The HelioClim-1 Database of Daily Solar Radiation at Earth Surface: An Example of the Benefits of GEOSS Data-CORE

Mireille Lefèvre, Philippe Blanc, Bella Espinar, Benoît Gschwind, Lionel Ménard, Thierry Ranchin, *Senior Member, IEEE*, Lucien Wald, Laurent Saboret, Claire Thomas, and Etienne Wey

***Abstract*—The HelioClim-1 database contains daily values of the solar radiation reaching the ground. This GEOSS (Global Earth Observation System of Systems) Data Collection of Open Resources for Everyone (Data-CORE) covers Europe, Africa and the Atlantic Ocean, from 1985 to 2005. It is freely accessible at no cost through the SoDa Service (www.soda-is.com). Several assessments of the HelioClim-1 data against measurements made in meteorological networks reveal that the HelioClim-1 database offers a reliable and accurate knowledge of the solar radiation and its daily, seasonal and annual variations over recent years. The HelioClim-1 data may help in qualifying *in situ* measurements and may supplement them, thus offering 21 years of accurate daily means of surface solar irradiance. Several published works benefited from openness, availability and accuracy of the HelioClim-1 database in various domains: oceanography, climate, energy production, life cycle analysis, agriculture, forestry, architecture, health and air quality. This demonstration of the benefit of the HelioClim-1 database draws attention to resources open to everyone such as those labeled GEOSS Data-CORE.**

***Index Terms*—Africa, agro-meteorology, air quality, architecture, climate, Europe, GEOSS, health, irradiance, meteosat, ocean, solar energy.**

I. Introduction

The surface solar irradiance (SSI) is the power received from the sun over the whole spectrum on a horizontal surface at ground level per unit surface [1]. The SSI is an Essential Climate Variable (ECV) as established by the Global Climate Observing System in August 2010 [2]. Knowledge of the SSI and its geographical distribution is of prime importance for several domains where the SSI plays a major role such as weather, climate, biomass, or energy [3].

Manuscript received May 02, 2013; revised July 23, 2013; accepted September 24, 2013. Date of publication October 17, 2013; date of current version June 13, 2014. This work was supported by the European Union's Fifth Framework Programme (FP5/1998-2002) under Grant Agreement no. IST-1999-12245 (SoDa project) and by the ADEME (French Agency for Energy) (grant no. 08 05 C 0049, 2008-2010).

M. Lefèvre, P. Blanc, B. Espinar, B. Gschwind, L. Ménard, T. Ranchin, and L. Wald are with MINES ParisTech, Center Observation, Impacts, Energy, 06904 Sophia Antipolis cedex, France (e-mail: lucien.wald@mines-paristech.fr).

L. Saboret, C. Thomas, and E. Wey are with Transvalor Innovations, 06904 Sophia Antipolis cedex, France.

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Digital Object Identifier 10.1109/JSTARS.2013.2283791

Accurate assessments of the SSI can now be drawn from satellite data and several studies demonstrate the superiority of the use of satellite data over interpolation methods applied to sparse measurements performed within a radiometric network [4], [5]. Stations measuring the SSI on the long-term are rare and satellites are an accurate way to supplement them [6]. Several databases have been developed that contain hourly or daily means of the SSI. The HelioClim-1 database, hereafter abbreviated in HC-1, is one of them.

In this paper, brief introductions to the HelioClim Project and the GEOSS (Global Earth Observation System of Systems) Data-CORE (Data Collection of Open Resources for Everyone) are followed by a description of the HC-1 database and how it has been constructed. The HC-1 database is available for everyone and provides data of known quality. Several examples of use of HC-1 data in various domains have been found in scientific journals. These case studies are briefly mentioned to illustrate the benefit of the HC-1 database in science. This paper aims at attracting attention to resources open to everyone such as the HC-1 database and at demonstrating through case studies how such freely supplied data on solar radiation support research, development and business in various domains.

II. The HelioClim Project

The HelioClim Project is an ambitious initiative of MINES ParisTech launched in 1997 after preliminary works in the 1980s [7], [8] to increase knowledge on the 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]. The project comprises several databases that cover Europe, Africa and the Atlantic Ocean. The HC-1 database offers daily means of the SSI for the period 1985–2005. It has been created from archives of images of the Meteosat First Generation.

The Meteosat series of satellites are geostationary and provide synoptic views of Europe, Africa and Atlantic Ocean for meteorological purposes. Initiated by the European Space Agency, the program is currently operated by Eumetsat, a European agency comprising the national weather offices.

Images taken in the visible band (Fig. 1) and other bands clearly depict clouds and more generally the optical state of the atmosphere. Several operational programs are currently processing Meteosat images, or have processed them, in order to assess the SSI and create and update databases.

