CLEAR SKY MODELS ASSESSMENT FOR AN OPERATIONAL PV PRODUCTION FORECASTING SOLUTION

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ABSTRACT: Photovoltaic production is mostly driven by the solar irradiance received at ground level. Forecasting surface solar irradiance remains to predict the cloudiness and combine it with the value of the irradiance modeled under a clear sky for the same area at the same forecast horizon. Thus, uncertainty of irradiance under clear sky can affect significantly the photovoltaic production forecast. Clear sky irradiance can be accurately computed if concentration of some atmospheric components (aerosol, water vapor and ozone) are sufficiently known above a location. Many clear sky models have been designed allowing a various number of inputs. In this work, we analyzed the performance of four different clear sky models. We compared their outputs against ground measurements located in Reunion Island, Corsica and French Guiana. We used the models with atmospheric parameters provided by two different sources (neighboring ground measurements and reanalysis). Best results lead to a relative root mean square error (rRMSE) of 3 % and an absolute relative mean bias error (rMBE) less than 1 %, for minutely irradiance. Using atmospheric parameters from reanalysis instead of punctual measurements significantly reduces errors in clear sky models.

1 INTRODUCTION

Accurate forecast of photovoltaic (PV) power production is essential for grid operators in order to accommodate this intermittent energy in their scheduling, dispatching and regulation of power.

Photovoltaic power production relies upon global solar radiation received at ground level on an horizontal plane, further called *GHI* (Global Horizontal Irradiance). The response time of a PV system is almost instantaneous. Its output follows the change in *GHI* due to the passing clouds. Thus, *GHI* forecasting methods remain to predict the transmittance of the cloud coverage through an attenuation factor that can be combined with the value of the *GHI* simulated for a clear sky situation, and further referenced as GHI_c. The attenuation factor can be expressed as a clear sky index K_c equal to 1 when the sky is clear and decreasing inversely with cloudiness. K_c is defined by (1).

$$GHI = K_c . GHI_c \qquad (1)$$

Then, an increasing uncertainty of GHI_c involves errors in *GHI* forecast, especially when K_c has a low value. Many clear sky models have been designed to compute GHI_c in the broadband visible spectrum. Survey and performance analyses of such models can be found in [1], [2] and [3]. The required inputs for such tools are varying from one model to another. The simplest models just take into account the solar elevation, while more detailed ones may include elevation of the site and ground albedo. The most advanced models take into account the concentration of atmospheric components absorbing and diffusing solar radiation in the shortwave. Concerned atmospheric components are aerosol water vapor and, to a lesser extent, ozone.

The availability of such data is not always guaranteed anywhere at anytime. Therefore, selecting the most suitable clear sky model for a given site implies to check either the model takes advantage of atmospheric variables when they are available or provides accurate GHI_c even if no or poor quality atmospheric data are available.

In the present study, we use *GHI* ground measurement time-series in three different locations to assess the performance of four clear sky models presenting distinct features. We summarize the clear sky models' characteristics (section 2). Atmospheric data are presented in section 3. *GHI* measurements are described in section 4. Results are then discussed in section 5.

2 CLEAR SKY MODELS

2.1 Models selection

Numerous clear sky models can be found in literature. [2] performed a large survey and analyzed the intrinsic performance of each model regarding a ground measurements data bank. This survey permitted to underline many similarities between atmospheric transmittance modeling approaches. Moreover, most of the presented models have not been used in an operational manner. We limited the study to four models providing the global component of solar irradiance. We chose them according to operational aspects respecting our needs. The criteria are:

- Models show various physical approaches to parametrize GHI_c;
- Models should take into account variable atmospheric components;
- Accuracy of models has been proven by comparison with ground measurements located in various climatic zones with several years of data;
- Models are or have been used for operational processes in real time, proving that no complex tunings are necessary to keep a constant accuracy in space and time.

2.2 Bird

The Bird model [4] has been widely used for several decades. It is based on empirical representations of radiative transfer equations, leading to an easy and relative fast implementation. Among Bird model inputs, aerosols optical depth, water vapor and ozone concentration are required.

2.3 ESRA

This model [5][6] was developed in the framework of the European Solar Radiation Atlas [7]. Its physical approach is based on the Rayleigh optical depth parametrization [8]. This model constitutes the clear sky scheme of the Heliosat-2 method [9], currently feeding the solar database HelioClim [10]. The Linke turbidity at airmass coefficient 2 [11] is the unique atmospheric variable needed for this model.

