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Article

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Philippe Blanc, Benoît Gschwind, Mireille Lefèvre and Lucien Wald *

Center for Energy and Processes, MINES ParisTech, BP 207, 06904 Sophia Antipolis cedex, France;
E-Mails: philippe.blanc@mines-paristech.fr (P.B.); benoit.gschwind@mines-paristech.fr (B.G.);
mireille.lefevre@mines-paristech.fr (M.L.)

* Author to whom correspondence should be addressed; E-Mail: lucien.wald@mines-paristech.fr;
Tel.: +33-493-957-404; Fax: +33-493-957-535.

Abstract: Meteosat satellite images are processed to yield values of the incoming surface solar irradiance (SSI), one of the Essential Climate Variables. Two HelioClim databases, HC-1 and HC-3, were constructed covering Europe, Africa and the Atlantic Ocean, and contain daily and monthly means of SSI. The HC-1 database spans from 1985 to 2005; HC-3 began in 2004 and is updated daily. Their quality and limitations in retrieving monthly means of SSI have been studied by a comparison between eleven stations offering long time-series of measurements. A good agreement was observed for each site: bias was less than 10 W/m² in absolute value (5% in relative value) for HC-3. HC-1 offers a similar quality, though it underestimates the SSI for latitudes greater than 45° and less than −45°. Time-series running from 1985 to date can be created by concatenating the HC-1 and HC-3 values and could help in assessing SSI and its changes.

1. Introduction

This paper deals with the downwelling solar irradiance observed at ground level on horizontal surfaces and integrated over the whole spectrum (total irradiance), also called surface solar irradiance

(SSI). The SSI is an Essential Climate Variable (ECV) as designed by the Global Climate Observing System (GCOS) in August 2010 [1]. 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/m^2 or J/cm^2. The daily mean of SSI is expressed in W/m^2 and is derived by convention from the daily irradiation by dividing it by the number of seconds in 24 h, *i.e.*, 86,400 s.

Accurate assessments of 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 [2,3]. Stations measuring SSI on the long-term are rare and satellites are an accurate way to supplement them. Based on satellite data, the project Surface Radiation Budget (SRB) offers accurate monthly means of SSI over several years and covering the whole Earth with a low spatial resolution of 1 degree [4,5].

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°. 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). They are currently used to assess SSI with spatial and temporal resolutions better than those in SRB.

Figure 1. Example of a Meteosat image in visible channel, taken on 7 September 2010, at 1200 UTC. Reflectance increases from black to white. The area covered is the same for Meteosat First and Second Generations. (Copyright Eumetsat, 2010).
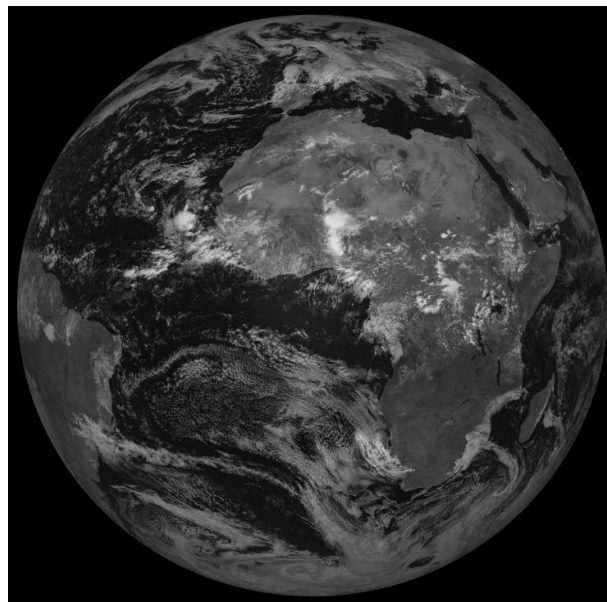
The HelioClim project is an initiative of MINES ParisTech launched in 1997, to increase knowledge on SSI and to offer SSI values for any site, any instant over a large geographical area and long period of time, to a wide audience [6]. It covers Europe, Africa and the Atlantic Ocean. The HelioClim-1 database, 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). The HelioClim-3 database,

abbreviated to HC-3, represents a step forward regarding spatial and time resolution, clarifying uncertainty on SSI, and time needed to access recent data. It exploits the enhanced capabilities of the series of satellites Meteosat Second Generation (MSG) to deliver values of SSI every 15 min with a spatial resolution of 3 km at nadir. To achieve this, MINES ParisTech acquired a MSG receiving station in 2003 building upon its experience gained with the previous Meteosat satellites [7] and has set up a routine operation for converting Meteosat data into SSI on a near-real time basis.