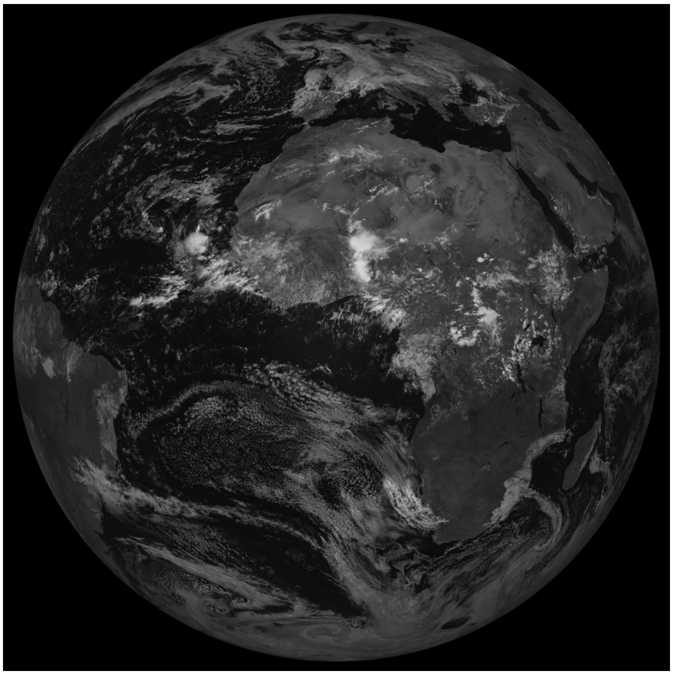

Fig. 1. Example of a Meteosat image in visible channel, taken on 7 September 2010, at 1200 UTC. Reflectance increases from black to white. Copyright Eumetsat, 2010.

The HelioClim Project is such a program. The HelioClim-3 database contains 15 min values of the SSI. It has been created in 2004 and is updated daily from images taken by the Meteosat Second Generation satellites. The HelioClim-4 database should be created in October 2013 with a daily update. It will contain values of the global, direct and diffuse components of the SSI.

III. The GEOSS Data-CORE

The Global Earth Observation System of Systems (GEOSS) is a project set up by the GEO (the Group on Earth Observation, www.earthobservations.org). It aims at proactively linking together existing and planned observing systems around the world and supporting the development of new systems where gaps currently exist. One strong statement of the 10-Year implementation plan [9] is that "the societal benefits of Earth observations cannot be achieved without data sharing."

The following principles in GEOSS Data Sharing have been set up:

- there will be full and open exchange of data, metadata and products shared within GEOSS, recognizing relevant international instruments and national policies and legislation;
- all shared data, metadata and products will be made available with minimum time delay and at minimum cost;
- all shared data, metadata and products being free of charge or no more than cost of reproduction will be encouraged for research and education.

The creation of the GEOSS Data Collection of Open Resources for Everyone (GEOSS Data-CORE) was effective in November 2010. The GEOSS Data-CORE is a distributed pool of documented data sets with full, open and unrestricted access at no more than the cost of reproduction and distribution.

The GEO Data Sharing Task Force has been tasked to identify potential data sets whose providers agree to make it available through GEOSS under the data sharing principles listed above. It is working closely with the GEOSS Infrastructure Implementation Board (formerly Architecture and Data Committee) to ensure that the updated GEOSS Common Infrastructure will provide an effective means for identifying GEOSS Data-CORE data sets and data services.

The HC-1 database has been identified as a Data-CORE by this Task Force in November 2011 [10]. Previously, the HC-1 database was open to researchers and students at no cost on a case-by-case basis. Further, a compound database has been created by combining using the NASA-SSE (Surface meteorology and Solar Energy) database, another Data-CORE, and the HC-1 database to enable simple access to data on solar resource for developing countries [11]. The NASA-SSE covers the whole world; the HC-1 database brings a better spatial resolution over Africa.

IV. Constructing a Consistent Time-Series of the SSI

When the HelioClim project started in 1997, obstacles to the production of a climate database were the large amount of data to process, the storage capacity, and the cost of Meteosat images [3]. To overcome these obstacles, a set of Meteosat images has been purchased in reduced spatial resolution. This data set is called ISCCP-B2, B2 for short, and was created for the International Satellite Cloud Climatology Project (ISCCP). At that time, several researchers have successfully used the B2 data set for the assessment of the SSI [12]. B2 images are available once every 3 h. Though the B2 images are built from a resampling of original images, these images can be considered as having a spatial resolution of 30 km at nadir in a first approximation [3]. The closer to the image limits the pixel, the larger the pixel size.

As for the method of converting the images into SSI, several well-performing candidates were available. The Heliosat-2 method was selected because it was easy to implement and to operate, and well known [3]. It is based on the general fact that the appearance of a cloud over a pixel results in an increase of reflectance in visible imagery, and further on the principle that the attenuation of the downwelling shortwave irradiance by the atmosphere over a pixel is determined by the magnitude of change between the reflectance that should be observed under a very clear sky and that currently observed [12]–[15].

The Heliosat-2 method and its application to the Meteosat images are detailed in Rigollier *et al.* [15]. The influence of uncertainties in input variables on the outcomes of the Heliosat-2 method was discussed by Espinar *et al.* [16]. Lefèvre *et al.* have described in detail the application of Heliosat-2 to the B2 images [17]. They have concluded that the combination of the B2 images and the Heliosat-2 method is accurate enough for creating a climate database of the daily or monthly mean of the SSI.