2.4 Simplified Solis

The Solis clear sly model was originally developed by [12] in the framework of the Heliosat-3 European project [13]. It is based on pre-computed outputs of the radiative transfer model LibradTran [14] and modified Beer-Lambert law formulation reducing significantly the time computation. [15] proposed a faster computing version using simplifying hypotheses for the representation of aerosol effects. Accuracy of global irradiance compared with the original model is less than 2 % with no bias. Atmospheric variable inputs are aerosol type, aerosol and water concentration. Ozone content is set as a constant.

2.5 McClear

McClear [16] is a clear sky model developed to exploit the benefit of the MACC (Monitoring Atmospheric Composition and Climate) datasets, described in section 3.2. This model is actually a set of abaci computed from LibradTran. Solar irradiance data from a wide variety of atmospheric optical states have been beforehand computed. McClear is available as a web service querying abaci. It has the strong advantage of obtaining solar irradiance under a clear sky without a radiative transfer equation resolution at each request. Such fast results delivery does not require approximation computation existing in many models and leading to a loss of accuracy.

Testing this model with other atmospheric data than those used to build the abaci remains in an obvious manner to build new abaci. The current version of McClear needed several months of computation time to complete abaci. In this study, McClear has only been used with MACC parameters.

3 ATMOSPHERIC PARAMETERS DATASETS

3.1 AERONET

The AErosol RObotic NETwork [17] is an optical ground based aerosol monitoring network and data archive supported by NASA's Earth Observing System and expanded by federation with many non-NASA institutions. For several decades, AERONET measurements have constituted a reference in atmospheric parameters standard data banks. It provides algorithm validation of satellite aerosol retrievals and characterization of aerosol properties that are unavailable from satellite sensors. Among numerous research using AERONET data, many clear sky models taking into account atmospheric components concentration have been validated through this network.

However, such valuable measurement instrumentation requires a high level of maintenance. Therefore, the number of stations is limited as shown on figure 1. Moreover, availability of data changes from one station to another. Some stations do not present continuous datasets in time. Aerosol optical depth (AOD), which is a spectral physical value, is not always available at the same wavelength from one station to another. A spectral interpolation of AOD is often necessary.

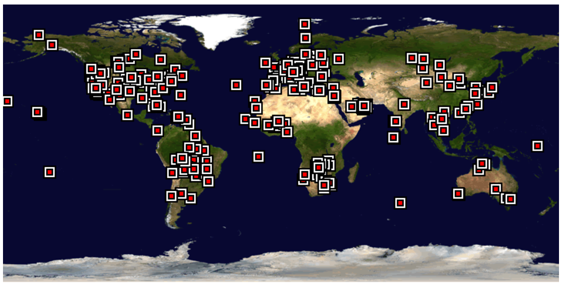

Figure 1: Map of AERONET stations (from NASA)

Finally, using AERONET data makes sense if area study is located close to an AERONET station.

3.2 MACC

The MACC project funded by the European Commission, ensures the operational provision of global aerosol properties forecasts together with physically consistent total column content in water vapor and ozone [18][19]. A multi-annual reanalysis dataset is provided and used here [20]. Such information has not been available so far from any operational numerical weather prediction model.

Such datasets represent the expected complement of AERONET. MACC permits to obtain continuous and regular atmospheric inputs in space and time almost anywhere in the world. Figure 2 shows an example of available data coverage. Data are available from 2003 onward.

In the current study, MACC data have been collected using the same protocol as [16]. A bilinear spatial interpolation has been performed within the four closest points surrounding the ground measurement site. Data are available every 3 hours, we interpolated them at minute time step.

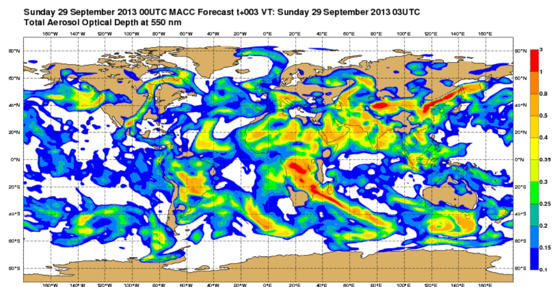

Figure 2: An example of aerosol optical depth map provided by MACC service (from Copernicus)

4 GROUND MEASUREMENTS DATA BANKS

Three independent *GHI* data banks have been used in three different sites. Atmospheric data from MACC were available at each site for the required period.

4.1 Reunion Island

GHI data are collected with a solar reference cell located in Sainte-Marie, Reunion Island (latitude : -20.89°; longitude : 55.53° in decimal degrees). The site is in a maritime and tropical environment at 4 meters of altitude.

