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European Geosciences Union General Assembly 2015, EGU

Division Energy, Resources & Environment, ERE

Comparison of hourly solar radiation from a ground–based station, remote sensing and weather forecast models at a coastal site of South Italy (Lamezia Terme)

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Abstract

The solar radiation is a critical input parameter when working with solar energy and radiation dependent surface processes. In this study, we present preliminary results from an inter-comparison between hourly values from a pyranometer, MSG-SEVIRI sensor and two meso-scale models, WRF and RAMS, in clear and cloudy sky conditions. Cloudy sky condition is the most important because the attenuation of solar radiation in the atmosphere is strongly dependent on the cloud variability. Bias and RMSE errors are evaluated at a coastal site in the Mediterranean area. These statistics show the tendency of both models to overestimate short-wave radiation.

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1. Introduction

The solar radiation is a very complex parameter to model because of its dependence on complex phenomena as cloudiness, changeable weather conditions and environmental conditions e.g. aerosols. Therefore the fluctuation of this parameter is very important when working with solar energy. Methodologies for solar radiation forecasting for different time horizons, from minutes to hours on a specific location, need accurate observational datasets. The use of geostationary satellites measurements for estimating downward solar radiation can provide the necessary time and space resolution, but the local accuracy of the products has to be specifically assessed. In several studies, comparisons have been performed to validate the solar radiation dataset retrieved from the SEVIRI instrument on board of the Meteosat Second Generation (MSG), in various European Region [1, 2, 3], and to predict solar radiation using mesoscale atmospheric models [4, 5]. In this work, we present preliminary results from an inter-comparison between observed hourly values from a ground-based pyranometer, the MSG-SEVIRI sensor and two atmospheric regional models: the Weather Research and Forecasting System (WRF) [6] and the Regional Atmospheric Modeling System (RAMS) [7] over the South Italy in Central Mediterranean Area (Fig. 1.). The aim of this study is to show the performance of the irradiance retrieved from the MSG and forecasted values from RAMS and WRF for clear sky and cloudy sky and as well as for both conditions. Cloudy sky conditions are especially interesting because the attenuation of solar radiation in the atmosphere is strongly dependent on the cloud variability. Additionally, the variability of the optical depth of the clouds reduces the amount of irradiance reaching the surface [8, 9].

Nomenclature

PIR   Down-welling Surface Short-wave Radiation Flux (W/m^2) observed by ground station sensor.
DSSF   Down-welling Surface Short-wave Radiation Flux (W/m^2) estimated by MSG-SEVIRI satellite.
SWd   Down-welling Surface Short-wave Radiation Flux (W/m^2) forecast by models.

2. Experimental site and dataset

2.1. Experimental site

The experimental field is located at the CNR-ISAC coastal experimental site of Lamezia Terme on the west coast of the Calabrian region (Fig. 1.), the southernmost tip of the Italian peninsula situated in the central Mediterranean Basin. The site is located at 600 m from the coastline in open position into one of three main planes of the region (38.88N and 16.24E) and it is one of the CNR ISAC super-sites being a Climatological and Environmental Observatory recently included in the GAW (Global Atmospheric Watch-WMO) regional measurement station network.
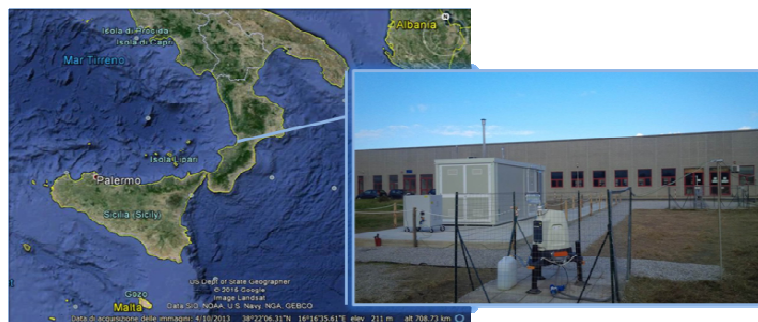

Fig. 1. Calabrian Region and experimental field.

