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Satellite Derived Irradiance: Clear Sky and All-Weather Models Validation on Skukuza Data

Ineichen P.
Institute for Environmental Sciences
University of Geneva,
Carouge/GE 1227
Switzerland,
E-mail: pierre.ineichen@unige.ch

ABSTRACT

Downward short wave incoming irradiances play a key role in the radiation budget at the earth surface. The monitoring of this parameter is essential for the understanding of the basic mechanisms involved in climate change, such as the greenhouse effect, the global dimming, the change in cloud cover and precipitations, etc. Unfortunately, the density of the ground measurement network is insufficient, especially on continents like Africa, or countries in the Near East. To circumvent this lack of measured data, the meteorological satellites are of great help and models converting the satellite images into the different radiation components become increasingly performing. If these converting models are well validated over the United States and Europe, it is not the case over the African continent. A previous study [1] conducted on data covering the year 2006 over 12 sites situated in Western Africa at latitudes from 17°N to 5°S show that the global irradiance retrieved from satellite images is highly dependent on the knowledge of the aerosol optical depth (*aod*) and the water vapor content of the atmosphere (*w*). The satellite derived irradiance components are obtained from two inputs: the clear sky irradiance obtained from the atmospheric parameters (*aod* and *w*), and the cloud properties obtained from the Meteosat images. In Skukuza, aerosol optical depth is acquired within the aeronet network simultaneously with the global irradiance from 2004 to 2007. The state of the art satellite irradiance deriving algorithms use as input the aerosol optical depth from the MACC-II project (Monitoring Atmosphere Composition and Climate [2, 3]) on a daily basis. The present paper analyses the performance of two clear sky models routinely used in the state of the art satellite algorithms, as well as a validation of the irradiance obtained from the satellite images. The first results show that the clear sky models stays within 4% for the global component acquired in Skukuza; the all-weather estimated irradiance is derived with a low bias, and a standard deviation of 8%, 24% and 32% for respectively the monthly, daily and hourly values.

INTRODUCTION

The meteorological satellite images as data source to evaluate the ground irradiance components become the state of the art in the field of solar energy systems. The strongest argument is the high spatial coverage, and the fifteen minutes temporal granularity when using images from MSG. They also have the advantage to provide «real time» data used for example to assess the proper operation of a solar plant. On the other hand, long term ground data are very scarce concerning the beam irradiance. The use of secondary inputs such as for example from polar satellite data, and ground information increases significantly the precision of the algorithms. The two evaluated models use different turbidity inputs: aerosol data from the MACC project on a daily basis and climatological Linke turbidity. Following a paper from Zelenka [4] concerning the nuggets effect, the interpolation distance to the nearest ground measurement site is limited to 10 to 30 km, depending on the irradiance parameter. This strengths the satellite derived data argument.

GROUND DATA

Data acquired at Kruger Park site are used in the present work; they cover non-continuously the year 2004 to 2007. They were kindly provided by the Council for Scientific and Industrial Research (CSIR - Natural Resources and the Environment, Global Change and Ecosystem Dynamics Research Group) in South Africa through the fluxnet project.

The data used in the present study have an hourly time granularity and concern the global irradiance *G* expressed in [Wh/m^{2}h]. The data have been quality controlled by the person in charge of the acquisition, and assessed by the author following the procedure described below.

QUALITY CONTROL

Sensor calibration is the key point for precise data acquisition in the field of solar radiation. The radiation sensors should be calibrated by comparison against a sub-standard before the beginning of the acquisition period, and then every year. Due to possible errors and inaccuracies, a post-calibration is difficult to conduct.

The validity of the results obtained from the use of measured data is highly correlated with the quality of the data bank used as reference. Controlling data quality is therefore the first step to perform in the process of validating models against ground data. This essential step should be devised properly and automated in order to rapidly detect significant instrumental problems like sensor failure or errors in calibration, orientation, levelling, tracking, consistency, etc. Normally, this quality control process should be done by the institution responsible for the measurements. Even if some quality control procedures have been implemented, it might not be sufficient to catch all errors, or the data points might not be flagged to indicate the source of the problem. A stringent control quality procedure must therefore be adopted in the present context, and its various elements are described in what follows.

