Hourly forecast of solar radiation up to 48h with two runs of Weather Research Forecast model over Italy

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Abstract

Growth and vast usage in renewable energy implies better hourly and daily planning for reliable and constant renewable energy distribution. In this sense, the forecast of renewable energy becomes more and more important. In this work, we used the Weather Research and Forecasting Model (WRF) to forecast solar radiation. We run two forecast simulations with WRF and WRF-Solar model. Models have been running on daily basis to forecast solar radiation up to 48h with hourly outputs. In this paper we elaborated one summer month of 2017 with both model forecasts compared with ground measured data for solar irradiance at one location in Italy (lat 42°02.5' North; lon 12°18.4' East). Both models represents in good manner global irradiance with RMSE for a selected maximum of a daily range of about 13% while direct (25%) and diffuse (40%) solar radiation obtained by models differ from measured values.

1. Introduction

The random nature of renewable sources, day by day and hour by hour, is one of major difficulties to overcome in energy demand. Constant change in renewable sources is a problem for those who manage energy transits on a power grid. On the other hand, those who sell or buy energy from renewable sources on the electricity market, suffers vary in prices continuously and need advance payments of a few days. On even longer period there are the needs in planning energy costs to invest the capital on production plants. Typically, the capital invested in renewable energy is subject to return the investments in period of 10 years. As small notice, the complex circulation in atmosphere-ocean dynamics will increasingly constitute in renewables and so in electrical system. The interactions between the two systems, energy and atmosphere, must necessarily involve the skill in the field of atmospheric dynamics and the variability of renewable sources. Studies in this field could essentially be done with the usage of meteorological observations and modeling tools. It comes out that the Numerical Weather Prediction models (NWP) could be a good tool to overcome the hourly management on the energy system and to better plan its development [1].

The ground observations with appropriate instruments solar-metric station are expensive and in most locations do not have long time series and continuous observations. The measuring techniques also include meteorological satellites, which make it possible to determine the characteristics of the cloudiness, albedo, solar radiation that reaches the ground, indirectly. NWP tools in good manner come out to be indispensable to estimate the renewable energy, like solar radiation. Meteorological NWP models in their calculation, as inputs consider the observed meteorological variables, a regional geographical configuration and simulate the dynamics, physical relationships between the variables, consider complicated atmospheric chemistry, aerosol contents with various parametrizations and different physical schemes in time and space steps over the calculation domain. The advantage of meteorological models is their great spatial and temporal coverage and flexibility of use, able to simulate the past and the future atmospheric conditions.

The two survey techniques the observations and the models, complements one and another. Meteorological forecast models, nowadays, are able to estimate the solar radiation in its global, direct and diffuse components, like temperature, wind, precipitation etc. NWP starts to be present in any research on solar radiation. Reliable measurements of solar radiation on the ground are essential to verify the model estimates, even in a few locations.

It this work, we will present the outputs of two forecast models (WRF-ARW and WRF-SOLAR) and compared the availability of those models in hourly planning of renewable need up to 48h. Up to now, this is the first known run of WRF-SOLAR over the region of Italy. The main objective of this work is the identification and quantification of the model capability to forecast solar irradiance components in selected configuration. The solar radiation components, downward total flux called as global horizontal irradiance (GHI), the direct normal irradiance (DNI) and the diffuse downward flux called as diffuse horizontal irradiance (DIF) are compared here. The nomenclatures of GHI, DNI, and DIF are followed in entire work.

2. Data and methods

2.1 Observational data

The availability of data with hourly intervals of direct radiation is very poor. The detailed study of concentrating solar plants (CSP) cannot disregard the knowledge of this parameter. In addition direct solar radiation is the fundamental for calculation the potential energy that a given system could produce. The hourly trends of direct radiation make it possible to identify any critical issues on the control and regulation system depends on the thermomechanical stress to which the components of CSP plant are subjected. Finally, the knowledge of the direct radiation profiles in time such as in typical meteorological year at a specific location allows the correct sizing of the storage system based on technical-economic considerations.

Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA), has installed several stations for the measurement of temperature, GHI, DNI and DIF in a region of Italy. A meteorological solar-metric station counts two pyranometers; one to measure hemispherical solar irradiance, a global horizontal (solar) radiation of a given atmosphere and second which consists with a shaded rotating arm to measure diffuse horizontal radiation, and one pyrheliometer, a solar tracking system to ensure the system consistently aimed toward the sun, to measure a direct beam solar irradiance. The following study takes into consideration the data acquired by one installed ENEA station, Casaccia near Rome [2].

2.2 Description of NWP models and WRF family

The solar radiation is the main energy source in ocean-atmosphere system, where thermal structure is determined in the dynamic of the atmosphere. The representation of the radiative transfer process is an essential component of the NWP models. The development of solar radiation governing the NWP models becomes dominant applications that have motivated the formulation of the schemes and solar parameterizations in the atmospheric models. At first, the main interest of the solar parameterizations in the atmospheric models was to include the diurnal cycle, required for a realistic representation of the surface fluxes in a column of atmosphere. Now, atmospheric forecast models solve algorithms in radiative transfer, layer by layer, and their interaction with the atmospheric particles within the cumulus and microphysics schemes. The advance knowledge of solar radiation available on the site of a solar plant allows to conveniently managing the plant itself.

The Weather Research and Forecasting Model (WRF) is a state of the art mesoscale numerical weather prediction system designed for both atmospheric research and operational forecasting applications. WRF was developed at the National Center for Atmospheric Research (NCAR) which is operated by the University

Corporation for Atmospheric Research (UCAR). The model features two main dynamical cores (ARW and NMM), a data assimilation system, and software architecture to support parallel computation and system extensibility. The model, in its both cores, is used in a wide range of meteorological applications with different time and horizontal scales from tens of meters to thousands of kilometers [4]. In this work, we will present two simulations of WRF model, ARW and SOLAR. SOLAR, in different words, is modified ARW core to meet with the new framework of solar energy application, developed to diagnose internally relevant atmospheric parameters required by the solar industry. Recent studies of the WRF model contributed in better and more reliable solar power forecasting where are improved representation of aerosol-radiation feedback, incorporation of cloud-aerosol interactions, and improved cloud radiation feedback [5].

2.3 WRF run and domain simulation

Both models grid size is set to 10x10 km. Simulations has 151x151 grid points with the center of the computational domain at latitude 41.25° and longitude 13.5°, covering the region of Italy (Fig. 1).

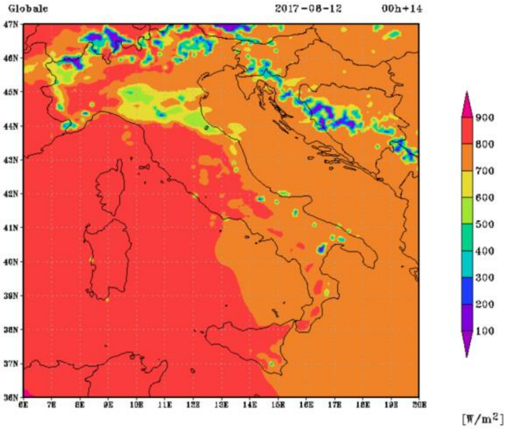

Fig. 1: WRF family computation domain, example; Global horizontal radiation at surface

Vertical resolution of models is 30 sigma levels and 4 soil levels. The NCEP/NCAR Global Forecast System (GFS) [6] (1°x1°) was used as an input data for both simulations, considering four time daily input. The Dudhia's scheme is used for the shortwave radiation parametrization for both models. Simulations are run for each day of the evaluation period up to 48 hours, starting from 0:00 UTC where first hours are considered as model spin up. The run outputs are then compared with ground observation data. We set the WRF-SOLAR run the same physical parameters, in order to be compared with ARW outputs. Only new developed parametrization of WRF-SOLAR model differ than WRF-ARW run.