2.2. Ground station dataset

The CNR4 Net Radiometer-Kipp&Zonen is included in a Weather Station at 2m above the ground. The CNR4 consists of a pyranometer and pyrgeometer pair that faces upward and a complementary pair that faces downward. The pyranometer and pyrgeometer measure shortwave and long-wave infrared component of the radiation, respectively, with a spectral range of 300nm to 2800nm for short-wave and of 4.5µm to 42µm for long-wave. Data are recorded at the frequency of 1min. We consider hourly averages of solar radiation retrieved from MSG and simulated from WRF and RAMS models data and compared with in-situ observations (PIR) collected for a six-month period from July 2013 to December 2013.

2.3. Satellite dataset

We retrieved the DSSF (Down-welling Surface Short-wave Radiation Flux) from MSG-SEVIRI instrument developed by LSA-SAF (Land Surface Analysis Satellite Application Facility), over Europe. The 6 months of DSSF products are downloaded from the LSA-SAF web site. A standard day consists of 48 files in HDF5 format, one image every 30min. Analyses are carried out in the original projection and spatial resolution of the DSSF products in order to reduce impact of data re-sampling caused by re-projection; retrieved data were extracted at the Lamezia Terme site. Additionally, for a quantitative analysis, measurements are co-located in time taking into account a specific linear function of the longitude as reported in the Product User Manual [10]. The LSA-SAF algorithm [9] estimates the DSSF from the three short-wave SEVIRI channels (centered at 0.6, 0.8, 1.6 µm) at 3km spatial resolution. Different parameterization procedures for clear and cloudy sky conditions were developed for this algorithm because DSSF is strongly depended on solar elevation and cloud coverage. These elements are collected into the cloud mask in binary code and developed by the SAF on Support to Nowcasting and Very Short-Range Forecasting [11, 12]. The estimated DSSF product derived from LSA-SAF covers Europe has been validated with in situ data. The results showed a difference between instantaneous satellite estimates and ground measurements of about 55W/m^2 and 87W/m^2, for clear and cloudy sky conditions, respectively.

2.4. The RAMS and WRF Models

We used the mesoscale models RAMS v.6.0 [7] and WRF v.3.5.1 [6]. Both models are configured with three two-ways nested grids at horizontal resolutions of 27km, 9km and 3km respectively (Fig. 2.). Thirty vertical levels are adopted, from the surface up to 16300m of altitude in the terrain following vertical coordinates. The levels are not equally spaced: layers within the Planetary Boundary Layer (PBL) are between 23 and 200m thick, whereas layers in the middle and upper troposphere are 1000m thick.
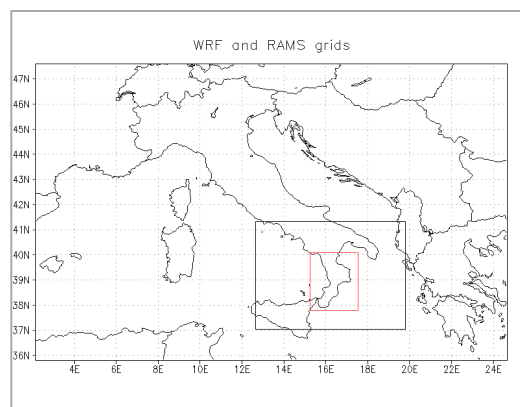

Fig. 2. WRF and RAMS domains.

Atmospheric initial and dynamic boundary conditions are derived from GFS operational forecast/analysis cycle. The RAMS and WRF model outputs were stored hourly, and each run lasts 78 hours. Every day is simulated starting at 18:00UTC on the previous day and the first 6 hours are spin-up time. Only the first day of the run is considered for the comparison to the ground based dataset. For the comparison, we have interpolated the 3km grid output to the Lamezia Terme site for both models.

The Goddard two-stream multi-band scheme for short-wave radiation is used in WRF; it accounts for ozone climatological distribution and cloud effects. A RRTMG (Rapid radiative Transfer Model for GCM) spectral scheme is used to simulate the long-wave radiation for WRF; it accounts for random cloud overlap and interactions with cloud fractions. A two-stream single-band radiation scheme is used in RAMS to calculate short-wave and long-wave radiation [7]. This scheme accounts for condensate in the atmosphere considering the liquid state only.

3. Results and discussion

The simulations of the solar radiation from the two models (SWd) and the retrieved values from MSG-SEVIRI (DSSF) are evaluated against the ground values using different statistical scores and measures of errors with data segmented into clear sky, cloudy sky and all sky conditions. All sky condition is the total dataset including both clear and cloudy sky cases.