Inputs to the Heliosat-2 method are not the original Meteosat images in digital counts (grey levels) but images of radiances. Radiance is obtained from digital counts by applying a calibration function of an affine type whose two parameters vary with time. Nowadays, these parameters are provided by Eumetsat with each Meteosat image. This was not the case prior to 2004:

Meteosat satellites had no onboard calibration system in the visible range. To palliate this lack, Earth-viewing approaches can be used which provide a vicarious calibration [18].

The major challenge in applying the Heliosat-2 method to the whole B2 data set was actually the consistent calibration of images spanning from 1985 to 2005. For each sensor, the change of the calibration coefficients with time had to be estimated. The various Meteosat sensors in visible channels have different sensitivities due to small but existing differences in spectral sensor response. Each sensor can be operated on one of the 16 different gain levels. These gain levels were used to obtain the optimum dynamic range and were adjusted as required. These changes affect the sensitivity of a given sensor and are to be compensated accordingly by an adjustment of the operational calibration coefficients.

The difficulty was increased by the numerous changes in sensors over the period considered. Images from six satellites (Meteosat-2 to -7), i.e. six sensors, were used for creating the HC-1 database. In case of failure, maintenance or other reasons, the operational satellite was replaced by its spare during a period lasting a few days or longer. During this period, up to 28 changes in sensor were experienced, not counting changes in gain [19]. A method for the self-calibration of Meteosat images was proposed by Lefèvre *et al.* [20] and an operational version of this method was devised by Rigollier *et al.* [19] to produce a consistent set of B2 images of radiances. A series of calibration coefficients was produced for each day, from 1985 to 1998, available on Internet. After that date, Eumetsat produced daily sets of coefficients. The similarity of the two series of coefficients was demonstrated [21] and a consistent time-series of images of radiances was constructed spanning from 1985 to 2005.

V. The HelioClim-1 Database

The accuracy of the HC-1 data has been assessed by comparison with ground measurements made by high-quality pyranometers on a daily basis [17], [22]–[25] and monthly basis [3]. If well-calibrated and well-maintained, these pyranometers exhibit a relative uncertainty of 10% of the daily mean of SSI at a 95 per cent confidence level [26]. The above-cited authors have computed the deviations by subtracting the ground measurements from the HC-1 data.

The deviations were summarized by the bias–the mean of the deviations, the root mean square deviation (RMSD) and the correlation coefficient. Graphs were also drawn. Two examples of correlograms are presented in Fig. 2 for the stations of De Aar in South Africa and Goteborg in Sweden.

As an example, Table I synthesizes the results obtained by Lefèvre *et al.* [17] using 55 sites in Europe for the period June 1994–July 1995 and 35 sites in Africa for the period 1994–1997. The correlation coefficient is high in all cases and larger than 0.9: day-to-day variations are well reproduced. As a whole, the bias is negative for Europe (underestimation) and positive for Africa (overestimation). The bias varies from one year to another and from one site to another. For example, the bias for De Aar is negative (-0.2 Wm^{-2} for a mean SSI of 241.3 Wm^{-2}, Fig. 2 left) and that for Goteborg is positive (6.9 Wm^{-2} for a mean SSI of 143.3 Wm^{-2}, Fig. 2 right), contrary to the overall trend. The bias is of order of a few percent in relative value. The

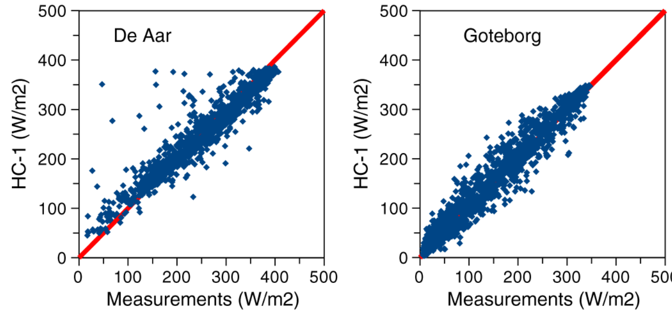

Fig. 2. Correlogram between the ground measurements of daily mean of SSI (horizontal axis) and the HC-1 data (vertical axis) for the station De Aar in South Africa (left) and Goteborg in Sweden (right). The red line is the 1:1 line.

TABLE I
Results of the Comparison Between the HC-1 Data and Ground Measurements of Daily Mean of SSI (in Wm^{-2}). The Bias and the RMSD Are also Expressed in Percent of the Mean Value

	Mean value	Bias	RMSD	Correlation coefficient	Number of data
Europe	143	-8 (-6%)	33 (23%)	0.94	12701
Africa	223	5 (2%)	36 (16%)	0.90	35789

relative RMSD ranges between 15 and 25%, i.e. greater than the uncertainty of the pyranometers.

The accuracy of HC-1 data in retrieving monthly means of the SSI has been studied by a comparison between eleven stations offering long time-series of measurements [3]. Results are similar to those of Lefèvre *et al.* [17]. A good agreement was observed for each site: bias was less than 10 Wm^{-2}.