The main objectives of this article are to share this experience in building these two climatological databases of SSI, to describe their construction, to discuss their quality and limitations, and to analyze whether both databases can be combined to provide seamless time-series of daily and monthly means of SSI spanning from 1985 to date.

We will first discuss the general challenges that we have encountered in the HelioClim project. Then we will focus on those specific to the HC-1 database, how we solved them and our choice of a set of Meteosat images in reduced resolution. We will describe the construction of the HC-1 database of daily means of SSI by explaining the practical problems and their influence on the uncertainty of the resulting SSI. We will show several examples of HC-1 time-series of monthly values and compare them to existing ground-based measurements. These examples illustrate the performances and limitations of the HC-1 database. Then, we will discuss the new challenge that we faced in 2003 with the advent of the MSG series of satellites. We will describe the new HC-3 database and discuss also its performances and limitations. We will analyze the concatenation of the two databases to create a virtual single climatology and will study the consistency in time of this combination. Finally, we will conclude on the HelioClim family of databases.

2. What Are the Challenges?

Creating a climatological database of SSI involves selecting: (i) a set of satellites images; (ii) a method to process these images; and (iii) a tool for disseminating the data. All elements must be consistent with each other: the method should be appropriate to the given images, the created database should adapt to the dissemination tool. Each of the three elements is important; their combination is a necessary condition for the climatology to exist and be exploited by users.

Of course, there are several constraints on any project. Usually, a project has limited resources in skilled manpower, computer, storage and money. The HelioClim project was no exception. We tried to find the best trade-off between the constraints, our ambitions and maintain scientific quality. As a consequence, we have limited our own development of methods and tools. We opted for a set of images in reduced resolution as input images, the Heliosat-2 method to convert these images into SSI, and the SoDa Service for dissemination. These elements are discussed in the following.

One obstacle to the production of a climatological database is the large amount of data to process. Considering the example of the MFG satellites, one third of the surface of the Earth was imaged every half-hour with a pixel size of 2.5 km at nadir, yielding series of images of 5,000 $\times$ 5,000 pixels. Within an image, approximately 30% of pixels are outside the Earth rim (Figure 1) and therefore offer no interest for the computation of the SSI. Considering the remaining pixels, one year of data means approximately a storage capacity of 243 GB. A set of Meteosat images in reduced spatial resolution, called ISCCP-B2 data, B2 for short, was created for the International Satellite Cloud Climatology

Project (ISCCP) to better handle and exploit this wealth of information [8]. Using B2 data allowed a very large gain in data storage, as it needs only 0.2 GB for one year. In addition, B2 data was cheaper than high-resolution data, at least for Meteosat satellites and before the latest changes in data policy of Eumetsat, which is the owner of the Meteosat data. For example, fifteen years ago, when our project started, one year of high-resolution data was more than 20,000 euro worth while the cost was only 500 euro for B2 data. This was the second pragmatic reason for choosing B2 data. We were strengthened in our decision by several articles that had successfully used the B2 data set for the assessment of SSI [9,10].

As for the method of converting the images into SSI, several well-performing candidates were available. We opted for the Heliosat-2 method because it was easy to implement and to operate, and well known. 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 [9,11]. The Heliosat-2 method and its application to the Meteosat images are detailed in [11]. The authors assessed the uncertainty of the derived SSI with respect to ground-based measurements. Implementations of the Heliosat-2 method have been used in several places, benefiting from the free availability of software on internet [12-15]. The influence of uncertainties in input variables on the outcomes of the Heliosat-2 method was discussed by [16]. The application of Heliosat-2 to the B2 images has been described in detail [17]; results were compared to ground-based measurements and it was concluded that the combination of the B2 images and the Heliosat-2 method offers enough accuracy for creating a climatological database of the daily or monthly mean of SSI. The findings of [17] on uncertainty of monthly means of SSI are recalled in the following section.