Two steps of quality control have been applied on the ground data before to approve them for the validation:

- **Time stamp**: this can be done by symmetry in the irradiance values for clear and stable days. The irradiance is plotted against the solar elevation, if the time stamp is correct, the rising and downward curves should follow the same path. The test can also be done on all the hourly values by plotting in a different colour the morning and the afternoon values of the clearness index K_t (global irradiance normalized by the corresponding extra atmospheric value) versus the solar elevation angle. In this case, the upper limits, representing clear conditions, should show a similar pattern. This is illustrated on Figure 1. When these tests are fulfilled, the time stamp of the data bank can be considered as correct, and the solar geometry can be precisely calculated.

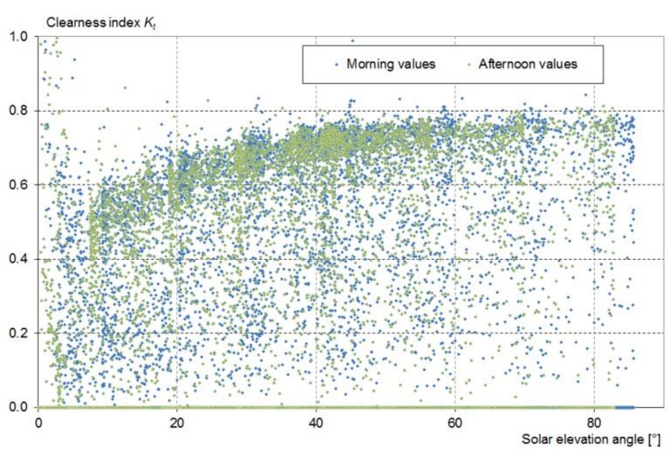

Figure 1 Time stamp validation with the help of the hourly clearness index

- **Calibration factor of the sensor**: this can be verified for clear sky conditions by comparison against data from a nearby station or with the help of additional measurements. For each day, the highest hourly value of G is selected from the measurements and plotted against the day of the year for two nearby sites, or for two different year for the same site on the same graph. These points are representative of the clearest daily conditions. As the highest value for each day is selected, the upper limit normally represents clear-sky conditions and should show the same values (it happens that higher-than-clear-sky values are obtained under partly cloudy or scattered clouds, high-sun conditions, this is why this test should not be applied for data with time granularity lower than hourly). If the aerosol optical depth (*aod*) and the water vapour content of the atmosphere (*w*) are known, a clear sky model like Solis [5, 6, 7] can be used to calculate the highest irradiance, and the obtained values represented on the same graph than the measurements. Here again, the upper limit should be similar. An illustration is given on Figure 2 where data are represented for the years 2004 and 2007. The green triangles are ground measurements; the brown triangles represent the clear sky irradiance evaluated with Solis and the aeronet aerosol optical depth and water vapour. The lower points represent the corresponding clearness indices. The higher dispersion in the summer values can be an issue of scattered clouds.

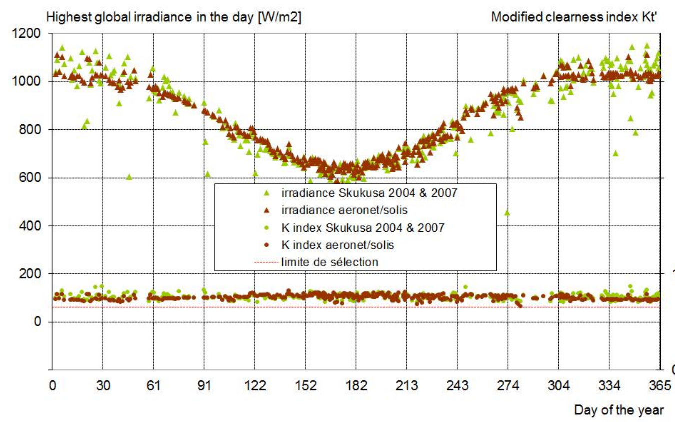

Figure 2 Ground data calibration coefficient assessment

VALIDATION STATISTICS

The comparison is done on an hourly, daily and monthly basis. The following indicators are used to describe the capability of the model to represent the measurements:

- the first order statistics: the **mean bias** (*mbd*) and the **standard deviation** (*sd*). The visualization is made with the help of scatterplots of the modelled values versus the corresponding measurements,
- the dependence of the bias with the type of conditions (clear, intermediate or cloud sky represented by the clearness index K_t), the seasons and the aerosol optical depth *aod*,
- comparison in terms of frequency of occurrence and cumulated frequency of occurrence: for the irradiance, it gives an indication of the repartition for each level of radiation. For the clearness index, it assesses that the modelled level of radiation occurs at the right time during the day,
- the second order statistic is represented by the Kolmogorov-Smirnov (*KSI%*) test [8]. It represents the capability of the model to reproduce the frequency of occurrence at each of the irradiance level,
- the distribution of the difference between the model and the measurements around the 1:1 model-measurements axis in

term of histograms around the mean bias, and the corresponding cumulated frequency of occurrence,

These statistical parameters include the dispersion due to:

• the retrieval procedure (clear sky algorithms, input parameters, cloud properties, etc.),

• the comparison of point measurements (ground data) with spatially averaged values (pixels),

• the comparison of the average of four instantaneous values (satellite images) with 60 minutes integrated ground measurements.

SATELLITE MODELS

The two satellite algorithms validated in the present paper are SolarGIS from GeoModel Solar (Slovakia), and Helioclim-3 from Mines Paris Tech (France). They are briefly described below.

• **SolarGIS**: the irradiance components are the results of a five steps process: a multi-spectral analysis classifies the pixels, the lower boundary (LB) evaluation is done for each time slot, a spatial variability is introduced for the upper boundary (UB) and the cloud index definition, the Solis clear sky model is used as normalization, and a terrain disaggregation is finally applied. Four MSG spectral channels are used in a classification scheme to distinguish clouds from snow and no-snow cloud-free situations. Exploiting the potential of MSG spectral data for snow classification removed the need of additional ancillary snow data and allowed using spectral cloud index information in cases of complex conditions such as clouds over high albedo snow areas. The broadband simplified version of Solis model was implemented in the main schemes as well as in the global to beam Dirindex algorithms to calculate Direct Normal Irradiance component [9, 10]. Processing chain of the model includes post-processing terrain disaggregation algorithm based on the approach by Ruiz-Arias [11].

• The **Helioclim-3** data bank is produced with the Heliosat-2 method that converts observations made by geostationary meteorological satellites into estimates of the global irradiation at ground level. This version integrates the knowledge gained by various exploitations of the original Heliosat method and its varieties in a coherent and thorough way. It is based upon the same physical principles but the inputs to the method are calibrated radiances, instead of the digital counts output from the sensor. This change opens the possibilities of using known models of the physical processes in atmospheric optics, thus removing the need for empirically defined parameters and of pyranometric measurements to tune them. The ESRA models [12, 13] are used for modelling the clear-sky irradiation. The assessment of the ground albedo and the cloud albedo is based upon explicit formulations of the path radiance and the transmittance of the atmosphere. The turbidity is based on climatic monthly Linke Turbidity coefficients data banks.