3. Results

3.1. Analysis of observational and forecasted data for August 2017

We are oriented to the sources of error as an intrinsic limitation of the WRF model family and its solar schemes. The initial idea was to focus on the solar resource applications. Nevertheless, the deep statistical analysis of the physical aspects of the capability of WRF model in forecast solar irradiance is presented.

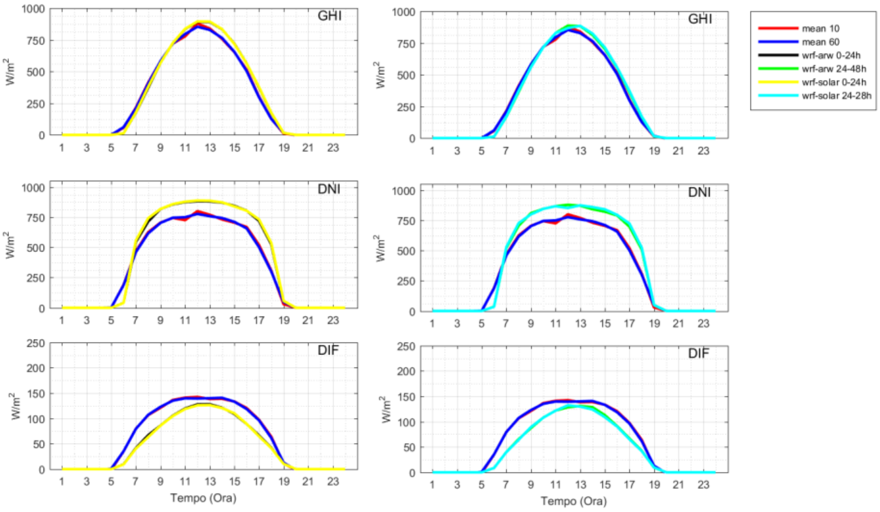

Fig. 2: Monthly mean for August 2017 for observed and forecasted on the left 0-24 and on the right 24-48h values of global horizontal (GHI), direct normal (DNI) and diffuse horizontal (DIF) irradiance.

We compared two runs of WRF model, ARW and SOLAR, with observed ground measurements of the component of solar radiation. Acquired forecast outputs of 0-24h and 24-48h were the subjected in reproduction of daily irradiation. In this work we present the mean monthly values (August 2017) of all radiation components, where on the left, first day forecast values are compared with observations, and on the right, second day forecast are compared with the observations (Fig.2.), with already defined nomenclatures. Ground observations are separated in two different averaged values, one as 10min (±5min) averaged and another as 60min (±30min) averaged vales, both centered over round hourly values. The instantaneous measurements for August do not differ with 10min averaged values and with this on mind are omitted in the analysis.

On Fig.2 we observed that there are no big differences in first and second day forecasts for the month of August, 2017. WRF model in both runs and in both time scale, overestimate the values of GHI slightly, and DNI, while underestimation is presented in DIF. The model represents in good manner the shape of daily values for GHI and DNI, while the shape of DIF suffers some limitations. Despite not good representations in shape of average monthly time series, the maximum values for DIF are represented quite well in both time scales. In the next part, we will present the rigorous statistics of daily representation for both runs and observations.

3.2 Statistics

In order to give a value of our forecast models, we determine and equate the standard statistical parameters of a daily hourly values range, between 10h and 15h in forecast for a both time scales against observations. First, we compared GHI, than DNI and finally DIF values, where scatter plot is presented with entire statistics available in table. The statistics in tables contain the values in mean, maximum, mean absolute error (MEA), mean absolute error percentage (MEA%), mean bias error (MBE), mean bias error percentage (MBE%), root mean square error (RMSE) and root mean square percentage error (RMSE%).