The Root Mean Square Error (RMSE), the Mean Absolute Error (MAE), the arithmetic mean value of the errors (Bias) and the correlation coefficient (R^2), for hourly, daily and monthly averaged solar radiation have been estimated. The statistics used in this paper is detailed in equations 1, 2, 3, 4:

$$RMSE = \sqrt{\frac{\sum_i (e_i - o_i)^2}{n}}$$ (1)

$$MAE = \frac{\sum_i |e_i - o_i|}{n}$$ (2)

$$Bias = \frac{\sum_i (e_i - o_i)}{n}$$ (3)

$$R^2 = \frac{\sum_i (e_i - \bar{e})}{\sum_i (o_i - \bar{o})^2}$$ (4)

In all formulae, e_i, is the estimate value of the specific variable (DSSF and/or SWd models output), o_i, is the in-situ observations (PIR), n is the number of data-points. The number of estimation–observation pairs varies from case to case depending on the number of available PIR and DSSF or SWd data reports. Statistics are shown in Table 1.

3.1. Methodology and statistical analysis

In this work, we show the comparison from PIR, DSSF and SWd predicted by the two weather forecast models, RAMS and WRF. The hourly evaluation from DSSF products was performed only using pixels recording the same quality flags, during each hourly interval, in terms of cloud mask and DSSF algorithm. This approach uses a similar method of extraction of pixels as reported in [13, 14]. In particular, we choose the hourly bins of the pixels where cloud conditions were stable over the hourly sampling interval of the in-situ datasets. We define as stable condition the case in which the hourly bins have been the same pixel masked information, as for

example "cloudy conditions" at 13:00 UTC and 13:30 UTC, otherwise, the bin is excluded from the analysis. In Fig. 3. and Fig. 4., we show the maps of comparison of DSSF hourly bins and predicted SWd from RAMS model in the Calabrian region for two cases of clear and cloudy conditions. Similar results are obtained for WRF model (not shown).
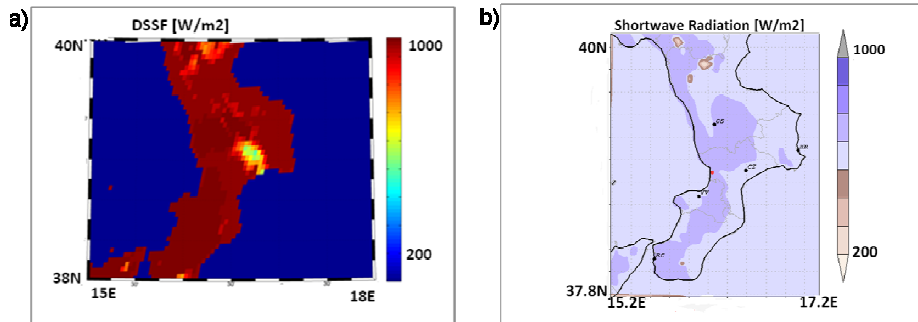

Fig. 3. Clear sky conditions 17-07-2013 13:00 UTC a) DSSF product; b) SWd predicted of RAMS model.
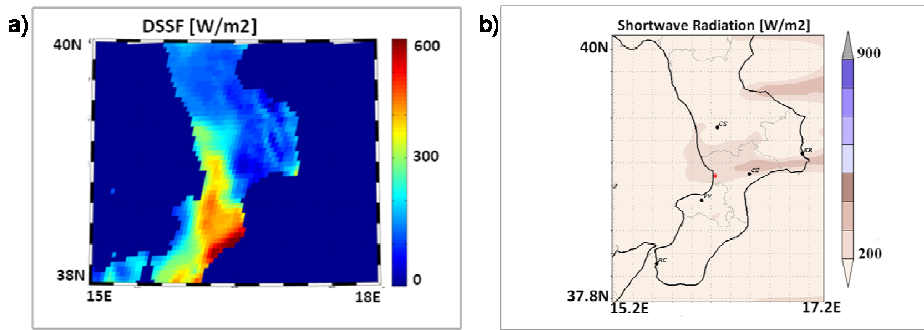

Fig. 4. Cloudy sky condition 01-09-2013 13:00 UTC a) DSSF product; b) SWd predicted of RAMS model.