These cited works demonstrate that the HC-1 database offers good quality for Africa, the Mediterranean Basin, and more generally for latitudes comprised between $-45°$ and $+45°$. Outside these limits, the quality may decrease because of the increasing effects of the reduced resolution in time and space of the ISCCP-B2 images used as inputs [3]. This decrease in accuracy is not a systematic effect and local conditions may prevail. For example, the bias is respectively 7 Wm^{-2} for Goteborg (latitude 57.70, Fig. 2), and 12 Wm^{-2} for Helsinki (latitude 60.32) [3]. One should be cautious in using HC-1 data in high latitudes and in any case where the variability in SSI with respect to space and time is large for scales of order of 10 km and 1 h, apart from the variability induced by the sun course.

Blanc *et al.* [3] have concluded that the availability of these HC-1 time-series for virtually any location in the field-of-view of the Meteosat satellites should help any community interested to perform steps towards a better knowledge of the SSI and its variation over recent years, even if uncertainty is currently too great for accurate analyses of climate.

One limitation to the value of HC-1 database is that the Heliosat-2 model behind use monthly climatological values of the Linke turbidity factor as the sole descriptor of the clear-sky optical conditions. The Linke turbidity factor is a convenient approximation to model the atmospheric absorption and scattering of the SSI under clear sky. The climatology of Remund *et al.* [27] comprises 12 maps, one per month, covering the world by cells of 5' of arc angle in size. As a consequence of this use

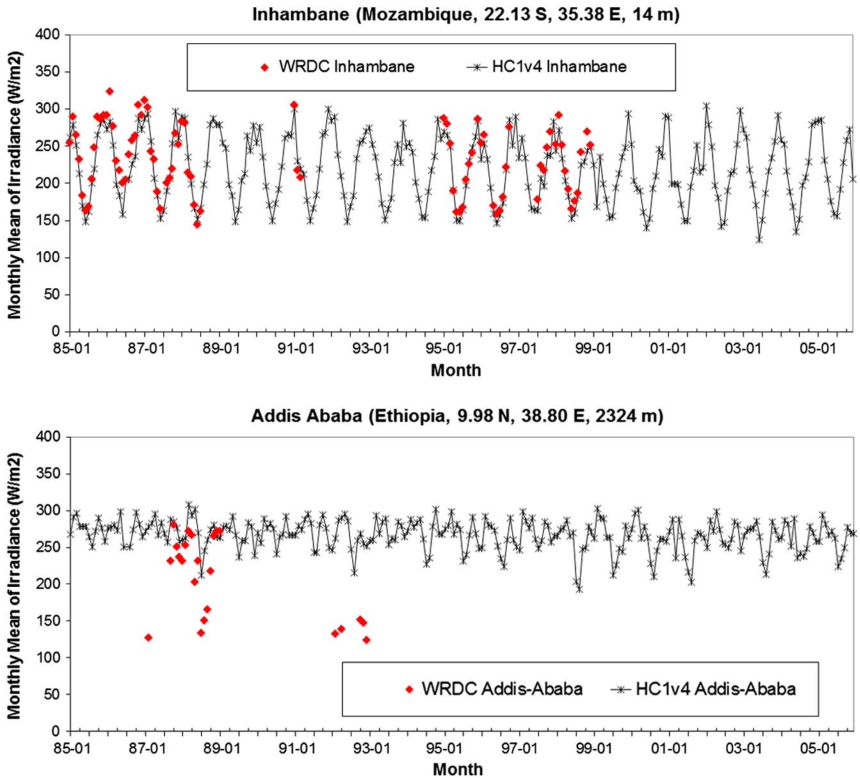

Fig. 3. Monthly means of the SSI from HC-1 (crosses and black line) in Inhambane, Mozambique (left) and Addis-Ababa, Ethiopia (right), during the period 1985–2005 and comparison with the available ground-based measurements (WRDC) (diamonds).

of climatology, for a given site and a given day, the SSI under clear-sky is constant from year to year. Any change in aerosol properties is not accounted for. Volcanic eruptions release large amounts of ashes in the atmosphere, increasing the scattering of the sun rays by the atmosphere. The beam component of the SSI, also called direct component, is the SSI coming from the direction of the Sun, while the diffuse component is the sum of radiances originating from all other directions from the sky vault. The global SSI is the sum of the beam and the diffuse, and is less affected by such events than the beam component because most of the radiation is scattered in the forward direction by the aerosols.

Based on numerous comparisons between ground-made measurements and the HC-1 data, an empirical model was developed that produces an uncertainty for each daily mean equivalent to a RMSD [28]. Inputs to this model are the SSI from the HC-1 database, the SSI that should be observed under a clear sky for this day and location [29], and the number of B2 images used to construct the daily mean of the SSI. As requested by users [30], this uncertainty is delivered together with the daily mean of the SSI.