Scatter plot of GHI for first day forecast (WRF-ARW presented in black, WRF-SOLAR presented in yellow) against the observations, both averaged over 10 min (on the left) and 60 min (on the right) are presented in Fig. 3, while in Fig.4, the same pattern is followed for the second day forecast (WRF-ARW presented in green, WRF-SOLAR presented in blue). On both scatter plots, we observe that the forecasts in both runs and in both time scales are in quite good correlation with the observations, with small overestimation scatters in forecasted values. Slight overestimation in entire range of GHI is also presented in the graph of monthly mean values. In Table 1, entire statistics is presented in GHI values of selected daily range for both model runs in both time scales, compared with 10min and 60min observed values. The statistic values for first day forecast show better adequacy than for the second day forecast. Mean values are slightly overestimated while maximum values are underestimated by both models. RMSE% for GHI is about 14% for first day forecast compared with 10min averaged while 12% for 60min averaged of compared data. The second day forecast ARW model achieve lower RMSE% than SOLAR. In this sense, we could say, that the both models reproduce in good manner GHI values.

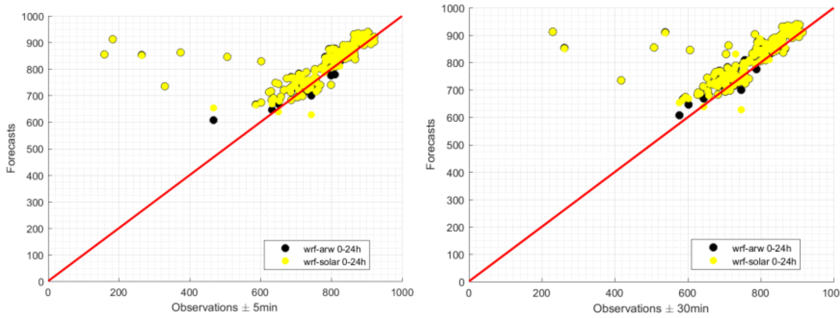

Fig. 3: GHI scatter plot, ±5min mean observation mean on the left and ±30min mean observation on the right compared with 0-24h WRF-ARW (black) and 0-24h WRF-SOLAR (yellow).

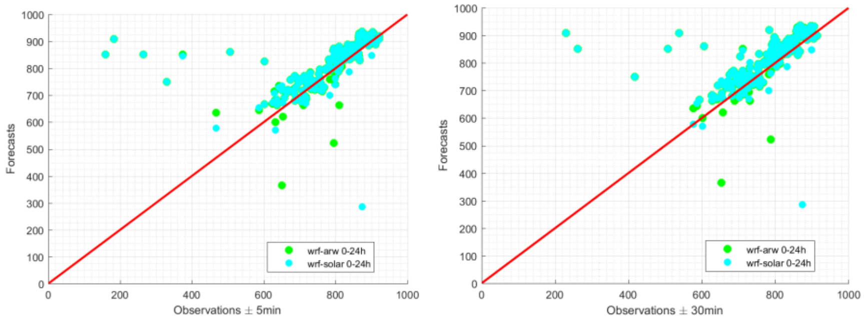

Fig. 4: GHI scatter plot, ±5min mean observation mean on the left and ±30min mean observation on the right compared with 24-48h WRF-ARW (green) and 24-48h WRF-SOLAR (blue).

