Spatial and temporal downscaling of solar global radiation and mean air temperature from weather forecast data - an introductory numerical study and validation

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Abstract - **This short paper presents a numerical method for spatial and temporal downscaling of solar global radiation and mean air temperature data from global weather forecast models and its validation. The final objective is to develop a prediction algorithm to be integrated in energy management models and forecast of energy harvesting in solar thermal systems of medium/low temperature. Initially, hourly prediction and measurement data of solar global radiation and mean air temperature were obtained, being then numerically downscaled to half-hourly prediction values for the location where measurements were taken. The differences between predictions and measurements were analyzed for more than one year of data of mean air temperature and solar global radiation on clear sky days, resulting in relative daily deviations of around -0.9±3.8% and 0.02±3.92%, respectively.**

Resumo - **Neste artigo apresenta-se um método numérico para a realização e validação de uma regionalização (*downscaling*) espacial e interpolação temporal de dados de radiação solar global e temperatura média do ar provenientes de modelos globais de previsão do tempo. O objetivo final é o desenvolvimento de um algoritmo de previsão que poderá ser integrado em modelos globais de gestão de energia e de previsão de produção energética em sistemas solares térmicos de média/baixa temperatura. Numa primeira abordagem foram obtidos dados de previsão e medição horários de radiação solar global e temperatura do ar média tendo sido utilizados métodos de *downscaling* estatístico para o cálculo de previsões de meia em meia hora para o local de medições. As diferenças entre as previsões e as medições são analisadas para uma série de mais de um ano de dados de temperatura média do ar e radiação solar global, apenas em dias de céu limpo, sendo obtidas diferenças diárias relativas de cerca de -0.9±3.8% e 0.02±3.92% respetivamente.**

Key words – Solar Energy, Prediction Models, Short-term Forecast, Air Temperature, Downscaling.

INTRODUCTION

Weather forecast is a field of study that aims to predict the meteorological conditions based on physical laws and mathematical and numerical models used in high capacity computers that also incorporate observations made throughout the world, thus generating prognostic data [1]. This data is used in many applications and it can help people plan their days, prevent damage in case of extreme atmospheric conditions, it is important for businesses related to agriculture, transportations and energy among others [2]. Renewable energy resources like solar and wind energy are particularly dependent on the weather and so, weather forecast can be used to predict the energy output of systems converting such resources and adapt auxiliary systems or even the electric grid.

In this short paper an initial approach to the development of a global solar radiation and mean air temperature prediction algorithm is presented, which can be used in energy management models and energy harvesting prediction in solar thermal systems of medium/low temperature. The input data of the algorithm are the hourly predictions from the European Centre for Medium-range Weather Forecast (ECMWF) at a 0.125×0.125° grid [3]. The values of solar global radiation and mean air temperature in the four grid points surrounding a given location are selected. This will then be numerically downscaled to obtain half-hourly values of solar global radiation for the next 72 hours for the selected site. In this first approach, the raw data predictions and the predictions after the downscaling process are compared to the measured values.

METHODS

Initially, solar global radiation and mean air temperature predictions were obtained as accumulated hourly values in J/m^2 and hourly averaged values in Kelvin, respectively, from the ECMWF prediction grid over Portugal. Measured data was obtained with 1 minute of time step from sensors located in the Observatory of the Institute of Earth Sciences in the University of Évora [4] (38,567687N;7,91704W), in W/m^2

for solar global radiation using a Kipp & Zonen pyranometer (model CM6B) and °C for mean air temperature using a Thies thermo-hygrometer. All experimental data was collected from May 2015 until September 2016 and then treated and converted to hourly values of solar global radiation in J/m^2 and mean air temperature in Kelvin.

In this stage, groups of 3 consecutive days of clear sky conditions (clearness index - ratio of the horizontal global irradiance to the corresponding irradiance available out of the atmosphere [5] - equal or higher than 70%) were selected for analysis, having been identified 80 of these 72h groups. For mean air temperature there were 447 prediction groups of 72 hours available for analysis.

