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An ensemble-in-time forecast of solar irradiance

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Abstract. The increment of solar energy production requires an accurate estimation of surface solar irradiance. A forecast of surface solar irradiance allows estimate the energy production, and therefore minimizes the fluctuations in the electric grid supply.

In this work, hourly solar irradiance is estimated by means of the Weather Research Forecast meteorological model (WRF) in operational mode along 1-year. Different WRF outputs were combined to obtain an ensemble-in-time forecast, with four members. This solar irradiance forecast is validated against ground measurements at three locations in the northwest (NW) of Galicia (NW of the Iberian Peninsula) along one year.

Key words

Solar irradiance forecast, WRF, ensemble, validation.

1. Introduction

Global solar irradiance can be estimated in advanced by a numerical weather forecast model, to be applied in the exploitation of solar energy systems. The use of this approach has been extensively tested [1]-[5]; however, differences over a specific location usually arise in regions with changeable weather and typical partially cloudy days [1], [4].

In this work a high resolution implementation of WRF model [6] for Galicia, a changeable weather region, was done, in order to increase the spatial accuracy of the solar irradiance forecast.

Surface solar irradiance hourly forecast for 72 hours was performed by WRF model in this testing region, and modeled downward short-wave radiation results were compared against measurements at three different locations. Considering the typical synoptic patterns around the region, this WRF configuration included three one-way nested domains with horizontal resolutions of 27, 9 and 3 km (fig. 1a), in order to obtain a high resolution forecast. A variable distribution of vertical levels up to 21 km, with more levels near the surface, was applied. Initial and boundary conditions were obtained from the Global Forecast System (NCEP-GFS) forecasts (1ºx1º and 3 hours time interval). Elevation and land cover data were provided by the digital terrain model from the United States Geological Survey [7].

In spite of this high resolution forecast, during cloudy days some discrepancies between model results and measurements were expected; particularly, the uncertainty associated with solar irradiance forecasts at specific locations obtained directly from a grid model [3]. These differences are mainly because of the difficulty to forecast the clouds development and transport over a single location. Therefore, in this work an ensemble-in-time of the model outputs, with four different members, were also tested for each location.

First member, namely M0, includes properly the WRF hourly solar irradiance forecast, without any change. Second member, namely M1, is represented by the irradiance for the hour H as the weighted mean of the irradiance data forecasted using WRF model for one hour before (namely H-1), the current hour (H) and the next hour (namely H+1), according to the following expression (1),

$$R_{H\,(M1)} = a + b \cdot R_{H-1} + c \cdot R_H + d \cdot R_{H+1} \qquad (1)$$

where R is the WRF hourly solar irradiance forecast at every specified hour and *a*, *b*, *c*, *d* are the empirical adjustment parameters.

As WRF model was run every day along one year, covering 3-days per run, a combination of two different WRF runs (with different initial and boundary conditions) for the same period is possible. Therefore, the third member of the ensemble, namely M2, is obtained combining the model output of the 24-48 time range from the WRF run executed on day D (namely $[D_{24\text{-}48}]$) and the model output of the 48-72 time range from the WRF run executed on day D-1 (namely $[(D\text{-}1)_{48\text{-}72}]$) following the expression (2),

$$R_{H\,(M2)} = e + f \cdot R_H\,[D_{24\text{-}48}] + g \cdot R_H\,[(D\text{-}1)_{48\text{-}72}] \qquad (2)$$

where R_H is the hourly irradiance forecast provided by WRF model at the hour H at every run and time interval and e, *f*, *g* are the empirical adjustment parameters.