CLEAR SKY MODEL

The clear sky model validated in this study is the new MacClear model developed by MinesParis Tech [14]. The model is fully physical and is based LibRadTran calculations [15]. A complete set of aerosol optical depths and water vapor columns values has been used in the physical calculations to derive a look up table used for fast computational evaluation of the clear sky components. The input parameters to the model are daily values derived from the MACC-II project. An extensive validation will be published in a next report. The main results are the following:

• the validation is conducted on 2600 hourly clear sky values selected from data acquired from 2004 to 2007 in Skukuza with an average global irradiance of 530 [Wh/m2h],

• the hourly global irradiance is evaluated with a 3.8% positive bias and a 5.4% standard deviation, the daily values with a standard deviation of 4.4%,

• the bias frequency distributions around the 1:1 axis show a near-normal distribution as given in Figure 3. This makes the first order statistics reliable,

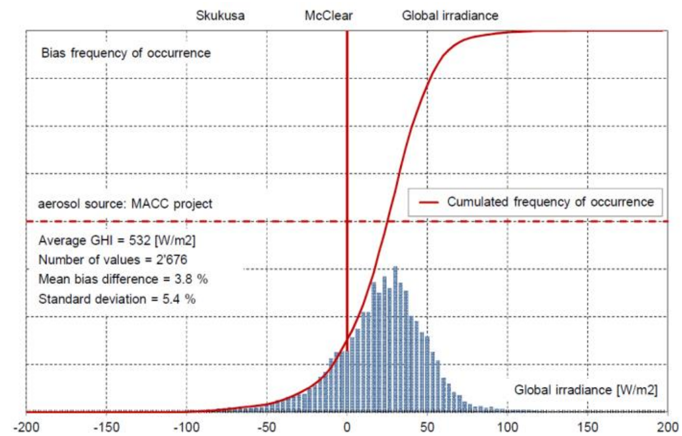

Figure 3 Bias distribution around the 1:1 axis

• when representing the model bias versus the aerosol optical depth obtained from the aeronet network, it can be seen that the bias is higher for low values of *aod* as illustrated on Figure 4,

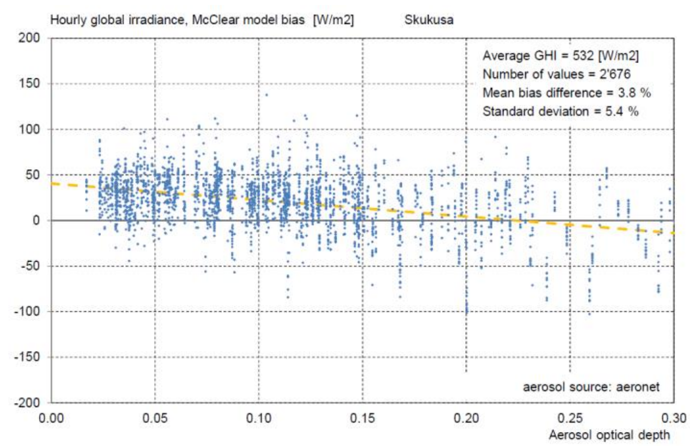

Figure 4 Model bias versus the aod obtained from aeronet

• also a slight seasonal pattern on the hourly bias can be seen on Figure 5. This effect is certainly correlated with the *aod* dependence. This will be analyzed in the McClear validation paper.

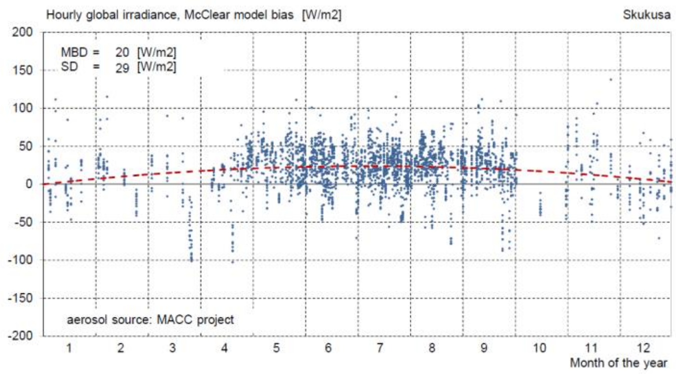

Figure 5 Seasonal trend of the bias

GLOBAL IRRADIANCE VALIDATION

The general result of the validation is a positive bias (3% and 8% for SolarGIS and Helioclim) and a standard deviation of around 32% for the hourly values, 23% for the daily values, and 7% for monthly total.