VI. Using HC-1 Data to Analyze and Complement Ground Measurements

The HC-1 data may be helpful in analyzing and complementing time-series of ground measurements. To illustrate these capabilities, the authors have collected monthly means of ground-based measurements of the SSI made by pyranometers from the World Radiation Data Center (WRDC). The WRDC was established in 1964, and since that time it centrally collects, screens, archives and publishes radiometric data for the world, to ensure the availability of these data for research purposes by the international scientific community. As examples, Fig. 3 exhibits monthly means for the stations of Inhambane, Mozambique, on left and Addis-Ababa, Ethiopia on right, during the period 1985 to 2005. In both cases, there are gaps in measurements at both sites: the measurements (red diamonds) are available for a limited number of months over the whole period. Therefore variation in SSI with time cannot be depicted with the sole measurements.

Estimates from the HC-1 database are also reported in Fig. 3 and one notes visually that the agreement of HC-1 with the actual measurements is fairly good for Inhambane (left). The black line (HC-1) matches the diamonds of the measurements. In that case, the HC-1 data may help in filling the gaps in-between the WRDC measurements. If an accurate sort of calibration function can be found between the HC-1 values and measurements for a given period and given site, then the entire set of HC-1 values for this site can be transformed into an accurate and complete time-series reproducing the measurements. This example illustrates that the HC-1 database can be used in combination with ground measurements to depict the change in SSI over the 21 years period, and may palliate gaps in ground-based measurements.

Another use of HC-1 is to help validate and identify remaining problems in measurements. Though WRDC performs a quality check on pyranometer measurements before releasing them with a quality flag, and that only unquestionable data have been downloaded from WRDC in this paper, one may see unexpected features in the measurements in the case of Addis-Ababa (Fig. 3 right, red diamonds). Ground-based measurements in 1991–1992 are approximately half of those in 1988–1989, a difference which is unexpected even taking into account the possible effects of the aerosols emitted by the eruption of Mount Pinatubo in June 1991, Philippines. There is a very large discrepancy between ground-based measurements and HC-1 data, contrary to the previous case. Given the usual good performance of the HC-1 data reported in a number of other locations, and the current knowledge on changes of SSI over the years, one may believe that this station experienced measuring problems though it may be admitted that the HC-1 data might not be accurate in this particular location. Though an extreme case, this example shows that the HC-1 database may help in qualifying ground-based measurements by showing noticeable drifts in measurement quality. Using HC-1 daily values, one may go back to a questionable data set and maybe locate and identify the suspicious data and rehabilitate them.

VII. How to Access the HC-1 Database

The SoDa Service (www.soda-is.com) was selected as an efficient means to disseminate the HC-1 database. This Web site was established by MINES ParisTech in 2003 [31] and is managed by the Transvalor company since 2009 for the common good. The service is widely used by communities interested in solar radiation. There were approximately 35000 unique visitors to the Web site in 2012. Therefore, being part of it, the HC-1 database benefits from the reputation of the SoDa Service. Transvalor is providing a helpdesk for all resources available in the SoDa Service, including the HC-1 database.

Data can be retrieved by users using a standard Internet browser, freely without registration. The graphical user interface allows selecting a given location on a map, or by entering geographical coordinates or name of a place, e.g., Nice, France. Other inputs are the period (dates begin and end) and the period of aggregation: day, week, or month. Outputs may be either displayed on the screen in HTML format or returned in a CSV file in ASCII format. Outputs comprise the mean SSI, its uncertainty, the corresponding irradiation, the irradiance at the top-of-the-atmosphere and the SSI that would be observed if the sky were clear. In one click, one may download 21 years of daily mean of SSI at a given site.

Efforts were recently made to offer access through an OGC (Open Geospatial Consortium) standard Web processing service (WPS) taking benefit from the interoperability promoted by GEOSS [32]. This WPS is a means to access the HC-1 database by a computer without human interaction [33]. It is located in the GEOSS energy community portal: www.webservice-energy.org, and is published in the geo-catalog of this portal (geocatalog.webservice-energy.org). A set of ISO 19139 metadata describes the WPS. The following keywords recommended by GEOSS: *GEOSS Data CORE*, *geossDataCore*, and *geossNoMonetaryCharge* have been written in one of these metadata fields, thus providing the necessary information related to the use and constrains attached to this service. During the 4th phase of the GEOSS Architecture Implementation Pilot whose results were presented at Istanbul in 2011, an application has been devised and set up temporarily on the web site of the European-funded GENESIS project exploiting this WPS in order to deliver SSI time-series for up to five locations at the same time [34].

New means of access deal with maps. Yearly means of irradiance were mapped for each year between 1985 and 2005. A Web map server was established at webservice-energy.org to interactively display these maps. These maps are available in the geo-catalog as well as in the WebGIS of the Global Atlas of the IRENA (International Renewable Energies Agency, www.irena.org/globalatlas/).

VIII. Examples of Use of the HC-1 Database

The HC-1 database is of free access without registration. Therefore, exact uses and users of the HC-1 database are unknown. A few testimonies have been left in the SoDa web site where the HC-1 data can be downloaded. For example, there is a testimony from a company studying the maximum SSI impinging on their gas tanks in a risk analysis, and others from MSc and PhD students in renewable energy, climate or architecture. Other uses of the HC-1 database can be found in published literature; several are briefly described hereafter as examples.