We selected a time series of minutely *GHI* measured from August 19th 2010 to June 6th 2012. Sainte-Marie is located at less than 10 kilometers from the AERONET station of Saint-Denis (Reunion Island). Thus, we can consider that AERONET data are collocated with the *GHI* measurement site.

4.2 Corsica

Two complete years (2010-2011) of hourly *GHI* measured in Ajaccio (latitude: 41.92°; longitude: 8.8°) has been collected for our study. Data from pyranometer have been collected in a maritime environment and Mediterranean climate. Altitude of the site is 5 meters. The nearest AERONET station providing data at the same period is located in Ersa, in the northern part of Corsica, at more than 150 kilometers of Ajaccio. Atmospheric parameters measurements in this case cannot be considered as collocated.

4.3 French Guiana

Four month of minutely *GHI* data of Kourou (latitude 5.12°, longitude -52.70°, altitude 41 meters) were collected from April 19th to July 31 th 2013. Nearest AERONET station is located in Surinam and only 3 years of data are available from 1998 to 2001. Such case illustrates the typical problem of AERONET network. Even if data measurements are standard all over this network, the maintenance of material and data delivery is not the same from one station to another. Using climatological average permits to overcome the unavailability of data. Thus, we built monthly average of aerosol, water vapor and ozone concentration from this restricted dataset.'

5 COMPARISON METHODOLOGY

5.1 Clear-sky instant detection

There is no objective definition of a clear-sky instant from global irradiation measurements. The ratio between the direct and global irradiance is a good indication. Indeed, when the sky is totally clear, diffuse component of radiation is very low meaning that direct and global component are equivalent. Unfortunately, our measurements include only global component. To detect clear sky moments from global radiation, [21] computed a corrected clearness index K_t' from the clearness index K_t and air mass (m) defined by [22], where :

$$K_T' = K_T/[1.031 \exp(-1.4/(0.9 + 9.4/m)) + 0.1]. \quad (2)$$

[1] suggests that the sky is clear when $K_t' > 0.65$, notifying that this threshold is arbitrary but leads to satisfactory results. We complete this condition by considering that standard deviation of K_t' during an interval of 180 minutes centered on the given instant must be inferior to 0.02. This filter permits to confirm that sky vault is totally homogenous in addition to sunshine conditions [16]. We applied these conditions to minutely *GHI* (Sainte-Marie and Kourou). For hourly measurements (Ajaccio), it is impossible to compute standard deviation in a 180 minutes interval. We only kept filter of [1] but we increased the threshold to 0.75.

Such filters were reasonably restrictive considering local climate conditions in term of cloudy sky frequencies (4 % and 30 % of *GHI* measurements are considered as clear-sky measurements for Sainte-Marie and Ajaccio, respectively). Unfortunately, a too weak number of measurements remained for the site of Kourou (less than 10). At this step, we did not continue the study on this site before gathering a larger ground measurements dataset.

5.2 General methodology

Following the ISO standard [23], we computed the deviations: subtracting ground measurements for each instant from clear-sky models estimations and summarizing these differences by the mean bias error (MBE), the root mean square error (RMSE) and the correlation coefficient. Relative values of MBE and RMSE were computed from the average of measured GHI_c values.

Measurements with solar elevation angles greater than 15° were kept, avoiding shading effects by eventual obstacles around measurement points.

6 RESULTS

6.1 Results in Sainte-Marie

18328 clear-sky *GHI* measurements with an average of 821 W.m^{-2} were compared to model outputs. As mentioned in 4.1, AERONET data are considered as collocated with ground measurements for this site. AERONET atmospheric components were available twice a day. They have been interpolated at minute time step.

The first highlight in the results shown in table I is the high correlation coefficient whatever the model. This fact underlines the constant quality of the ground measurement instrumentations over the time period, at least under clear-sky.

A second significant fact is the difference between the performances of Bird and Solis using either AERONET or MACC. These two models allowed the possibility to choose between these two datasets. The results clearly demonstrate that MACC data leads to a better clear sky modeling than AERONET data.

Table I: Results in Sainte-Marie (Reunion Island)

Clear Sky Model	**Atmospheric input data set**	**Relative RMSE (%)**	**Relative MBE (%)**	**Corr. Coeff.**
Bird	AERONET (minute)	5,1	3,7	0,98
Bird	MACC (minute)	3,4	1,3	0,99
Solis simplified	AERONET (minute)	5,8	-2	0,96
Solis Simplified	MACC (minute)	4,8	1,2	0,97
ESRA	Monthly T. Linke (HelioClim)	5,4	1,7	0,98
McClear	MACC (minute)	3	0,8	0,99

McClear is outperforming the other models. These results are of the same order than those computed by [16] in the frame of McClear validation. Despite of using a monthly climatological dataset of atmospheric inputs, ESRA shows better results than Solis and Bird using AERONET data.