Fig. 3. shows the presence of small clouds (fair weather cumulus) developing along the peninsula as a result of local breeze circulations [15, 16]. Some of these clouds are well simulated by the model, as in the north part of the peninsula, even if most of them are missed. The exact co-location in space and time is difficult to simulate, nevertheless the model is able to represent the meteorological situation for the day, showing cloudiness forced by local circulations. In Fig. 4. the forecast results are worse. For the date and time of Fig. 4., MSG-SEVIRI shows an extended cloudiness over the northern part of the peninsula, which is only in part forecast by the model. The comparison of Fig. 3. and Fig. 4. show the difficulty to forecast the short-wave radiation in presence of extended cloud coverage, which is, in most cases, associated with a synoptic disturbance passing over the area.

In Table 1 we show the statistical analysis computed from hourly data. The RMSE from PIR vs DSSF, is reduced of about $30W/m^2$ in clear sky condition with respect to all sky condition, also for both mesoscale models the values of RMSE is reduced of about $15W/m^2$. In cloudy sky conditions, the values of RMSE are slightly increased with respect to the values of all sky condition, for both DSSF and SWd predicted by forecast models respectively of about $6W/m^2$ and $60W/m^2$.

Considering the whole validation period there is a small positive Bias of about $4W/m^2$ between DSSF product and in-situ measurements (PIR). The positive Bias, between RAMS model and in-situ measurements (PIR) is $8W/m^2$ and the WRF Bias is $44W/m^2$. These statistics show the tendency of both models to overestimate short-wave radiation.

Table 1. Hourly solar radiation statistics. Period July 2013-December 2013. RMSE, MAE, Bias in W/m^2, n is the number of cases.

| All sky	RMSE	R^2	MAE	Bias	n
PIR vs DSSF	82.20	0.96	40.19	3.9	4080
PIR vs RAMS	118.92	0.94	57.49	7.99	4032
PIR vs WRF	121.68	0.93	58.79	43.9	4056
Clear sky	RMSE	R^2	MAE	Bias	n
PIR vs DSSF	55.2	0.98	26.7	2.5	2140
PIR vs RAMS	100.526	0.96	56.97	11.57	2113
PIR vs WRF	111.475	0.95	57.82	45.19	2118
Cloud sky	RMSE	R^2	MAE	Bias	n
PIR vs DSSF	86.6	0.85	43.1	4.1	1930
PIR vs RAMS	186.47	0.72	79. 84	13.065	1870
PIR vs WRF	193.53	0.70	84.47	56.455	1863
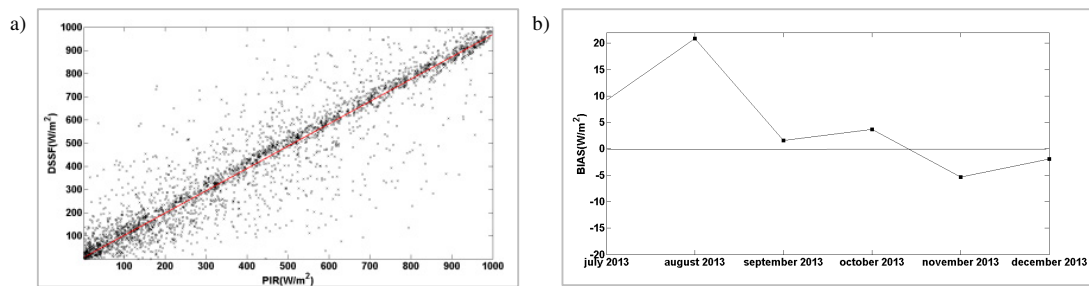
Fig. 5. a) Scatter plot DSSF vs PIR with exact acquisition times of satellite in all sky conditions;
b) The monthly bias error from DSSF vs PIR.

In Fig. 5.a the scatter plot for whole period and all sky conditions are shown the good correlation between DSSF and PIR is apparent. The coefficient of determination is larger than 0.9 in all sky and clear conditions (Table 1). In cloudy conditions the DSSF shows a good correlation with observations (R^2=0.85). Good correlations (R^2>0.9) are also found between WRF and RAMS models with pyranometer. In cloudy sky conditions, the R^2 value is about of 0.7 for both models indicating a reasonable, yet less satisfactory, agreement between models forecast and the pyranometer. In Fig. 5.b we show a temporal evolution of monthly Bias of DSSF with respect PIR. Bias show positive values during summer and fall months, from July to October, and negative for remaining months, likely due to a major solar radiation, at our latitude, with respect to the European region. Forecast models overestimate solar radiation with respect to the ground based sensor and DSSF product.