A. Oceanography

The SSI is an element of the radiation budget, an essential component in the modeling of the ocean. The network of stations measuring radiation is very scarce in the ocean and coastal areas. Lefèvre *et al.* [35] have proposed to use the HC-1 database in support of the Global Ocean Data Assimilation Experiment (GODAE) [36].

Muacho *et al.* [37] have studied the effects of internal tidal waves on near-surface chlorophyll concentration in the central region of the Biscay Bay in N-E Atlantic Ocean. They found that high values of chlorophyll concentration can remain for several days after the peak of internal wave activity (spring tides). A simple model that uses HC-1 data has been developed to account for the effect of light variability in phytoplankton during internal wave events.

B. Climate

Several publications have studied the benefit of the HC-1 database in climate studies. Blanc *et al.* [3], [24], Lefèvre *et al.* [17] and Wald *et al.* [23] show that the monthly and yearly means of the SSI depicted in the HC-1 database follow closely those observed in measurements made in meteorological networks for many sites in Europe and Africa, and conclude that the HC-1 database offers a reliable and accurate knowledge of the solar radiation and its daily, seasonal and annual variations over recent years.

Abdel Wahab *et al.* [22] have studied changes in SSI from 1985 to 2005 in Northern Africa (Algeria, Egypt, Libya, Tunisia) using both ground stations and the HC-1 database. They have established a map of change and found that these four countries as a whole experienced dimming in the recent years that may be explained by 1) transportation of sand dust northwards from the Sahel, 2) an increase in urbanization, and 3) an increase in cloud cover and aerosol loading.

C. Solar Energy and Electricity Production

The HC-1 database is often used in the form of time-series for a given location. It has also the ability to being integrated into geographic information system (GIS) to produce maps showing the potential of sun for energy production [38]. For example, the HC-1 data have been integrated in the PV-GIS system of the Joint Research Center (Ispra, Italy), an efficient tool to assess the solar electricity potential by photovoltaics (PV) in Africa [39][40], and in a further step to help decision-makers in energy solutions [41]. By adjusting the HC-1 data onto in-situ measurements made at 14 sites, Pettazzi and Salson [42] obtained a very accurate map of Galicia, Spain, for energy planning and private investment.

Several papers have proposed methods calculating the energy produced by a PV system connected to the grid, among which [43], [44] used HC-1 data. Dekker *et al.* [45] used the HC-1 database for off-grid residential applications in South Africa.

Small hydropower plants most often use "run of river" and may not satisfy power demand all year long. In equatorial Africa, the least favorable season for hydropower resource corresponds to the dry season when solar resource is highly available. Kenfack *et al.* [46] studied combinations of other renewable sources to form a hybrid system that can help solving rural electrification problems in a village in Cameroon. Using HC-1 data, they concluded that one the most judicious combinations is the use of PV together with a diesel and batteries. Bilton *et al.* [47] developed a method for an optimal design of sustainable off-grid power systems for the developing world. HC-1 data were used as inputs in the illustrating case of a hospital in Uganda.

Suri *et al.* [48] analyzed the variability of solar radiation in the Mediterranean and Black Sea regions by comparing yearly and monthly averages to long-term average values calculated from the HC-1 database. They concluded that the solar resource has distinctive time and geographical patterns that might affect financing of large photovoltaic systems, as well as management of the distributed electricity generation.

The integration of wind and solar energy was discussed by Aboumahboub *et al.* [49] who underlined the challenge caused by the high temporal and geographical variability of these resources. These authors investigate the optimal structure of a prospective renewable-based power supply system on two different scales: on the global and the European levels. HC-1 data were used for the latter. As results ideal energy mixes, generation sites, storage and interregional power transmission capacities required for different scenarios of highly renewable supply were obtained.

The state of the art of residential PV systems in Belgium was performed by Leloux *et al.* [50] by using HC-1 data and analyzing the operational data of 993 installations. They found that the energy produced by a typical PV system in Belgium is 15% inferior to the energy produced by a very high quality PV system, and, on average, the real power of the PV modules falls 5% below its corresponding nominal power announced in the manufacturer datasheet.

The passive house concept has been developed in Germany since 1991. Using HC-1 as inputs in their simulation, Rotar and Badescu [51] studied if the design solutions developed in Germany ensure the fulfillment of passive house standard requirements when implemented in areas with different climates, such as South-Eastern Europe.

D. Life Cycle Analysis in Solar Energy

The life cycle assessment (LCA) documents and analyses the different impacts over the environment due to the existence of the system, from the manufacturing to the dismantlement and recycling. Several studies deal with grid-connected PV systems. Blanc *et al.* [52] studied the sensibility of the LCA to changes in inputs and found that the solar irradiation brings the greatest variation on environmental impact when considering French regions with large difference in irradiation level as depicted by the HC-1 data.

To better take into account the influence of the geo-localization of PV systems on their environmental performances, Ménard *et al.* [32], [34] developed a Web-based tool aiming at providing decision-makers and policy-planners with reliable and precise knowledge of several impacts induced by the various technologies used in the PV sector. Users were able to select up to five locations in Europe. The SSI from the HC-1 database was provided for each location in graphical and tabular forms and users were comparing them in order to, e.g., select the most appropriate site for a PV plant.