The goal of this data analysis is to evaluate the weather prediction performance and of its downscaling through comparison with observed data. Trough numerical downscaling, a bi-linear interpolation and the average of the four neighboring prediction grid points were made. Like so, there are prediction values for the northwest, southwest, southeast and northeast points regarding the sensor location, and for the sensor site through the bi-linear interpolation and average of the four neighboring points. With this data one can obtain the hourly differences hereinafter called as simple hourly difference calculated through (1) for each of these cases with irradiance values in J/m^2 and temperature values in Kelvin.

$$\begin{matrix} Simple \\ Hourly \\ Difference \end{matrix} = \frac{Hourly\ Prediction - Hourly\ Measurement}{Hourly\ Measurement} \times 100\% \quad (1)$$

One can also obtain a daily difference calculated by (2) using the daily-integrated prediction and measured values of solar global radiation in J/m^2 and the daily mean prediction and measured values of air temperature in Kelvin.

$$\begin{matrix} Daily \\ Difference \end{matrix} = \frac{Daily\ Prediction - Daily\ Measurement}{Daily\ Measurement} \times 100\% \quad (2)$$

To get a better perception of the impact of the hourly differences between predicted and real values regarding the daily irradiation (total energy), a weighted hourly difference was calculated through (3).

$$\begin{matrix} \text{Weighted} \\ Hourly \\ Difference \end{matrix} = \frac{Hourly\ Prediction - Hourly\ Measurement}{Daily\ Measurement} \times 100\% \quad (3)$$

In a first approach, the final algorithm will determine half-hourly prediction outputs and so a temporal downscaling was also performed in this study.

The half-hourly values of solar global radiation (J) were obtained through (4) for the first half hour and through (5) for the second half hour, in which I_i is the predicted solar global irradiation, in J/m^2, for the hour i.

$$J_{i-1/2} = \frac{1}{2} I_i \left[1 - \frac{1}{4}\left(\frac{I_{i+1} - I_i}{I_{i+1} + I_i} + \frac{I_i - I_{i-1}}{I_i + I_{i-1}}\right)\right] \quad (4)$$

$$J_i = \frac{1}{2} I_i \left[1 + \frac{1}{4}\left(\frac{I_{i+1} - I_i}{I_{i+1} + I_i} + \frac{I_i - I_{i-1}}{I_i + I_{i-1}}\right)\right] \quad (5)$$

This allows the preservation of the hourly solar irradiation for the hour i, and results from averaging the half hour values obtained by linear interpolations between the values for the hours before and after i. The particular cases of the hours during which sunrise and sunset occur must be accounted for in a specific way. When the sunrise occurs in the second half of the hour i, the solar global irradiation is considered 0 in the first half hour and the hourly value of solar global irradiation is assigned to the second half hour. When the sunrise occurs in the first half, the value of solar global irradiation of the first and second half hours are given by (6) and by (7), respectively, where $0 \leq x \leq 1/2$ represents the time fraction (in hours) between the hour before the sunrise and the sunrise.

$$J_{i-1/2} = \frac{(1/2 - x)^2}{(1-x)^2} I_i \quad (6)$$

$$J_i = \frac{3/4 - x}{(1-x)^2} I_i \quad (7)$$

As for the sunset, when it occurs in the first half of the sunset hour i, the hourly solar global irradiation value is assigned to that first half hour while the second half hour is 0. When the sunset occurs in the second half of the hour i, the solar global irradiation value in the first and second half hours are given by (8) and by (9), respectively, where $1/2 \leq y \leq 1$ represents the time fraction (in hours) between the hour before the sunset and the sunset.

$$J_{i-1/2} = \frac{y - 1/4}{y^2} I_i \quad (8)$$

$$J_i = \frac{(y - 1/2)^2}{y^2} I_i \quad (9)$$

This numerical procedure also preserves the hourly solar global irradiation and results from the partition in half hours of the solar irradiation from the time of sunrise and sunset till the hours after and before, respectively, assuming that the irradiance varies linearly and maintaining the hourly irradiation.

In the case of the air temperature, the first and second half hour values of mean air temperature (U) were calculated through (10) and (11), respectively, being T_i the mean air temperature value, in Kelvin, for the hour i.

$$U_{i-1/2} = T_i - (T_{i+1} - T_{i-1})/8 \quad (10)$$

$$U_i = T_i + (T_{i+1} - T_{i-1})/8 \quad (11)$$

This procedure preserves the hourly mean value and results from averaging the half hour values obtained by linear interpolations between the hourly values of the hours after and before. After determining the half-hourly values, the simple and weighted half-hourly differences for solar global irradiation were obtained according to (1) and (3), respectively, and the simple half-hourly differences for temperature according to (1) using half-hourly values instead of hourly values.