	Global Horizontal (Solar) Irradiance (GHI)							
STATISTICS	obs(10') vs ARW (0-24)	obs(10') vs SOLAR (0-24)	obs(60') vs ARW (0-24)	obs(60') vs SOLAR (0-24)	obs(10') vs ARW (24-48)	obs(10') vs SOLAR (24-48)	obs(60') vs ARW (24-48)	obs (60') vs SOLAR (24-48)
mean (Obs.)	771.5	771.5	769.7	769.7	771.5	771.5	769.7	769.7
mean (Forc.)	816.3	817.3	816.3	817.3	805.9	806.5	805.9	805.5
Max(Obs.)	1089	1089	914	914	1089	1089	914	914
Max(Forc.)	940.3	940.3	940.3	940.3	935.8	935.7	935.8	935.7
MAE [W.m^{-2}]	49.6	51.3	47.5	49.2	50.7	51.3	47.2	48.9
MAE %	6.9	7.1	6.6	6.8	7.0	7.1	6.6	6.8
MBE[W.m^{-2}]	42.6	43.6	44.2	45.3	32.8	33.4	34.4	35.0
MBE %	5.9	6	6.1	6.3	4.5	4.6	4.8	4.9
RMSE [W.m^{-2}]	110.0	110.8	92.1	93.1	113.4	117.3	95.4	101.3
RMSE %	14.3	14.4	12.0	12.1	14.7	15.2	12.4	13.2

Table 1: Statistics analysis of GHI for daily values for time range of 10-15h.

DNI forecasts are overestimated in almost all observed daily range values. Presented overestimation could be the poor ability of model not to involve in detail humidity in atmosphere and complicated chemistry presented in atmospheric particles included in solar parametrization schemes applied in presented model runs. Nevertheless, overestimation in first day forecast is presented in almost entire compared region, while in second day forecast, underestimated scatters are also observed. ARW shows better correlation than SOLAR run for second day forecast. Both models in the second day represent the forecast values in the compared range more scattered. The statistic values of DNI, as for GHI, represents the better quality in first day forecast compared with 60min mean observations. We observe RMSE% of 25% for the DNI when compared with the first day forecast while the percentage slightly increase for the second day forecast. The RMSE% decreases when the forecast are compared with 60min average values.

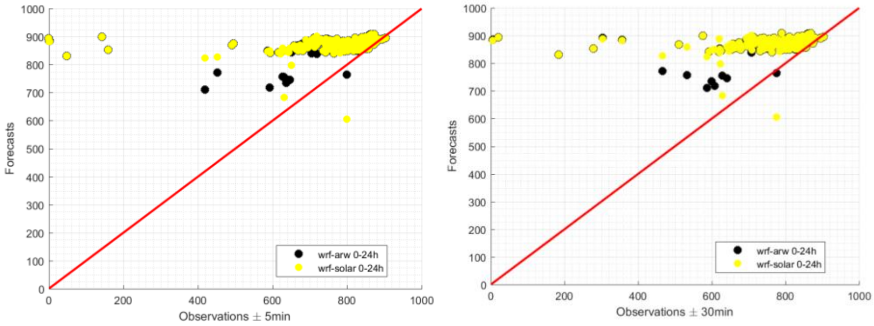

Fig. 5: DNI scatter plot, plot, ±5min mean observation mean on the left and ±30min mean observation on the right compared with 0-24h WRF-ARW (black) and 0-24h WRF-SOLAR (yellow).

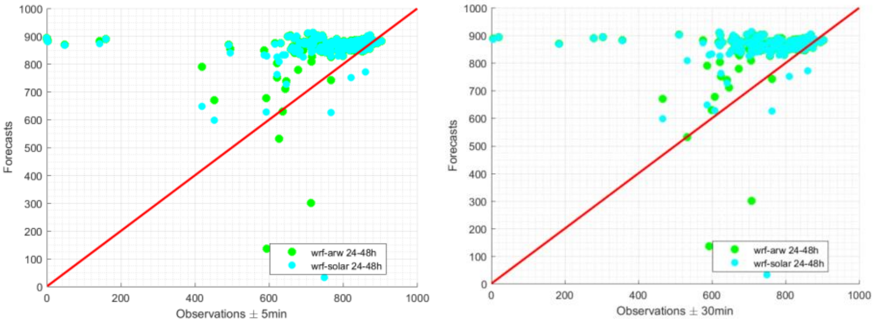

Fig. 6: DNI scatter plot, ±5min mean observation mean on the left and ±30min mean observation on the right compared with 24-48h WRF-ARW (green) and 24-48h WRF-SOLAR (blue).