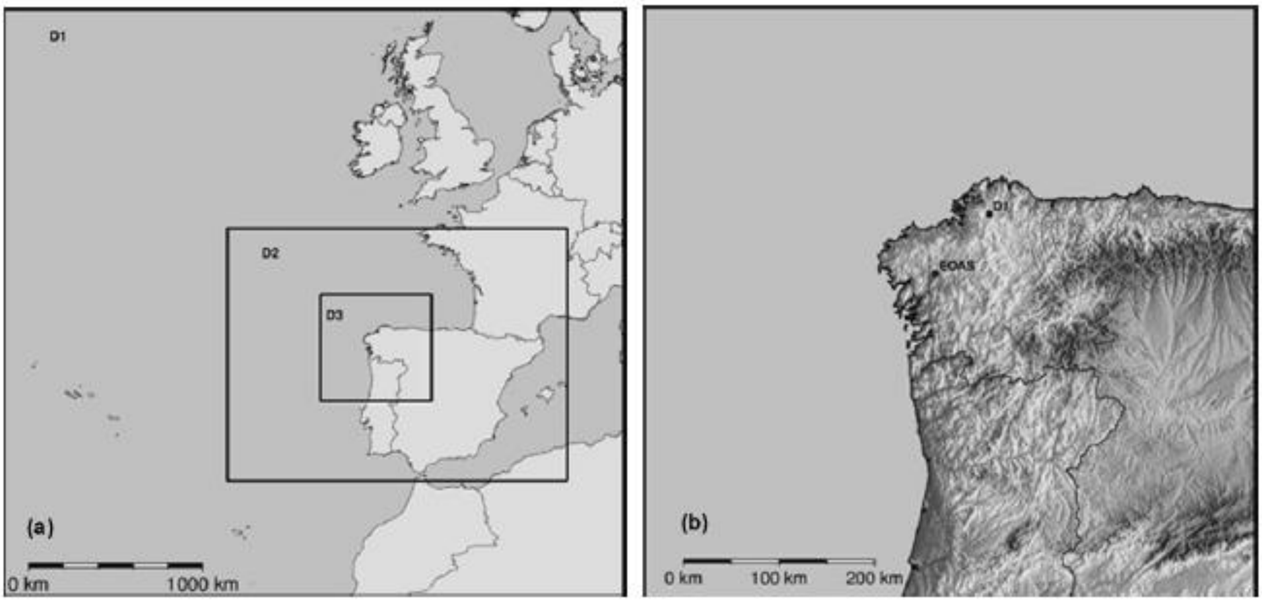

Fig. 1. (a) WRF nested domains and (b) locations of D1-A Mourela, EOAS-Santiago and CIS-Ferrol weather stations.

The last member, namely M3, is a combination of the M1 and M2 components, following the expression (3),

$$R_{H\,(M3)} = h + i \cdot R_{H\,(M1)}\,[D_{24\text{-}48}] + j \cdot R_{H\,(M1)}\,[(D\text{-}1)_{48\text{-}72}] \quad (3)$$

Again, *h*, *i*, *j* are the empirical adjustment parameters.

A 72-hour operational forecast system, including a daily WRF model run, allows obtain these four members ensemble from just one WRF run per day. This is a significant computational time saving respect to typical ensemble approaches [8], [9]; and, every member can be validated against measurements in order to select the most accurate of them.

2. Results

Three different locations (fig. 1b) at the NW of Galicia were selected for the forecasts testing: one in the Atlantic coast (CIS-Ferrol), 34 meters above sea level (asl-m), and the others placed inland, around 32 km (Santiago-EOAS, 255 asl-m) and 30 km (D1-A Mourela, 450 asl-m) far from the sea, respectively. CIS-Ferrol and Santiago-EOAS are weather stations classified as suburban and urban stations, respectively; whereas D1-A Mourela is a rural site.

The sunshine hours are even lower than the regional average (less than 2000 sunshine hours per year) in some of these stations, with values between 1600 and 1800 hours per year at the northern locations (CIS-Ferrol and D1-A Mourela) and around 2000 hours at EOAS-Santiago station [10].

Measurements of global solar radiation were obtained from Class A pyranometers installed at every location.

To assess the performance of the different solar irradiance forecasts, some statistics have been considered. The main score to compare forecast irradiance (R_f) and measured irradiance (R_m) was the root mean square error RMSE (eq. 4),

$$RMSE = \sqrt{\frac{1}{N} \cdot \sum_{1}^{N} \left(R_f - R_m\right)^2} \quad (4)$$

where N is the number of evaluated data pairs of hourly irradiance.

Furthermore, other two additional statistical measures were considered: the mean bias, MB (eq. 5) to describe systematic deviation of the forecast, and the mean absolute gross error, MAGE (eq. 6), that considers a linear weighting of all deviations.

$$MB = \frac{1}{N} \cdot \sum_{1}^{N} \left(R_f - R_m\right) \quad (5)$$

$$MAGE = \frac{1}{N} \cdot \sum_{1}^{N} \left|R_f - R_m\right| \quad (6)$$

Relative values of these error measures (rRMSE, rMB, rMAGE) are obtained by normalization to the mean ground measured irradiance of the testing period.

These statistical parameters for model evaluation were calculated using the dataset based on hourly global solar irradiance ground measurements from the aforementioned three weather stations. Model performance metrics were calculated for dates covering the July 2010, 1^{st} – June 2011, 30^{th} period. Night value without irradiance ($R_m = 0$) are neglected in the evaluation procedure.

This 1-year dataset was applied to calculate the different empirical adjustment parameters in section 1, in order to obtain a MB equal to zero. These adjustment parameters of ensemble members are summarised in the following tables, for the three weather stations.