RESULTS

TABLE I
DAILY AVERAGE AND STANDARD DEVIATION OF DIFFERENCES BETWEEN PREDICTED AND MEASURED VALUES OF SOLAR GLOBAL IRRADIATION

Prediction Day	Northeast Point	Northwest Point	Southeast Point	Southwest Point	Interpolation	Spatial Average
1	-1.508±3.614%	-1.736±3.747%	-1.157±3.343%	-1.347±3.488%	-1.409±3.510%	-1.437±3.526%
2	-0.606±3.193%	-0.902±3.491%	-0.395±3.114%	-0.620±3.401%	-0.587±3.226%	-0.631±3.281%
3	-0.645±2.633%	-0.878±2.814%	-0.408±2.425%	-0.555±2.589%	-0.593±2.560%	-0.621±2.584%

TABLE II
DAILY AVERAGE AND STANDARD DEVIATION OF DIFFERENCES BETWEEN PREDICTED AND MEASURED VALUES OF MEAN AIR TEMPERATURE

Prediction Day	Northeast Point	Northwest Point	Southeast Point	Southwest Point	Interpolation	Spatial Average
1	0.0028±2.2420%	-0.1032±2.2424%	0.0966±2.2429%	0.0252±2.2409%	0.0193±2.2408%	0.0053±2.2404%
2	0.0315±3.9104%	-0.0736±3.9045%	0.1279±3.9172%	0.0590±3.9098%	0.0497±3.9107%	0.0362±3.9095%
3	0.0003±2.2074%	-0.1046±2.2055%	0.0978±2.2111%	0.0311±2.2053%	0.0193±2.2065%	0.0061±2.2057%

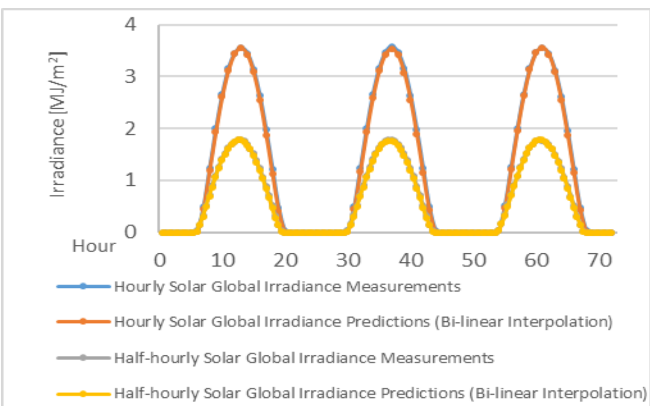

FIGURE 1
PREDICTED AND MEASURED VALUES OF HOURLY AND HALF-HOURLY SOLAR GLOBAL IRRADIATION

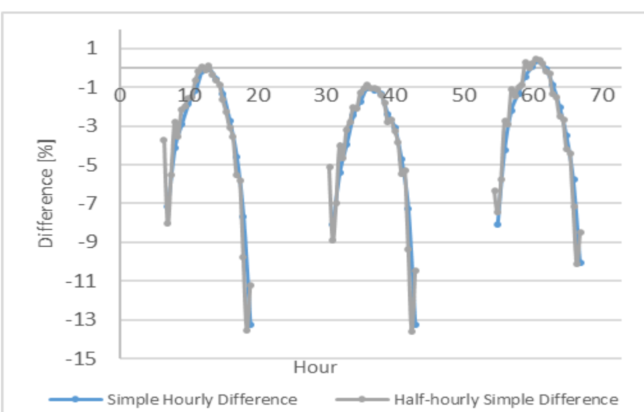

FIGURE 2
AVERAGE HOURLY AND HALF-HOURLY DIFFERENCES BETWEEN PREDICTED (BI-LINEAR INTERPOLATION) AND MEASURED VALUES OF SOLAR GLOBAL IRRADIATION

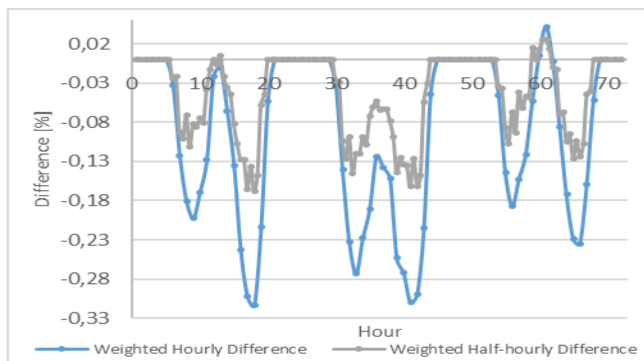

FIGURE 3
WEIGHTED AVERAGE OF HOURLY AND HALF-HOURLY DIFFERENCES BETWEEN PREDICTED (BI-LINEAR INTERPOLATION) AND MEASURED VALUES OF SOLAR GLOBAL IRRADIATION