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. This function is of an affine type and its two parameters vary with time. Nowadays, these parameters are provided by Eumetsat with each Meteosat image. This was not the case prior to 2004: MFG 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 [18,19].

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, we had to estimate the change of the calibration coefficients with time. The various Meteosat sensors in visible channels have different sensitivities due to small but existing differences in spectral band. 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. Six sensors were used: Meteosat-2 to -7, but 28 changes in sensor were experienced, not counting changes in gain [20]. A method for the self-calibration of Meteosat images was proposed by [21] and an operational version of this method was devised by [20] 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 by [22] who concluded that a consistent time-series of images of radiances can be created from 1985 to 2005 from the B2 images.

Finally, we opted for the SoDa Service (www.soda-is.com) as a means to disseminate the HelioClim databases. This service was established in an operational way in 2003 [23] and is now widely used by communities interested in solar radiation: more than 50,000 users in 2010. Data can be retrieved by users using a standard internet browser. Therefore, by choosing this service, the HelioClim database benefits from the notoriety of the SoDa Service.

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

The B2 data set was produced by Eumetsat from Meteosat images by first performing a time sampling that reduced the frequency of observation to the standard meteorological synoptic 3-h intervals, starting at 0000 UTC. This sampling is not time averaging; the first image available and of good quality was selected to represent each 3-h interval. Secondly, the higher-resolution data in the visible-channel were averaged to match the lower resolution of infrared-channel data (*i.e.*, an image of 2,500 $\times$ 2,500 pixels with a resolution of 5 km). Finally, a spatial sampling was performed by taking 1 pixel over 6 in each direction, starting with the south-easternmost pixel.

The B2 data set spans from 1985 to 2005. It covers the whole field of view of Meteosat, *i.e.*, Europe, Africa and the Atlantic Ocean. Meteosat data were converted into radiances as discussed earlier. Each image of radiances was processed by the Heliosat-2 method, 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.

The assessment of SSI for any geographical site is made by the means of a linear interpolator of gravity-type applied to the nine nearest B2 pixels. After several comparisons with the nearest neighbor and the geodetic distance, we selected the effective distance proposed by [24] and used by [25] for mapping solar radiation climate in Africa. In a first approximation, one may consider that HC-1 has an effective pixel of 30 km in size at nadir.

An application—more precisely, a web service—in the SoDa Service provides a time-series of SSI for any site, and any period between 1 January 1985 and 31 December 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 necessary. One major drawback was due to errors in navigation in original Meteosat images and was discovered in January 2005. The HC-1 database was then reconstructed and the current version HC-1v4 has been available since March 2006.

Figures 2 and 3 are examples of the capabilities of HC-1. Monthly means of ground-based measurements made at the meteorological station Inhamabe, are reported in Figure 2 for each month, from 1985 to 2005. There are gaps in measurements and one cannot describe any variation in SSI with time. Estimates from HC-1 are also reported in Figure 2. Meteosat images are unavailable for July 1986; the missing value was replaced by the corresponding ground-based measurement to prevent a gap and allow the computation of the yearly values for further discussion. Except July 1986, the HC-1

time-series is complete. One notes visually that the agreement of HC-1 with the actual measurements is fairly good. HC-1 can be used to provide a first description of the change in SSI over the 21 year period, thus palliating gaps in ground-based measurements. If an accurate sort of calibration function can be found between existing HC-1 values and measurements, then HC-1 values can be transformed into an accurate and complete time-series reproducing the measurements.