Perpiñan *et al.* [53] have done a review of existing studies about LCA and completed the information in order to calculate the energy payback time of double and horizontal axis tracking and fixed systems. The HC-1 database was an input to their model. They concluded that a grid connected PV system is able to produce back the energy required for its existence from 6 to 15 times during a life cycle of 30 years, depending on the geographical zone studied.

E. Agriculture–Forestry–Ecology

Researchers in agriculture and forestry often build radiative budget to estimate gross primary production, net primary production, and net ecosystem production, or to simulate crop growth. In several cases, the HC-1 data were used as inputs to radiative budget models to predict production [54], or estimate evapotranspiration [55]. Bois *et al.* [56] analyzed the relationship between the Bordeaux vineyards terrain and the change in irradiation with space and time as depicted in the HC-1 database.

The Breitenbach is a single small stream located in Hessen in Central Germany, whose ecology has been studied extensively from 1951 to 2006. Wagner *et al.* [57] wrote "HC-1 daily data demonstrated such amazing agreement with our data that they can always be used to compensate for gaps in our measurements."

Lack of solar radiation data has led many researchers to propose methods for estimating the SSI from other meteorological data, such as air temperature or sunshine duration. Mavromatis [58] has discussed several such methods and has used the HC-1 database as a reference to assess their relative performances.

F. Health–Air Quality

Boniol *et al.* [59] conducted a study to compare measurements of UVA and UVB exposure of children recorded with personal dosimeters with assessment through a detailed questionnaire and satellite measurements. The SSI from HC-1 database was converted into UVA and UVB using the method proposed by Wald *et al.* [60]. It was concluded that using the HC-1 database gives a fairly good estimate of individual UVA and UVB exposure and could be used to estimate actual exposure. It was further decided to construct a database of daily ultraviolet exposure in France to begin with, then in Europe from which exposures to regions and individuals can be assessed and monitored [61]. This database has been partly created from the HC-1 database.

Paulescu *et al.* [62] developed a model to predict daily changes in UV. They converted the SSI extracted from the HC-1 database into UV radiation with the same method as above [60] and used the results to validate the capability of their model to reproduce day-to-day variability.

Summer 2003 was one of the hottest in the history of Western Europe. Anomalous anticyclonic conditions led to an increase in the monthly mean of the SSI of 20% with respect to the mean value for the 10 previous years. This was clearly seen in the HC-1 data. These data were used by Tressol *et al.* [63] in their analysis of the air pollution during this heat wave.

IX. Conclusion

HC 1 is a database of daily mean of SSI that offers good quality for Africa, Europe, the Mediterranean Basin, the Atlantic Ocean, and more generally for latitudes comprised between -45° and $+45^\circ$ and provided that the site under concern is not located too close to the rim of the Earth as seen by the Meteosat satellites. In the latter case, the large viewing angle may induce a shift in the actual location of clouds and, in conjunction with the corresponding large size of the pixels, may contribute to decreasing performances in the case of fragmented cloud cover [62].

This paper has shown the possible synergy of the HC-1 data and *in situ* measurements. The HC-1 data may help in qualifying the *in situ* measurements by providing ranges of plausible values. They may supplement the *in situ* measurements to provide 21 years of daily means of SSI.

The HC-1 database has many usages as illustrated by examples given here in various domains: oceanography, climate, energy production, life cycle analysis, agriculture, ecology, human health, and air quality.

The HC-1 database is freely available at no cost. Several means of access are available: from graphical user interface in a Web browser to automated access by computers. Not accounting for requests made by MINES ParisTech and Transvalor, approximately 104,000 requests were made in 2012 to the HC-1 database by users, ten times more than before it was declared a GEOSS Data-CORE. This makes an average of 400 requests per workday and demonstrates the usefulness of the HC-1 database.

The HC-1 database is a full GEOSS Data-CORE and supports research and business by providing data of known quality on surface solar irradiance. Several examples of use of HC-1 data were found in scientific journals in various domains. This paper demonstrates through case studies how such freely supplied data on solar radiation support research, development and business in various domains. This demonstration of the benefit of the HC-1 database should draw more attention to resources open to everyone such as those labeled GEOSS Data-CORE.

Acknowledgment

The creation of the HelioClim 1 database has received funding from the European Union's Fifth Framework Programme (FP5/1998-2002) under Grant Agreement IST-1999-12245 (SoDa project). The authors thank the ADEME (French Agency for Energy) (Grant 08 05 C 0049, 2008-2010) and the GEOSS for their support in the dissemination of the HelioClim databases and the European Commission FP7 funded project GENESIS (http://www.genesis-fp7.eu) for its support in the framework of the GEOSS AIP-4 pilot project, leading to the implementation of the HC 1 web processing service. The authors also thank the anonymous reviewers whose questions and comments helped in bringing more clarity to the work.

