Blanc, Ph., Gschwind, B., Lefèvre, M., Wald, F., Wald, L., 2011. Validating Meteosat-derived surface solar irradiance in Mozambique. In Proceedings of the 30th Symposium of the European Association of Remote Sensing Laboratories, Ed. Halounova L., held in Prague, Czech Republic, 30 May – 2 June 2011, available at http://www.earsel.org/symposia//2011-symposium-Prague/Proceedings/, vol. 'Thermal Remote Sensing', pp. 1-8.

Validating Meteosat-derived Surface Solar Irradiance In Mozambique

Philippe Blanc, Benoît Gschwind, Mireille Lefèvre, Fabien Wald, and Lucien Wald
MINES ParisTech, Center for Energy and Processes, Sophia Antipolis, France;
e-mail: lucien.wald@mines-paristech.fr

Abstract. The solar radiation reaching the ground level on horizontal surfaces is of interest to many domains. The database HelioClim-1 contains daily values of radiation for 21 years: 1985-2005. It has been derived from Meteosat images and covers Europe, Africa and Atlantic Ocean. It is compared to ground-based measurements in Mozambique collected from the World Radiation Data Center. The quality of HelioClim-1 is good: the root mean square difference is approximately 30 W/m², and the correlation coefficient is greater than 0.85. These results are similar to those obtained by previous studies for Europe. HelioClim-1 is freely available through the SoDa Service and offers a reliable and accurate knowledge of the solar radiation and its daily, seasonal and annual variations over recent years.

Keywords. Essential Climate Variable, Africa, equatorial climate, remote sensing, satellite, radiation, GMES, Earth observation.

1. Introduction

The solar radiation reaching the ground level on horizontal surfaces is of paramount importance in many applications, from climate to health [1]. The amount of power available on a surface of 1 m² integrated over the whole spectrum of the solar radiation is called surface solar irradiance (SSI).

The SSI is an Essential Climate Variable as designed by the Global Climate Observing System in August 2010 [2]. Meteorological networks measure the density of energy received on a horizontal plane at ground level during the day: this is the daily irradiation, also called daily solar exposure, and expressed in MJ/m² or J/cm². The daily mean of SSI is expressed in W/m² and is derived by convention from the daily irradiation by dividing it by the number of seconds in 24 h, i.e., 86400 s.

Accurate assessments of SSI can now be drawn from satellite data [3]. Stations measuring SSI on the long-term are rare and satellites are an accurate way to complement or supplement them. The HelioClim project is an initiative of MINES ParisTech launched in 1997, to increase knowledge on SSI and to offer SSI values for any site, any instant over a large geographical area and long period of time, to a wide audience [3, 4]. It covers Europe, Africa and the Atlantic Ocean. The HelioClim-1 database, abbreviated in HC-1, offers daily values of SSI for the period 1985–2005. It has been created from archives of images of the Meteosat First Generation (MFG) satellites. The Meteosat series of satellites are geostationary and provide synoptic views of Europe, Africa and Atlantic Ocean for meteorological purposes. They are nominally located over the Gulf of Guinea at longitudes close to 0° at a distance around 36 000 km from the Earth surface. Initiated by the European Space Agency, the program is currently operated by Eumetsat, a European agency comprising the national weather offices. Only images taken in the visible channel are dealt with in this paper. Such images clearly depict clouds and more generally the optical state of the atmosphere (Figure 1).