Finally, one can observe that Bird model is more sensitive to its inputs data, certainly because of its empirical parametrization of atmospheric radiative transfer.

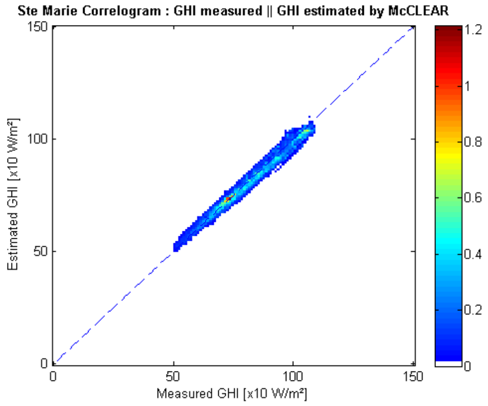

Figure 3: Scatter density plot of GHI computed by McClear model in function of ground measurements from Sainte-Marie. Color bar shows percentage of total samples number.

Figure 3 shows the scatter density plot of McClear model outputs against ground measurements. A majority of points are located in the 1:1 line. The results are almost unbiased. We can underline the lack of data for low GHI values. This is probably due to the clear sky instants detection relatively restrictive for low solar elevation.

6.2 Results in Ajaccio

2027 samples of hourly modeled GHIc. Model errors are slightly greater than in the case of Sainte-Marie. Results in Corsica are not directly comparable with those of Reunion Island. Indeed, ground measurements are not performed with the same instruments, *GHI* is hourly and clear sky detection instants is different.

Table II: Results in Ajaccio (Corsica)

Clear Sky Model	**Atmospheric input data set**	**Relative RMSE (%)**	**Relative MBE (%)**	**Corr. Coeff.**
Bird	AERONET	6.5	-7.3	0,99
Bird	MACC	4.2	-2.4	0,99
Solis simplified	AERONET	5.8	1.6	0,98
Solis Simplified	MACC	6	2	0,99
ESRA	Monthly T. Linke (HelioClim)	5.2	2.5	0,99
McClear	MACC	4.4	-1.3	0,99

Nevertheless, relative performance of models is the same. Bird is very sensitive to input data and shows better results with MACC. Solis simplified shows similar results with AERONET and MACC, which denotes its relative stability compared to Bird model. McClear do not present the lower RMSE but its bias is very low compared to the other models. Again, ESRA model shows a significant robustness. Its score is similar to the one of Sainte-Marie.

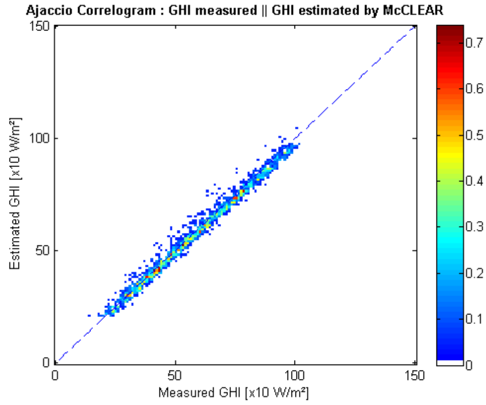

Figure 4 : Scatter density plot of GHI computed by McClear model in function of ground measurements from Ajaccio. Color bar shows percentage of total samples number.

7 CONCLUSION

Four different physical approaches of clear-sky modeling were tested facing independent ground measurements. Two different datasets of aerosol optical depth, water and ozone concentration have been used as well as monthly average of Linke turbidity.

A longer time-series of measurements from French Guiana must be collected in order to perform a valid study.

Clear-sky assessments in Reunion Island and Corsica show similar relative performance of the models. McClear model confirms its accuracy with new GHI data banks. Bird model shows a greater accuracy if atmospheric parameters are precisely known. The main result of the study lies in the superior quality of MACC data compared to AERONET.

From an operational point of view, McClear presents the advantage of delivering results in a very short time because computations are limited to interpolation between values in abacis. The limit of McClear is the fact that its input data cannot be changed except if abacis are re-built. Such process needs several months. Thus, McClear is more an on-line service than a classic clear-sky model.

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