuracy with a high temporal resolution and a good performance for different regions along on one of the biggest Mexico state.

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