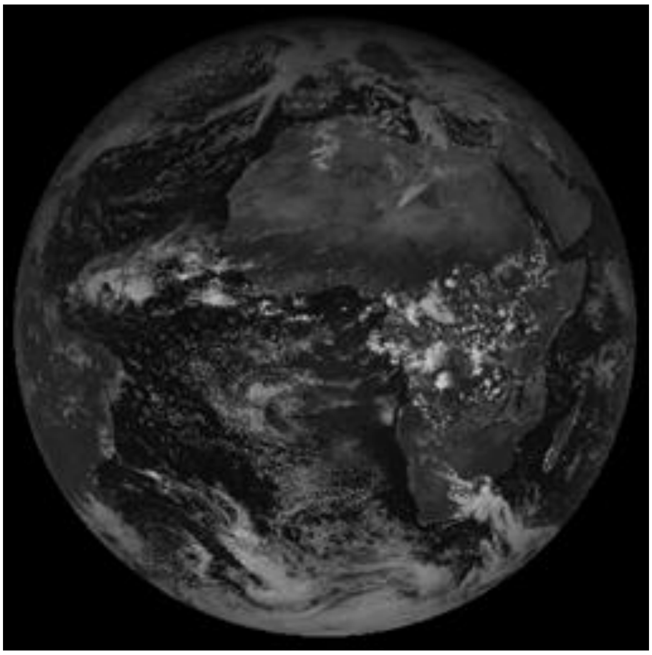

Figure 1. Example of a Meteosat image in visible channel, taken on 11 November 2003, at 1100 UTC. Reflectance increases from black to white. Copyright Eumetsat, 2003.

Several comparisons between HC-1 values and measurements made at a number of meteorological stations have been performed and concluded on satisfactory performances of HC-1 for daily means of SSI [5, 6]. However, most of the stations used in [5] were located in Europe, a few were available in Africa and very often for a limited period of time. As for [6], the stations were located in Northern Africa exclusively: Egypt, Tunisia, Algeria.

Therefore, efforts focused on equatorial and tropical Africa must be made in order to assess the quality of HC-1 in this region. This communication presents the first step: HC-1 is compared to ground-based measurements made in Mozambique. The database HC-1 is briefly presented in the next section. Then, we discuss the ground-based measurements, how to obtain them and their quality. The following section presents the results of the comparison. Finally, we conclude on the possible exploitation of HC-1 for studies in Africa.

2. The HelioClim-1 Database (HC-1)

When the project HelioClim was launched in 1997, storage and computing capacities were much more limited than today. In addition, Meteosat images in full resolution were too costly for our available resources. Therefore, we used a set of images in reduced spatial and temporal resolution called B2. This set was created for the International Satellite Cloud Climatology Project (ISCCP) to better handle and exploit this wealth of information [7]. This B2 data set was used previously by a European consortium to create the first atlas of solar radiation in Africa [8]. This atlas combined with ground-based measurements was exploited to propose a solar radiation climate map of Africa comprising 20 climates [9].

The B2 data set spans from 1985 to 2005. It covers the whole field of view of Meteosat. Meteosat data were converted into radiances taking into account the sucession in time of satellites, sensors, and gains [3]. A consistent time-series of images of radiances was thus obtained for this 21-years period. Each image of radiances was processed by the Heliosat-2 method [10], yielding an image of the hourly mean of SSI. Then, the daily mean of SSI is computed from all images available for this day and pixel. It is stored into the HC-1 database that comprises 118 500 B2 pixels.

A web service, i.e. an application that can be launched by the Web, provides a time-series of SSI for any site, and any period between January 1, 1985 and December 31, 2005. It performs the retrieval of the time-series for each of the nine nearest B2 pixels and their interpolation in space. This service also performs the temporal aggregation of the data: one can ask for daily or monthly means of SSI. The initial version of the HC-1 database was released in 2003. Several corrections were further made [3, 6]. The current version HC-1v4 has been available since March 2006 [3].

This database is disseminated on the Web by the SoDa Service [11] (www.soda-is.com). Thanks to the efforts made freely by the company Transvalor managing the SoDa Service, the access HC-1 is for free since 1st January 2011. Time-series spanning the whole period can be downloaded in a few clicks without registration.

3. Ground-based measurements

National meteorological services (NMS) usually measure solar radiation at a few sites. Data are sent to the World Radiation Data Center (WRDC), located in Saint-Petersburg, in Russia, under the control of the World Meteorological Organization (WMO). There the data are archived and published.

Not all African countries measure daily irradiation. Actually, most of them do not measure irradiation but only sunshine duration. Keeping a good quality in instruments such as pyranometers is very demanding in human resources and money. Not all NMSs have the necessary resources available from year to year, not taking into account the political troubles that occurred in tropical and equatorial Africa in the past decades. In addition, not all NMSs are sending their data to WRDC for reasons unknown to us.