Table 1. Adjustment parameters of ensemble member M1 in the weather stations: EOAS-Santiago, CIS-Ferrol and D1-A Mourela evaluated for three forecasting horizons (D+0, D+1 and D+2).

	a (W/m^2)	b	c	d
EOAS-M1-D+0	22.467	0.344	0.261	0.251
EOAS-M1-D+1	27.216	0.331	0.291	0.220
EOAS-M1-D+2	30.801	0.316	0.282	0.234
CIS-M1-D+0	39.501	0.326	0.244	0.219
CIS-M1-D+1	43.964	0.312	0.254	0.213
CIS-M1-D+2	50.352	0.287	0.234	0.238
D1-M1-D+0	36.597	0.365	0.296	0.137
D1-M1-D+1	37.317	0.376	0.271	0.155
D1-M1-D+2	47.776	0.367	0.242	0.174

The tables 2 and 3 show the adjustment parameters of ensemble member M1 fixing $d = 0$ and $c = 0$ respectively. These show the higher influence of adjustment parameter c (current hour), as expected.

Table 2. Adjustment parameters of ensemble member M1 in the weather stations: EOAS-Santiago, CIS-Ferrol and D1-A Mourela evaluated for three forecasting horizons (D+0, D+1 and D+2).

	a (W/m^2)	b	c
EOAS-M1-D+0	37.372	0.235	0.580
EOAS-M1-D+1	40.335	0.246	0.559
EOAS-M1-D+2	45.054	0.232	0.560
CIS-M1-D+0	53.053	0.238	0.512
CIS-M1-D+1	57.241	0.240	0.500
CIS-M1-D+2	65.904	0.216	0.497
D1-M1-D+0	44.963	0.323	0.451
D1-M1-D+1	46.690	0.325	0.448
D1-M1-D+2	59.023	0.319	0.431

Table 3. Adjustment parameters of ensemble member M1 in the weather stations: EOAS-Santiago, CIS-Ferrol and D1-A Mourela evaluated for three forecasting horizons (D+0, D+1 and D+2).

	a (W/m^2)	c	d
EOAS-M1-D+0	42.950	0.698	0.101
EOAS-M1-D+1	46.946	0.693	0.094
EOAS-M1-D+2	50.131	0.659	0.119
CIS-M1-D+0	59.785	0.643	0.088
CIS-M1-D+1	63.520	0.615	0.107
CIS-M1-D+2	69.170	0.551	0.153
D1-M1-D+0	60.725	0.708	0.023
D1-M1-D+1	61.766	0.700	0.032
D1-M1-D+2	73.145	0.637	0.074

Table 4. Adjustment parameters of ensemble member M2 in the weather stations: EOAS-Santiago, CIS-Ferrol and D1-A Mourela

	e (W/m^2)	f	g
EOAS-M2	39.414	0.457	0.350
CIS-M2	57.592	0.473	0.264
D1-M2	50.337	0.515	0.254

Table 5. Adjustment parameters of ensemble member M3 in the weather stations: EOAS-Santiago, CIS-Ferrol and D1-A Mourela

	h (W/m^2)	i	j
EOAS-M3	-10.263	0.608	0.421
CIS-M3	-10.335	0.717	0.313
D1-M3	-14.143	0.729	0.315

The results of evaluation statistical metrics are summarised for the selected locations, EOAS-Santiago, (table 6), CIS-Ferrol (table 7), and D1-A Mourela (table 8) using the adjustment parameters of tables 1, 4 and 5.

Table 6. Statistical parameters (RMSE, MAGE and BIAS) for the evaluation of predicted solar irradiance by WRF model in the EOAS-Santiago weather station. Direct model results (M0) and different ensemble members (M1, M2, M3) were evaluated, for three forecasting horizons (D+0, D+1 and D+2).

Forecast day	Member	RMSE (W/m^2)	MAGE (W/m^2)	MB (W/m^2)
D + 0	Direct results (M0)	145.6 (44.2%)	86.8 (26.3%)	29.1 (8.8%)
	M1 results	114.7 (34.8%)	80.3 (24.4%)	0.0 (0.0%)
D + 1	Direct results (M0)	155.4 (47.4%)	91.7 (28.0%)	29.1 (8.9%)
	M1 results	124.7 (38.1%)	86.9 (26.5 %)	0.0 (0.0%)
	M2 results	128.3 (38.7%)	89.1 (26.9%)	0.0 (0.0%)
	M3 results	122.2 (36.9%)	84.7 (25.6%)	0.0 (0.0%)
D + 2	Direct results (M0)	164.8 (50.6%)	98.6 (30.3%)	28.8 (8.8%)
	M1 results	134.2 (41.2%)	94.2 (28.9%)	0.0 (0.0%)

Table 7. Statistical parameters (RMSE, MAGE and BIAS) for the evaluation of predicted solar irradiance by WRF model in the CIS-Ferrol weather station. Direct model results (M0) and different ensemble members (M1, M2, M3) were evaluated, for three forecasting horizons (D+0, D+1 and D+2).