Finally in Fig. 6.a and Fig. 6.b, we show the comparison of down-welling surface short-wave radiation flux from a ground base station, MSG-SEVIRI, and predicted SWd forecast RAMS and WRF model. The difficulty to estimate and forecast the surface short-wavelength radiation in cloudy conditions is further shown also in these figures. It is apparent that the errors for DSSF and SWd forecast are much larger on 1 September 2013 (cloudy conditions) than on 17 July 2013 (clear sky conditions). Considering the analysis on a daily basis, the RMSE values, (not shown in Table 1), of PIR vs DSSF, are reduced of about 40W/m^2 in clear sky conditions with respect all sky conditions. For the same sky conditions the RMSEs of WRF and RAMS models are reduced of about 10W/m^2.
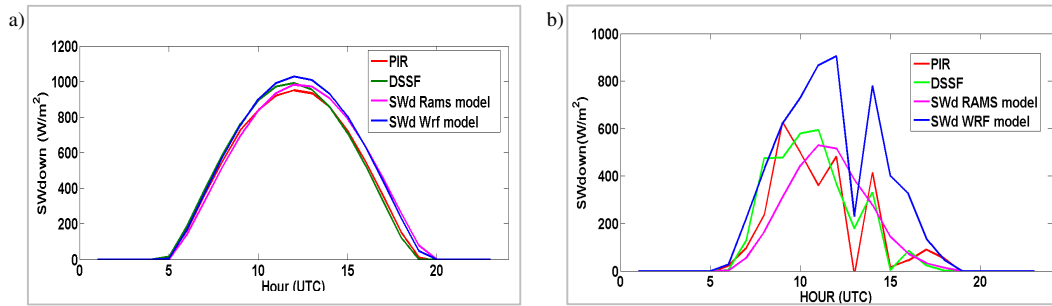
Fig. 6. Comparison of the down welling surface short-wave radiation flux from pyranometer sensor, MSG-SEVIRI, RAMS and WRF model. a) Clear sky condition (17-07-2013); b) Cloud sky condition (01-09-2013).

In cloudy sky conditions the values of daily RMSE are increased respect all sky conditions of about 5W/m^2 for PIR vs DSSF and of about 50W/m^2 for PIR vs both WRF and RAMS models.

These preliminary results are in agreement with previous studies reporting a much larger error in cloudy conditions compared to clear sky in flat terrain[14]. These results suggest the importance of i) the right parameterization in atmospheric models in order to reduce the errors in the prediction of SWd in cloudy conditions, ii) use of statistical methods such as post processing e.g. a multi-model approach and/or MOS (Model Output Statistics) technique. Furthermore these studies are functional for optimizing the algorithm developed for DSSF in the quality flag mask. Overall, the comparison between the observed surface radiation with the DSSF product, and the outputs of the two weather forecast models, for the period July 2013-December 2013, showed a reasonable agreement. Forecast models, in general, overestimate solar radiation with respect to the pyranometer and DSSF product, both in clear and cloud sky conditions.

4. Conclusion

We evaluated the short-wave down-welling radiance retrieved from the MSG-SEVIRI and forecasted by the WFR and RAMS meso-scale models against observations at a coastal Mediterranean site. Statistics is computed starting from hourly values considering both clear and cloudy sky conditions. Time series from the DSSF product from MSG-SEVIRI show a reasonable agreement with ground based pyranometer observations (Bias=4W/m^2; RMSE=50W/m^2).

Forecast models, especially WRF, overestimates the surface observations and, as expected, their RMSE is larger than the RMSE from MSG-SEVIRI of about 30W/m^2 considering the whole dataset. The impact of the clouds on the statistics is noticeable. The values of RMSE for PIR vs DSSF are reduced of about 40W/m^2 in clear sky conditions compared to cloudy sky. The RMSE values from PIR vs WRF and RAMS models, in cloudy sky is about 80W/m^2 larger than in clear sky conditions.

The results suggest that DSSF product and/or output of weather forecast models are a promising alternative to provide spatial variation of solar radiation over regions lacking surface stations. Nevertheless, future works is necessary to statistically refine the inter-comparison methodology in order to understand the satellite and model output limitations related to weather and local conditions. Moreover, post processing techniques as, for example, MOS (Model Output Statistics) or multi-model superensemble should reduce the forecast error and will be considered in the future.

Acknowledgements

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