Figure 2. Monthly means of SSI from HC-1 in Inhamabe during the period 1985–2005 and comparison with the available ground-based measurements (WRDC).
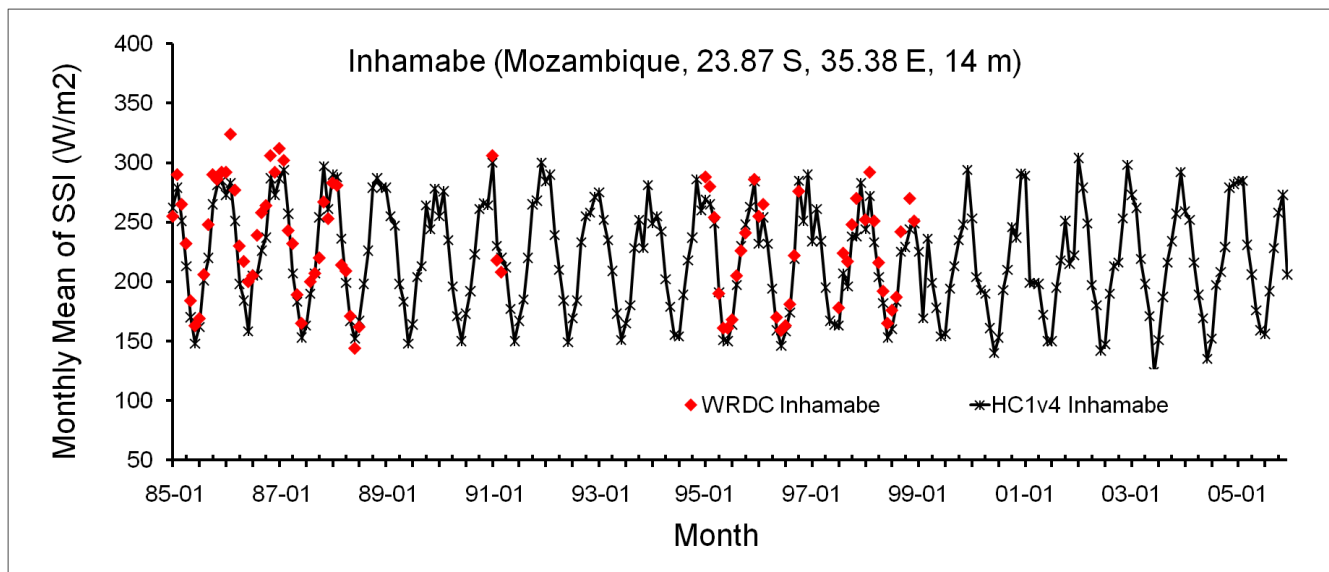
In another example, Figure 3 shows monthly means of SSI both from ground-based measurements and HC-1 in Addis-Ababa. One can see a very large discrepancy between both series; this discrepancy depends strongly on the year. It is also observed that the ground-based measurements in 1991–1992 are approximately half of those in 1988–1989, a difference which is unexpected. On the contrary, HC-1 shows fairly similar values for these years. Given the usual good performance of HC-1 reported in a number of other locations [17,26], one may believe that this station experienced measuring problems during 1991–1992 though we admit that HC-1 might not be accurate in this particular location. The HC-1 database may help in qualifying ground-based measurements by showing noticeable drifts in measurement quality.

The sampling rate in space and time yielding B2 images affects the accuracy of the retrieved SSI when compared to a precisely-located station. Pinker *et al.* [27] investigated the effects of spatial sampling: the estimated SSIs differed by 9% depending upon the sampling. The lower the spatial variability in SSI, the lower the adverse effects of spatial resampling. One may expect accurate retrieval over the ocean where orographic effects are inexistent. On the contrary, resampling effects may be exacerbated on very complex terrain. The situation is even more complicated by the sampling in time. The effects of the temporal sampling on the reconstruction of daily means of SSI were discussed by [28]; they found that the accuracy decreases as the sampling rate decreases. The Heliosat-2 method can only take into account pixels for which the solar zenithal angle is smaller than $75°$ [17]. Consequently, the construction of the daily means, and further of monthly means, is made with a limited number of images. Table 1 shows the number of hours used in the reconstruction, relative to

the day length in hours, for longitude 0 and various latitudes. This number does not vary significantly with longitude, except for those close to the borders of the Meteosat field-of-view.