The situation is that there is a fairly limited amount of African stations offering long time-series of daily irradiation of moderate to good quality available in WRDC. A few of them are located in Northern Africa, namely Egypt, Tunisia, and Algeria. In the tropical and equatorial Africa, Mozambique is one exception. Thirteen stations have reported radiation data to WRDC between 1985 and 1998. However, after 1998, only 3 stations reported radiation data with many gaps in data. At the time of writing, only 1 station measures radiation data, the others have stopped or report sunshine duration only.

Quality of measurement is difficult to assess from the WRDC archives. All data are scrutinized at WRDC and quality-flagged before entering archives. However, no information on quality is provided with the radiation data. Thus, we have to consider that these data meet the requirements set by WMO for international exchange: relative uncertainty is 5% to 10% for good to moderate quality [12].

Efforts were made and are being made to publish data on the Web. For data prior to 1994, a joint effort by WRDC and the National Renewable Energy Laboratory (NREL) of the USA resulted in an automatic delivery system based on e-mail. This system is very convenient though it has a few drawbacks. The major one deals with the format of data which are returned in ASCII format. Sometimes spaces between successive values are replaced by the digit 1, yielding large incorrect numbers that must be separated accordingly. Thus, one has to scrutinize the data returned by the automatic system to detect these cases and correct them. This may be an additional cause or error in data. For data in 1994 and after, WRDC has set up a Java-based interface which is very convenient to display the data but does not allow downloading data. Consequently, data have to be copied by hand or other solutions such as optical character recognition which are not fully satisfactory. Whatever the solution, it requests manual handling of numbers which may be another source of error.

Getting data from WRDC has some risk and burden. However, it is a much better situation than if one has to request data separately to each NMS.

4. Comparing HC-1 to ground-based measurements (WRDC)

The comparison between HC-1 and WRDC measurements follows the ISO standard [13]. For each day when HC-1 and WRDC data are available and valid, the difference (HC-1 – WRDC) is computed. These differences are summarized by the bias and the root mean square difference (RMSD). In addition, the correlation coefficient is computed.

The two time-series to compare are different in nature. WRDC data are made of pin-pointed time-integrated measurements, while satellite-derived values are space-averaged instantaneous assessments. Accordingly, a discrepancy is expected because of the natural variability of SSI in space and time. [14] established that a substantial part of the difference between satellite-derived data and ground-based measurements comes from three different sources. The error in measurements is one of the sources: it may amount to 5% to 10% in our case. The natural variability of the SSI within a pixel of a few km in size may amount to 5% of the mean SSI as shown by a few experiments [14]. Finally, when performing the comparison, one makes the hypotheses of ergodicity and spatial homogeneity of the SSI: this may induce an additional error of 3% of the mean SSI. Though it is difficult to predict because all these errors are not random variables, we can expect a discrepancy of a few percent relative to the daily mean of SSI.

We have selected three stations: Beira, Maputo, and Tete (Table 1). They are in flat areas, separated by hundreds of km, and therefore for a given day, the three sites experience different weather situations. Table 1 confirms what we wrote earlier: it is difficult to have time-series spanning over more than 15 years. However, the number of days having valid values for both HC-1 and WRDC is of order of thousands. Thus, the validation of HC-1 is statistically representative.

Table 1. Stations used in this study, and periods of data.

	Beira	Maputo	Tete
Latitude	-19.48	-25.58	-16.11
Longitude	34.54	32.36	33.35
Elevation a.s.l. (m)	10	70	123
Period of data	1985-01-01 to 1997-02-28	1985-01-01 to 2005-12-31	1985-04-16 to 1998-12-31

Figure 2 displays the correlogram between ground-based measurements (horizontal axis) and HC-1 (vertical axis) for Maputo. The identity line is also reported as well as the linear regression line. The scattering of measurements is fairly low. Points lie along the identity line except for largest irradiances; HC-1 has a tendency to underestimate the largest irradiances.