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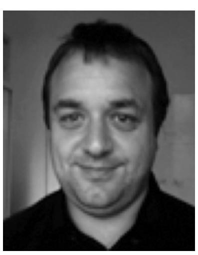
Mireille Lefèvre received the Ph.D. degree in marine biology from the University of Paris-VI, Paris, France, in 1986.

She worked as a consultant until 1993, then at the Joint Research Center of the European Commission, Ispra, Italy, from 1994 to 1996, and at the Institut Maurice Lamontagne of the Fisheries and Oceans Canada, Québec, Canada, from 1998 to 2000. Since 2003, she has been a senior scientist at the MINES ParisTech, Sophia Antipolis, France.



Philippe Blanc graduated from the Ecole Nationale Supérieure des Télécommunications de Bretagne, Brest, France, in 1995 with a signal and image processing specialization. He obtained in the same year a M.S. degree in signal, telecommunications, image and radar from the University of Rennes, France, and a Ph.D. in signal, automatic and robotics from the MINES ParisTech, Paris, in 1999.

He worked for nine years in the Research Department of the Alcatel Space company, then Thales Alenia Space in projects related to Earth observation and spaceborne systems. Since 2007, he has been a senior scientist at the MINES ParisTech.

Bella Espinar received the Master degree in physics from the University of Granada, Spain, in 2002, and the Ph.D. degree in applied physics from the University of Almeria, Spain, in 2009.

Since 2011 she has been with the MINES ParisTech, working on Earth observation data for solar resource assessment and meteorology for energy. She is experienced in solar radiation measurement, uncertainty analysis and data quality control assessment, atmospheric optics and development of methods exploiting Earth observation data and models.

Benoît Gschwind received the Ph.D. degree in computer science from the MINES ParisTech, Paris, France, in 2009.

Since 2010 he has been a researcher at the MINES ParisTech, focusing on research and development of Web services in the fields of energy and environment.

Lionel Ménard received the Master degree in information systems management from the University of Nice-Sophia Antipolis, Nice, France, in 2005.

He has been with the MINES ParisTech since 1983. Since 1994, he has been a software architect working on numerous European research projects in energy and Earth observation domains. Since 2006, he has been involved in the development of the Global Earth Observation System of Systems, and he has led team development contributing to the GEOSS Architecture Implementation Pilots phases.

Thierry Ranchin (M'01–SM'12) received the Ph.D. degree in applied mathematics in 1993 and the "Habilitation à diriger les recherches," in 2005, both from the University of Nice-Sophia Antipolis, Nice, France.

He has been with the MINES ParisTech since 1996 and has been a Professor since 2012. Since 2013, he has been the Director of the Centre for Observation, Impacts, Energy at the MINES ParisTech, Sophia Antipolis, France.

Prof. Ranchin is the Co-chair of the Energy Community of Practices and member of the GEO Societal Benefit Board and Institutions and Development Implementation Board of the Global Earth Observation System of Systems initiative. He was the recipient of the Autometrics Award in 1998 and the Erdas Award in 2001 from the American Society for Photogrammetry and Remote Sensing for articles on data fusion.

Lucien Wald received the M.S. degree in theoretical physics in Marseille and Paris, France, in 1977, the Ph.D. degree from the University Paris-6, Paris, in 1980, and the Doctorat d'Etat ès Sciences on the applications of remote sensing to oceanography from the University in Toulon, France, in 1985.

Since 1991, he has been a Professor at the MINES ParisTech. He is focusing his own research in applied mathematics and meteorology.

Prof. Wald was the recipient of the Autometrics Award in 1998 and the Erdas Award in 2001 from the American Society for Photogrammetry and Remote Sensing for articles on data fusion. His career in information technologies was rewarded in 1996 with the famous French Blondel Medal.

Laurent Saboret received the M.S. degree in computer sciences from Ecole Nationale Supérieure d'Electrotechnique, d'Electronique, d'Informatique, d'Hydraulique et des Télécommunications, Toulouse, France, in 1989.

He worked for several private companies and research laboratories as a senior developer specialized in image processing, 3D and user interface. He is now in charge of the back office of the SoDa web site for the Transvalor company, Mougins, France.

Claire Thomas received the B.S. degree in physics from the Ecole Nationale Supérieure de Physique de Strasbourg, Illkirch, France, and the M.S. degree in photonics, image, and cybernetics from the University of Strasbourg, Strasbourg, France, both in 2002, and the Ph.D. degree from the MINES ParisTech, Paris, France, in 2006.

She is currently with the Transvalor company, Mougins, France.

Etienne Wey graduated from the Institut National des Sciences Appliquées, Lyon, France, in 1979 and received the Ph.D. from the MINES ParisTech, Paris, France, in 1984.

He is currently General Manager of the Transvalor company, Mougins, France, in charge of Innovation. Previously, he created the first version of the Forge2 forging simulation software package and established and grew the software department of Transvalor from 1986 until 2009. In 2009, he initiated the Innovation department inside Transvalor, in order to extend the Forge successful transfer/commercialization model to other research results obtained by the research labs of the MINES ParisTech. Transvalor Innovation industrializes and commercializes with good success the HelioClim databases and manages the SoDa web site for the common good.