Figure 3. Monthly means of SSI from HC-1 in Addis-Ababa during the period 1985–2005 and comparison with the available ground-based measurements (WRDC).
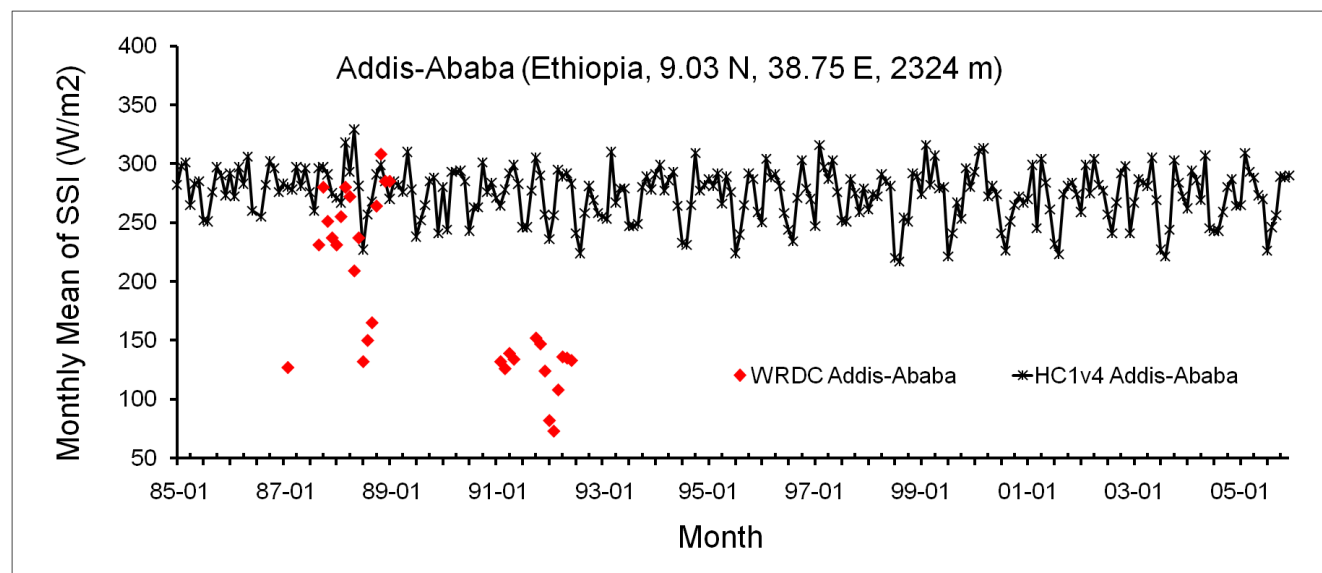

Table 1. Relative percentage of hours used in the construction of daily means of SSI in HC-1, knowing that maximum is 33% for B2 data set.

Latitude (deg.)	60 (−60)	55 (−55)	45 (−45)	35 (−35)	25 (−25)	15 (−15)	0
Rel. number min (winter)	0	0	14	21	24	24	24
Rel. number max (summer)	16	30	30	30	31	33	33

During winter, the sun is low above the horizon in middle to large latitudes and the day length is short. Therefore, the chance to have many observations with solar zenithal angle less than 75 °are small and the number of available hours is the lowest. The opposite occurs in summer. Nevertheless, one can see that, at most, only one-third of the hours can be used to assess the daily value: in all cases, the number of hours is not enough to describe complex highly-variable situations. Therefore, one may expect large discrepancies between HC-1 retrievals and actual SSIs.

In addition, the instants of sampling are defined in UTC—every 3 h—and are the same for all pixels. The few available hours are not necessarily well distributed with respect to the sun course and irradiance profile. It may well be that a specific climate is misrepresented. For example, given a month, if clouds occur frequently in the morning only, and if the one or two available B2 observations are made in the afternoon, then the month will be considered as most often clear. Other examples can be found where the rate and instants of sampling are inadequate to describe the cloud cover and therefore lead to inaccurate estimated SSI.