The results of the comparison for each station are presented in Table 2. It appears that the three stations exhibit similar results. The bias is negative: HC-1 underestimates the SSI. The bias is small: between 10 W/m^2 and 13 W/m^2 in absolute value. It corresponds to approximately 4 % to 5% of the mean SSI, and to 2% to 3% of the radiation at the top of atmosphere. The scattering of the differences is limited: the RMSD is 13% to 15% of the mean SSI. The correlation coefficient is large: greater than 0.85. HC-1 reproduces well the day-to-day variations of the actual SSI.

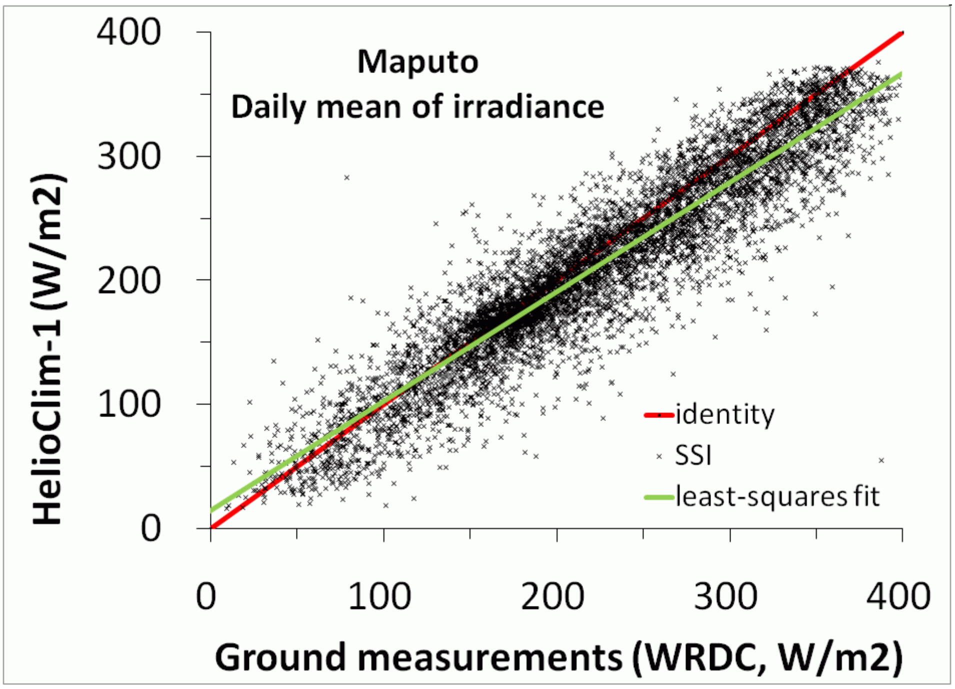

Figure 2. Scatterplot of daily mean of SSI between ground-based measurements and HC-1 for Maputo. The identity line is reported as well as the least-squares regression line.

Table 2. Comparison between HC-1 and WRDC for daily mean of SSI. Percentages are relative to the mean value.

Daily mean of SSI	Beira	Maputo	Tete
Mean value (W/m²)	234	222	229
Number of days	3403	7265	3716
Bias (W/m²)	-13 (-5%)	-12 (-5%)	-10 (-4%)
RMSD (W/m²)	33 (13%)	31 (14%)	36 (15%)
Correlation coefficient	0.900	0.932	0.849

The daily mean of the SSI I can be written as:

$$I(d) = I0(d)\ KT(d)$$

where d denotes the day, $I0$ the irradiance at the top of atmosphere on a horizontal plane and KT is the clearness index. $I0(d)$ can be perfectly modeled by analytical functions [1]. A similar equation holds for the SSI from HC-1, I_H:

$$I_H(d) = I0(d)\ KT_H(d)$$

and for the SSI I_W measured by ground-based stations

$$I_W(d) = I0(d)\ KT_W(d)$$

The presence of this common factor $I0$ in I_H and I_W creates a natural correlation. $I0$ offers low variation from one day to another and exhibits a marked yearly period.