	Direct Normal Irradiance (DNI)							
STATISTICS	**obs(10') vs ARW (0-24)**	**obs(10') vs SOLAR (0-24)**	**obs(60') vs ARW (0-24)**	**obs(60') vs SOLAR(0-24)**	**obs(10') vs ARW (24-48)**	**obs(10') vs SOLAR (24-48)**	**obs(60') vs ARW (24-48)**	**obs (60') vs SOLAR (24-48)**
mean (Obs.)	746.4	746.4	747.9	747.9	746.4	746.4	747.9	747.9
mean (Forc.)	868.8	871	898.8	871	854.5	857.1	854.5	857.1
Max(Obs.)	903	903	903.4	903.4	903	903	903.4	903.4
Max(Forc.)	908.8	908.9	908.8	908.9	912.2	913.7	912.2	913.7
MAE [$W.m^{-2}$]	133.9	117.8	112.3	116.9	111.6	114.4	109	112.8
MAE %	16.3	16.9	16.1	16.6	16	16.4	15.6	16.1
MBE [$W.m^{-2}$]	113.4	115.5	112	114.2	99.8	102.4	98.5	101.1
MBE %	16.2	16.5	16	16.3	14.3	14.7	14.1	14.5
RMSE [$W.m^{-2}$]	187.8	191.9	172.1	176.3	191.7	194.3	175.6	180.6
RMSE %	25.2	25.7	23	23.6	25.7	36	23.5	24.1

Table 2: Statistics analysis of DNI for daily values for time range of 10-15h.

Diffuse horizontal irradiance follows similar pattern as for GHI. SOLAR run has slightly better correlation than ARW model run. As for DNI, also the second day forecast of DIF is more scattered. Here, the underestimation in DIF values is presented, while in DNI the strong overestimation is observed. This underestimation in DIF and overestimation in DNI values are most probably correlated, and the ability of aerosol interaction and model parametrization. Maximum values of DIF are strongly underestimated while in mean values this underestimation is around 20W/m^2. The RMSE% is quite high for DIF, around 40% for both models and both forecasted days.

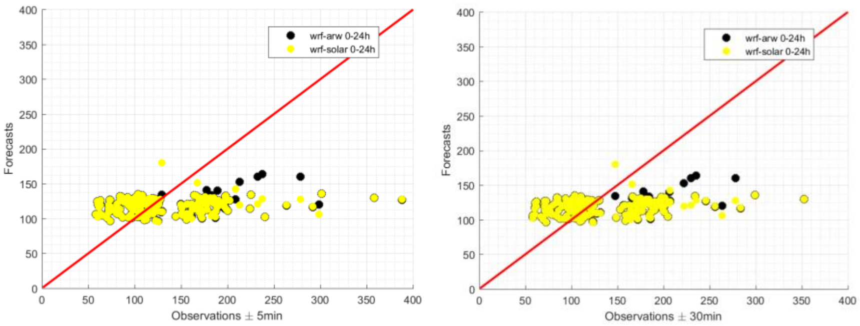

Fig. 7: Fig. 5: DIF scatter plot, plot, ±5min mean observation mean on the left and ±30min mean observation on the right compared with 0-24h WRF-ARW (black) and 0-24h WRF-SOLAR (yellow).