As a conclusion, one should be cautious in using HC-1 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.

4. Quality and Limitations of HC-1

To our knowledge, two articles have been published assessing the uncertainty of the daily and monthly means of SSI provided by HC-1 [17,26]. In both cases, this was done by comparing HC-1 values to ground-based measurements. The authors follow the ISO standard [29]: they compute the difference: estimated-measured for each day, and summarize these differences by the bias, the root mean square difference (RMSD) and the correlation coefficient.

It should be recalled that the two time-series to compare are different in nature: one is made of pin-pointed time-integrated measurements, the other of space-averaged instantaneous assessments. Accordingly, a discrepancy is expected because of the natural variability of SSI in space; [3] found a standard deviation of 10–15% within a pixel relative to the hourly mean of SSI. Though it is difficult to predict because spatial variability is not a random variable, we can expect a discrepancy of a few percent relative to the monthly mean of SSI.

Lefèvre *et al.* [17] used measurements for 55 sites in Europe covering July 1994 to June 1995, and 35 sites in Africa spanning over 48 months from January 1994 to December 1997. Their results of monthly means are reported in Table 2. The authors showed that their results are in accordance with those obtained by [5] with the NASA-SRB data set. Studying 11 stations in North Africa, [26] found similar performances between HC-1 and NASA-SRB.

Table 2. Comparison between HC-1 and ground-based measurements of monthly mean of SSI (in W/m^2) [17]. RMSD: root mean square difference. In brackets, quantities are relative to the mean measured SSI.

	Period	*Number of observations (months)*	*Mean SSI (measured)*	*Bias (relative)*	*RMSD (relative)*	*Correlation coefficient*
Europe	1994	172	147	−6 (−4%)	17 (12%)	0.97
Europe	1995	462	149	−14 (−9%)	24 (16%)	0.95
Africa	1994	280	228	−1 (0%)	24 (11%)	0.92
Africa	1995	322	224	5 (2%)	24 (11%)	0.92
Africa	1996	310	218	7 (3%)	27 (12%)	0.90
Africa	1997	269	219	8 (4%)	29 (13%)	0.90

Considering the quality of HC-1 (Table 2), Lefèvre *et al.* [17] concluded that a climatology of the SSI can be constructed from B2 data set. However, they underlined that the quality may vary strongly from one site to another.

We now examine their conclusions for a limited number of sites but over a longer period. We aim at providing further evidence on the capabilities of HC-1 for climate applications and detailing its limitations. Thanks to the World Radiation Data Center (WRDC), the Egyptian Meteorological Authority and Meteo-France, we have assembled monthly values measured by meteorological networks. Eleven stations were selected because they offer long time-series of monthly values—greater than 97 months—and cover major climatic areas (Table 3). The approximate size of the pixel in HC-1 and HC-3 is reported for each site in this table.

For Europe, we used more stations than the six shown in Table 3; we present here those that best illustrate the quality and limitations of HC-1. Arguably, we have selected two stations in France: Carpentras and Nice, which are geographically close, approximately 300 km apart, and experience approximately the same sunny climate in the Provence. We expect a similar performance from HC-1 for these sites and we will discuss this further.

Table 3. Ground-measuring stations used for comparison.

Station name	WMO ID	Latitude (°)	Longitude (°)	Altitude (m)	Pixel size HC-1 and HC-3 (km)	Country
Helsinki	29740	60.32	24.97	51	80, 8	Finland
Eskadalemuir	31620	55.32	−3.2	242	80, 8	UK
Vienna	110350	48.25	16.37	203	50, 5	Austria
Payerne	66100	46.82	6.95	490	50, 5	Switzerland
Carpentras	75860	44.07	5.05	106	50, 5	France
Nice	76900	43.65	7.20	4	50, 5	France
Sidi Bou Said		36.87	10.23	127	40, 4	Tunisia
Aswan	624140	23.97	32.78	192	40, 4	Egypt
Tamanrasset	60680	22.78	5.52	1377	35, 4	Algeria
Bulawayo	679640	−20.15	28.62	1343	40, 4	Zimbabwe
Inhamabe	67323	−23.87	35.38	14	40, 4	Mozambique

Five stations are in Africa. We would have been happy to have dealt with more stations, such as those used by Diabaté *et al.* [25] who define 20 solar radiation climates in Africa, but we stress here the difficulty in finding reliable long time-series of SSI measured by meteorological stations, and we acknowledge the work done by the meteorological networks and WRDC. The measurements taken at these African stations have already been compared to HC-1 for different time periods [17,26]. These published results will guide our own analyses.