Forecast day	Member	RMSE (W/m^2)	MAGE (W/m^2)	MB (W/m^2)
D + 0	Direct results (M0)	160.9 (51.1%)	103.9 (33.0%)	33.9 (10.8%)
	M1 results	120.0 (38.2%)	85.0 (27.0%)	0.0 (0.0%)
D + 1	Direct results (M0)	169.2 (54.2%)	107.9 (34.5%)	32.1 (10.3%)
	M1 results	128.0 (41.0%)	90.9 (29.1%)	0.0 (0.0%)
	M2 results	134.2 (42.7%)	96.7 (30.8%)	0.0 (0.0%)
	M3 results	127.7 (40.6%)	90.7 (28.9%)	0.0 (0.0%)
D + 2	Direct results (M0)	184.7 (59.7%)	119.9 (38.7%)	32.0 (10.3%)
	M1 results	142.5 (46.0%)	104.2 (33.7%)	0.0 (0.0%)

Table 8. Statistical parameters (RMSE, MAGE and BIAS) for the evaluation of predicted solar irradiance by WRF model in the D1-A Mourela weather station. Direct model results (M0) and different ensemble members (M1, M2, M3) were evaluated, for three forecasting horizons (D+0, D+1 and D+2).

Forecast day	Member	RMSE (W/m^2)	MAGE (W/m^2)	MB (W/m^2)
D + 0	Direct results (M0)	169.3 (51.9%)	111.3 (34.1%)	37.3 (11.4%)
	M1 results	128.2 (39.3%)	94.1 (28.8%)	0.0 (0.0%)
D + 1	Direct results (M0)	171.6 (53.0%)	114.0 (35.2%)	34.3 (10.6%)
	M1 results	132.2 (40.8%)	97.7 (30.1%)	0.0 (0.0%)
	M2 results	139.1 (42.4%)	103.9 (31.7%)	0.0 (0.0%)
	M3 results	129.5 (39.5%)	94.7 (28.9%)	0.0 (0.0%)
D + 2	Direct results (M0)	188.6 (58.4%)	126.0 (39.0%)	28.7 (8.9%)
	M1 results	149.2 (46.2%)	110.1 (34.1%)	0.0 (0.0%)

It must be noticed that M2 member of the ensemble (and M3, as it is derived from M2) are only available for forecast day D+1. It is due to the definition of the member M2, that only can provide solar irradiance forecast for the forecast day D+1 (24-48 hours time horizon).

In terms of relative root mean square error (rRMSE), hourly irradiation prediction varies between 34.8% and 51.9% for first day (D+0), 36.9% and 54.2% for D+1 and 41.2% and 59.7% for D+2. These results are comparable to previous one obtained at Central Europe locations [4] for a whole year, although better results for Spanish locations were presented in the same work. However, the Atlantic climate of this testing region is more similar to the Northern latitudes, so differences can be explained because of a higher cloudiness in this region than in other Spanish Southern locations.

About the variability of this testing dataset, despite of the proximity of the selected stations, the errors from these members vary significantly and depend on the location under study; the best accuracy was found for EOAS-Santiago station and the worst results were achieved at CIS-Ferrol and D1-Mourela stations. This can be explained because of the local meteorology influence (as differences between coastal, CIS-Ferrol, and inland locations) in the solar irradiation; this local influence cannot be well described by this WRF model forecast because of its limited horizontal resolution.

Direct WRF forecast results show an important bias for the evaluated forecast horizons. The bias is always positive, indicating a systematic overestimation of the irradiance between 8.8-11.4%. However, forecast irradiance data obtained from the ensemble members M1, M2 and M3 are more accurate than direct WRF irradiance forecasting due an adjustment. Referring the forecast day D+1, the ensemble member M3 (combination of members M1 and M2) works better, with improvements in RMSE: regards to the WRF direct results, relative RMSE was reduced 10.5% at EOAS-Santiago, 13.6% at CIS-Ferrol and 13.5% at D1-A Mourela station, whereas considering all stations the relative RMSE is improved a 12.5%.

3. Conclusions

As a solar irradiance forecast, an ensemble with four different members, including the direct output of WRF model and different linear combinations, were tested against measurements at three different locations along one year.

Forecast irradiance data obtained from the ensemble members M1, M2 and M3 are more accurate than M0 direct WRF irradiance forecasting. Referring the forecast day D+1, the ensemble member M3 (combination of members M1 and M2) works better, with improvements in RMSE: regards to the WRF direct results.

The best statistics were achieved with member M3 for the three locations, that linearly combines two different direct WRF runs outputs for the same period, and for the current hour, one hour before and one hour later. That is, this member reduces the uncertainty associated to the initial and boundary meteorological conditions (as in typical in ensemble forecasts, [8]) and the errors in the timing of the solar radiation at a specific location during cloudy days.

In addition, the availability of four different members allow estimate the forecast spread, in order to take into account the solar radiation forecast uncertainty in the exploitation of solar energy systems.

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