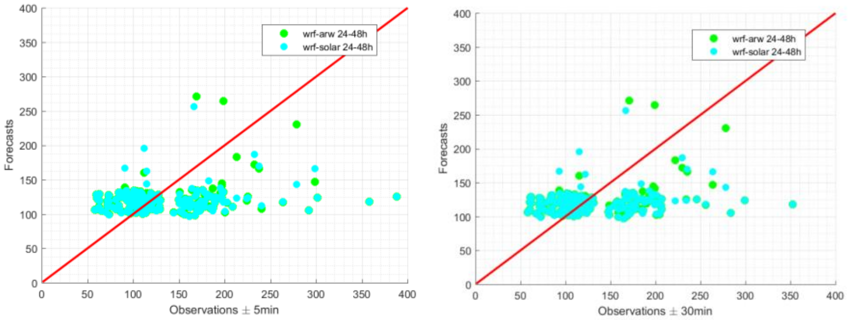

Fig. 8: DIF scatter plot, ±5min mean observation mean on the left and ±30min mean observation on the right compared with 24-48h WRF-ARW (green) and 24-48h WRF-SOLAR (blue).

	Diffuse Horizontal Irradiance (DIF)							
STATISTICS	**obs(10') vs ARW (0-24)**	**obs(10') vs SOLAR (0-24)**	**obs(60') vs ARW (0-24)**	**obs(60') vs SOLAR(0-24)**	**obs(10') vs ARW (24-48)**	**obs(10') vs SOLAR (24-48)**	**obs(60') vs ARW (24-48)**	**obs (60') vs SOLAR (24-48)**
mean (Obs.)	138.3	138.3	137.9	137.9	138.3	138.3	137.9	137.9
mean (Forc.)	118.3	117.7	118.3	117.7	121.7	120.7	121.7	120.7
Max(Obs.)	387.8	387.8	352.5	352.5	387.8	387.8	352.5	352.5
Max(Forc.)	164	180.2	164	180.2	270.7	256.3	270.7	256.5
MAE [W.m^{-2}]	40	41.3	39.2	40.3	40.3	41.6	39.4	40.7
MAE %	30.9	31.9	30.4	31.2	31.1	32.1	30.5	31.5
MBE [W.m^{-2}]	-18.2	-18.8	-17.8	-18.5	-15	-16.1	-14.7	-15.7
MBE %	-14.1	-14.6	-13.8	-14.3	-11.6	-12.4	-11.4	-12.2
RMSE [W.m^{-2}]	56.1	57.9	52.5	54.4	56.2	57.6	52.8	54.4
RMSE %	40.5	41.8	38.1	39.4	40.6	41.6	38.3	39.4

Table 3: Statistical analysis of DIF for daily values for time range of 10-15h.

4. Summary and conclusion

In this work, we presented the ability of WRF model family to represent the solar irradiance. Up to now, this is the first known run of WRF-SOLAR over the region of Italy. A complete one moth hourly data output are evaluated for GHI, DNI and DIF against the ground observations for one location in Italy. Results show that model represent in good manner GHI, while DNI and DIF needs additional post-processing technique for both runs. Recent studies showed that meteorological radiative models achieve a very high performance in DNI estimation under clear-sky conditions [7]. The problem begins when we observe high humidity, like there was the case in our observation location where seaside and lake are nearby (15km seaside and 7km lake in horizontal direction) and the constant change in aerosol optical depth presented in August.

Aerosol optical depth is not easily measurable and available value. In our model runs we set the climatological value of aerosol depth constant for entire region. As known, the GHI is much less sensitive to the optical properties of aerosol and water vapor than DNI and DIF, where this parametrization is optional in the radiative transfer equation and highly cost-consuming. In complete evaluation in solar energy application, first, different physical scheme should be evaluated for various options for aerosol optical depth, water vapor, land use, could cover, etc. Second, solar schemes are not isolated components within the model and hence, they interact with the other modules limiting a systematic comparison of the results of different parameterizations from the perspective of the scientific method. Finally, it is important to notice the optimization in low cost computational time maximizing the information to obtain the outputs or to focus research in post-processing of the data and filtering for the more correlated observed values. In future simulation, we would expect better results with WRF-SOLAR model when adopt satellite values for the aerosol optical depth. Studies like this lead to improve the models where every validation with valuable ground observational data is improvement.

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