Table I presents the average and standard deviation of the differences between the predictions for each of the four neighboring grid points for the daily solar global irradiation, and also the differences for the cases of bi-linear interpolation and average of the four points, and the measurements taken by the sensor for the first, second and third day of prediction. Figures 2, 3 and 4 show solar global irradiation data and its analysis for the 72h prediction starting 00:00UTC May 1st 2016 as an example, being the hours of sunrise and sunset excluded from Figure 2. Table II present the average and standard deviation of the same differences in the case of mean air temperature.

DISCUSSION AND CONCLUSION

For solar global radiation one can see in Table I that the differences between daily predictions and measurements are about -0.9% for clear sky days with a maximum standard deviation of 3.7%. The negative values of the differences show that the predicted irradiance is, in average, lower than the experimental values obtained by measurements. One can also see that the predictions for the second and third day are closer to the experimental values than the predictions for the first day, which was not expected, yet the daily differences are so close (the maximum difference between these values is of about 0.8%) that one can consider the same daily difference along the three days.

Being the northeast point the grid node that is closest to the measurement site, followed by the southeast point, the northwest point and finally the southwest point, a relation between the daily differences for each point and the distance between them and the measurement site was not discovered, since that, in average, the smallest daily difference exists for the southeast point followed by the one for the southwest point, the measurement site (through bi-linear interpolation), the four point average, the northeast point and finally the northwest point.

Figure 1 presents the curve of hourly irradiance measured and its prediction for the measurement site (using bi-linear interpolation) during three clear sky days. It also shows the temporal downscaling to half-hourly irradiation predictions that, as one can observe, are close to the measured half-hourly values as Figure 2 also shows.

In the case of solar global irradiance, the simple hourly differences for the hours near the sunrise and sunset are quite high due to the low irradiance values in those hours. So, even though the difference between prediction and measurement is high for these hours, it will not affect the energy production likewise. Except for these hours, the difference values vary between -7% and 0.5%. Figure 3 shows the weighted difference for these 72 hours of prediction. This way, one can obtain a better perception of the impact in daily solar irradiation (total energy) that these differences will have. In this example, the weighted hourly difference values vary between -0.32% and 0.05%, while the half-hourly difference vary in a smaller range (between -0.17% and 0.03%). These results are only for clear sky days and it is expected that the presence of clouds and higher levels of aerosols will affect these differences greatly as one can see in the example of 72h of cloudy sky starting 00:00UTC June 8th 2015 shown in Figure 4 being this one a topic to be studied in the future.

As for the mean air temperature, in Table II it is observed that the daily differences between predicted and measured values are of about 0.02% with a maximum standard deviation of about 3.92%. The positive value of differences shows that the predicted mean temperature is, in average, higher than the measured one. The predictions are closer to experimental data for the first day followed by the third and second days, being the differences for these three days very small (the maximum difference between them is of about 0.03%). Like for the solar global radiation, a relation between the proximity of the prediction grid point and the sensor and the difference between predictions and measurements was not found, being the closest prediction to measurements, in average, the one for the northeast point, followed by the average of the four points, the measurement site (through bi-linear interpolation), the southwest point, the northwest point, and finally the southeast point.

This first analysis is the base for the development of the solar global radiation predicting algorithm being the next stages the study of the influence of clouds and the performance of physical downscaling in comparison to the numerical downscaling presented here.

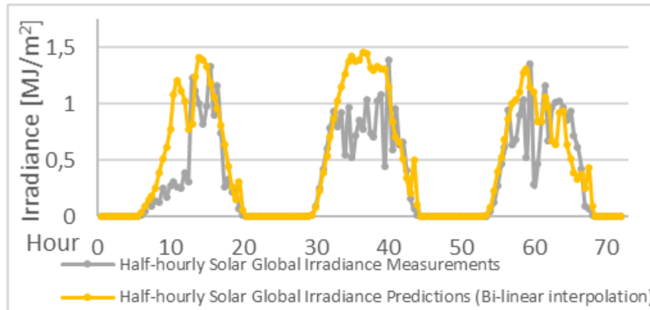

FIGURE 4
PREDICTED AND MEASURED VALUES OF HALF-HOURLY SOLAR GLOBAL IRRADIATION ON A CLOUDY DAY

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