On the contrary, KT represents the optical state of the atmosphere for the current day and has a stochastic nature. There is no mathematical reason for KT_H and KT_W being correlated; if they are, it is because the model Heliosat-2 underlying HC-1 is accurate. Therefore comparing KT_H to KT_W reveals the ability of HC-1 to depict the optical state of the atmosphere and its variations. In this comparison of clearness indices, we expect lower performances than in the comparison of SSI because of its stochastic nature.

Table 3 reports the results of this comparison on *KT*. Expectedly, the results are similar for all stations. The mean value of *KT* is 0.6 for all stations: this high value means that the sky is often clear. An analysis of the statistical distribution of *KT* reveals that for each station there is more than 25% of days in a year that are very clear. For these days *KT* is greater than 0.7, *i.e.* 70% of the radiation available at the top of atmosphere reaches the ground. The RMSD represents at most 0.09 of the irradiance at the top of atmosphere. The correlation coefficient is still large: greater than 0.82. HC-1 reproduces well the day-to-day variations of the optical state of the atmosphere.

Table 3. Comparison between HC-1 and WRDC for daily clearness index. Percentages are relative to the mean value.

Daily KT	Beira	Maputo	Tete
Mean value (unitless)	0.59	0.59	0.60
Bias (unitless)	-0.03 (-5%)	-0.03 (-4%)	-0.02 (-3%)
RMSD (unitless)	0.08 (13%)	0.08 (13%)	0.09 (14%)
Correlation coefficient	0.872	0.904	0.817

5. Conclusion

The results obtained for these three sites in Mozambique are the same than those obtained by [5] in a similar study but limited to a few years: 1994 to 1997. This agreement supports our observations. The RMSD found for European and African stations in [5] is fairly similar for all stations and is approximately 30 W/m^2, which is the value reported here. In Northern Africa, the performances of HC-1 are much better as the RMSD is approximately 15 W/m^2; this is likely due to the very frequent clear sky conditions. The previous studies [5, 6] have reported that the quality of HC-1 is comparable to that of similar databases among the best ones.

One conclusion of this work is that the WRDC is presently the most convenient means to access radiation data to African countries.

Overall, we have found that HC-1 is a good means to assess the daily mean of SSI in Mozambique. It accurately assesses the SSI level as well as its day-to-day variations.

HC-1 offers similar performances in Mozambique than in the northern hemisphere. It contains consistent time-series of daily SSI for a 21-year period. Even if uncertainty is currently too great for accurate analyses of climate change, the availability of these time-series for virtually any location in Mozambique should help any community interested in climate applications to perform steps towards a better knowledge of the SSI and its variation over recent years.

This period is long compared to what is usually available in WRDC for recent decades. HC-1 can be combined with time-series of ground-based measurements available for previous periods, such as made in Egypt [6] to form much longer time-series. There are other domains where HC-1 could prove very useful in Mozambique. For example, [15] exploits HC-1 data to estimate the evapotranspiration in agriculture studies; [16] mentions its usefulness in selecting the most appropriate sites for the production of electricity by solar plants.

HC-1 is now an element of the precursor radiation service of the GMES atmosphere service. GMES (global monitoring for environment and security) is the European programme for the establishment of a European capacity for Earth observation. It consists in a complex set of systems which collects data from multiple sources, process them and provide users through services in six domains: land, atmosphere, emergency, security and climate change (www.gmes.info).

HC-1 is available for free on the SoDa Service. Data can be downloaded easily. This availability aims at facilitating the use of the database HC-1.

Acknowledgements

The authors are grateful to Eumetsat and Meteo-France for the provision of Meteosat data, the World Radiation Data Center and National Renewable Energy Laboratory (USA) for supplying SSI data for ground measuring stations. The authors thank the company Transvalor which is taking care of the SoDa Service for the common good, therefore permitting an efficient access to the HelioClim databases, and acknowledge the help of Bella Espinar in clarifying the content of this paper. The research leading to these results has partly received funding from the European Union's Seventh Framework Programme (FP7/2007-2013) under Grant Agreement no. 218793 (MACC project).