Looking into the dependence of the bias with the clearness index and the season, the following points can be pointed out:

- the global irradiance bias with the sky conditions (represented by the clearness index) is very similar for Helioclim-3 and SolarGIS; it is illustrated on Figure 6,

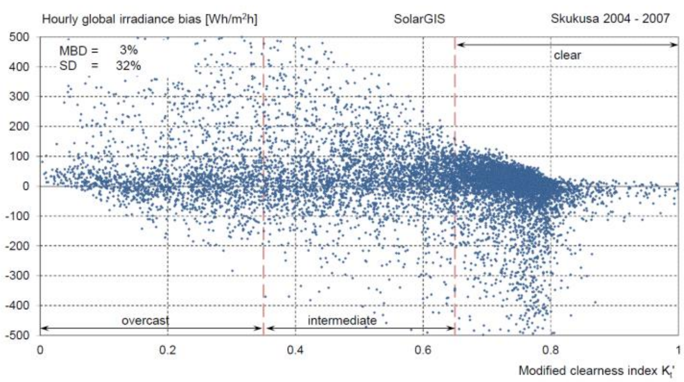

Figure 6 Bias dependence with the sky conditions

- the same observation can be done concerning the dependence with the aerosol optical depth, see Figure 7,

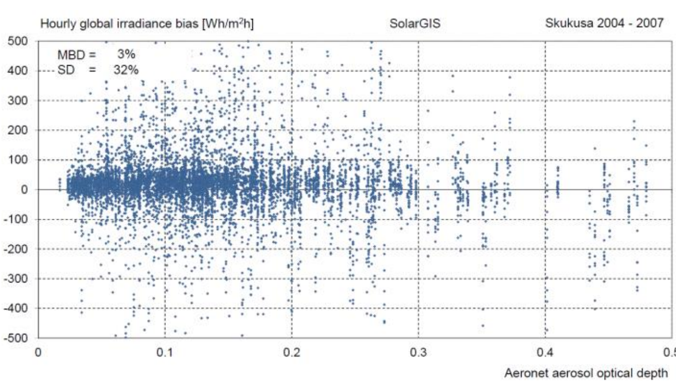

Figure 7 Bias dependence with the *aod*

- looking at the seasonal effect, it can be seen that the two models perform differently, the patterns are opposite. The effect is a result of the use of monthly climatic turbidity for Helioclim, and daily MACC aerosol optical depth for SolarGIS. As there are much more data in the winter period than in summer, these pattern have to be assessed on data acquired during a longer period. Nevertheless, the two models have a similar behavior during the winter, showing a positive bias. The seasonal dependence is illustrated for the two models on Figures 8 and 9,