References

[1] *European Solar Radiation Atlas*. Fourth edition, includ. CD-ROM. Edited by K. Scharmer, J. Greif. Scientific advisors: R. Dogniaux, J. K. Page. Authors : L. Wald, M. Albuisson, G. Czeplak, B. Bourges, R. Aguiar, H. Lund, A. Joukoff, U. Terzenbach, H. G. Beyer, E. P. Borisenko. Published for the Commission of the European Communities by Presses de l'Ecole, Ecole des Mines de Paris, Paris, France, 2000.

[2] Global Climate Observing System (GCOS) Essential Climate Variables. Available online: www.wmo.int/pages/prog/gcos/index.php?name=EssentialClimateVariables (accessed on 16 February 2011).

[3] Blanc Ph., B. Gschwind, M. Lefèvre, & L. Wald, 2011. *The HelioClim project: Surface solar irradiance data for climate applications*. Remote Sensing, 3, 343-361, doi:10.3390/rs3020343

[4] Rigollier C., & L. Wald, 1999. *The HelioClim Project: From Satellite Images to Solar Radiation Maps*. In Proceedings of the ISES Solar World Congress 1999, Jerusalem, Israel, July 4–9, 1999; Volume I, pp. 427-431.

[5] Lefèvre M., L. Diabaté, & L. Wald, 2007. *Using reduced data sets ISCCP-B2 from the Meteosat satellites to assess surface solar irradiance*. Solar Energy, 81, 240-253, doi:10.1016/j.solener.2006.03.008.

[6] Abdel Wahab M., M. El Metwally, R. Hassan, M. Lefèvre, A. Oumbe, & L. Wald, 2009. *Assessing surface solar irradiance in Northern Africa desert climate and its long-term variations from Meteosat images*. International Journal of Remote Sensing, 31(01), 261 – 280. doi: 10.1080/01431160902882645.

[7] Schiffer R., & W.B. Rossow, 1985. *ISCCP global radiance data set: A new resource for climate research*. Bulletin American Meteorological Society, 66, 1498-1503.

[8] *Solar Radiation Atlas of Africa*. 1991. Edited by Raschke E., R. Stuhlmann, W. Palz, & T. C. Steemers. Published for the Commission of the European Communities by A. A. Balkema, Rotterdam, 155 p.

[9] Diabaté L., Ph. Blanc, & L. Wald, 2004. *Solar radiation climate in Africa*. Solar Energy, 76, 733-744.

[10] Rigollier C., M. Lefèvre, & L. Wald, 2004. *The method Heliosat-2 for deriving shortwave solar radiation from satellite images*. Solar Energy, 77(2), 159-169.

[11] Gschwind B., L. Ménard, M. Albuisson , & L. Wald, 2006. *Converting a successful research project into a sustainable service: the case of the SoDa Web service*. Environmental Modelling and Software, 21, 1555-1561, doi:10.1016/j.envsoft.2006.05.002.

[12] *Guide to Meteorological Instruments and Methods of Observation*, 2008. WMO-No. 8, Seventh Edition, World Meteorological Organization, Geneva, Switzerland, page 1.7-3.

[13] *Guide to the Expression of Uncertainty in Measurement*, 1st ed., 1995. International Organization for Standardization: Geneva, Switzerland.

[14] Zelenka A., R. Perez, R. Seals, & D. Renné, 1999. *Effective accuracy of satellite-derived hourly irradiances*. Theor. Appl. Climatol., 62, 199-207.

[15] Bois B., P. Pieri, C. Van Leeuwen, L. Wald, F. Huard, J.-P. Gaudillère, & E. Saur, 2008. *Using remotely sensed solar radiation data for reference evapotranspiration estimation at daily time step*. Agricultural and Forest Meteorology, 148, 619-630.

[16] *Solar Energy Resource Management for Electricity Generation from Local Level to Global Scale*. 2006. Dunlop E. D., L. Wald, & M. Suri Eds, Nova Science Publishers, New York, USA, 205 pages. ISBN: 1-59454-919-2.