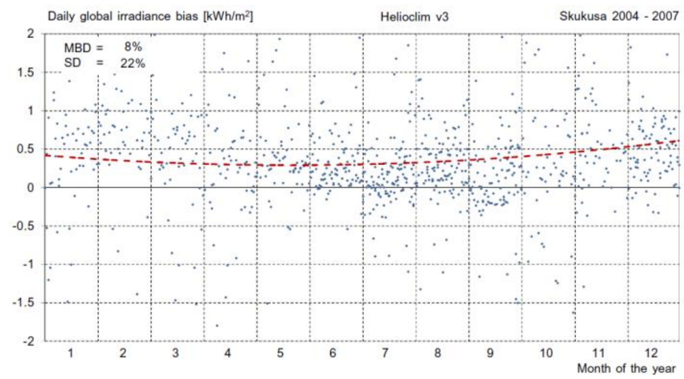

Figure 8 Heliosat data seasonal dependence

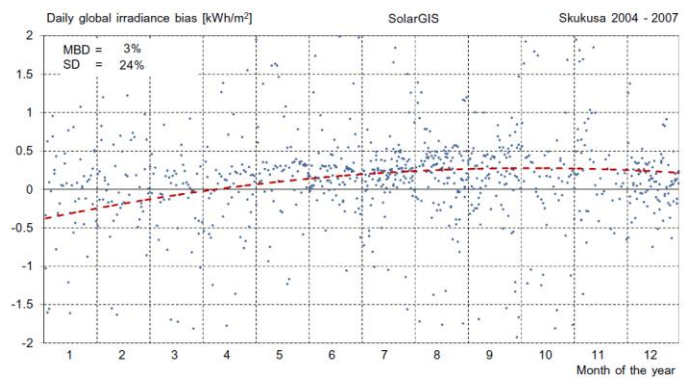

Figure 9 SolarGIS data seasonal dependence

- on Figure 10 it can be seen that both models are near of the measurements cumulated frequency of occurrence (measurements are represented in grey),

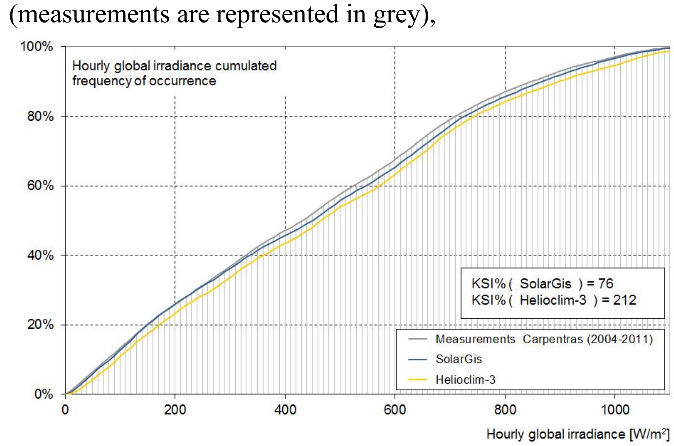

Figure 10 Irradiance cumulated frequency of occurrence

• if the irradiance cumulated frequencies of occurrence match satisfactorily the ground measurements, it is not the case for the Helioclim data with regard to the clearness index. It can be seen on Figure 11 that the frequency curve is shifted to the high values of indices to the detriment of the very low values. SolarGIS takes into account the low values of K_t, but also overestimates the high indices.

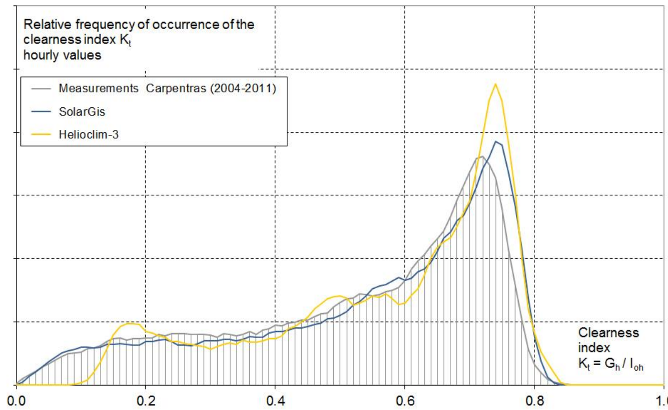

Figure 11 Clearness index frequency of occurrence

CONCLUSION

A model validation is done on four non-continuous years of data acquired at the site of Skukuza. SolarGIS model using MACC daily aerosol optical depths data as input, and Helioclim based on climatological Linke turbidity coefficients are involved in the present study.

The main conclusion is that if the two models give comparable results in term of standard deviation, the use of daily aerosol optical depth values as input to the algorithms is a valuable improvement to the capacity of the models to reproduce the clearness index frequency of occurrence at the site of Skukuza. The MACC project is a reliable source of these data; it has the advantage to have a high spatial coverage and resolution.

The new McClear clear sky model gives good results on data from the site of Skukuza, even if it shows a slight dependence with the aerosol optical depth. However, an in-depth analysis ought to be carried out with a view to point out the models' strengths and weakness.

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