Table 4 reports on the comparison between these measurements and the SSI from HC-1. The correlation coefficient is large in all cases: greater than 0.9. The month-to-month variations are well reproduced for each site.

Considering the relative bias and the RMSD, Table 4 can be split in two parts: the northernmost stations: Helsinki, Eskadalemuir, Vienna and Payerne, and the others. The northernmost sites exhibit large and negative bias (underestimation). The fact that the bias is larger, in absolute and relative values, than for sites located at lower latitudes is likely due to the poor number of images used to compute the daily means, especially in winter (Table 1). This is substantiated by a similar analysis made for three other stations at approximately 60 °N, eight in Germany and one in Austria, for the same period: relative bias was negative and as large as in Table 4. This is also in agreement with Table 2. We conclude that HC-1 underestimates SSI because of the sampling rate in time of the B2 images. As a first guess, sites of latitudes greater than 45 °, and most likely less than −45°, experience underestimation by HC-1. This conclusion may nevertheless be contradicted by local conditions, as previously discussed.

Table 4. Comparison between HC-1 and ground-based measurements of monthly mean of SSI (in W/m^2). RMSD: root mean square difference. In brackets, quantities are relative to the mean SSI.

	Period	*Number of observations (months)*	*Mean SSI (measured)*	*Bias (relative)*	*RMSD (relative)*	*Correlation coefficient*
Helsinki	1985-01–2005-12	186	138	−12 (−9%)	20 (15%)	0.980
Eskadalemuir	1985-01–2005-12	217	100	−10 (−10%)	21 (21%)	0.953
Vienna	1985-01–2005-12	246	135	−27 (−20%)	34 (25%)	0.978
Payerne	1985-01–2005-12	192	138	−19 (−14%)	28 (20%)	0.976
Carpentras	1985-01–2005-02	228	176	−11 (−6%)	17 (10%)	0.989
Nice	1985-01–2005-12	240	174	−8 (−4%)	16 (9%)	0.988
Sidi Bou Said	1985-01–2000-05	179	195	7 (3%)	13 (7%)	0.993
Aswan	1985-01–2005-12	252	260	−10 (−4%)	14 (5%)	0.983
Tamanrasset	1994-09–2005-12	136	263	−7 (−3%)	16 (6%)	0.946
Bulawayo	1985-01–2005-12	242	231	2 (1%)	15 (6%)	0.901
Inhamabe	1985-01–1998-12	80	232	−10 (−4%)	17 (7%)	0.950

As for the other sites, the bias is less than 11 W/m^2 in absolute value and most often less than 5% in relative value. It is close to what can be expected when comparing pin-pointed time-integrated data to instantaneous space-integrated data [3]. In addition, the results are close to those reported by [17] (Table 2). In most cases, the SSI is underestimated by HC-1. This may be particular to this set of stations, as Table 2 shows positive bias for Africa. In most cases, the RMSD is close to the bias: the scattering of differences with respect to the bias is therefore small. The results of the two stations in Provence, Carpentras and Nice, are very close as expected: this shows a consistency in space of HC-1 for similar conditions.

5. The Challenge of the Meteosat Second Generation (MSG)

The first satellite of the new series MSG was launched in 2003, and became operational on 1 February 2004. As the SEVIRI instrument has significantly enhanced technical capabilities compared to the previous sensor aboard MFG, this event created new challenges in the establishment of the databases for climate: How to cope with these new data? Can we create a single seamless database, starting with HC-1 data and updated with data from MSG?

SEVIRI has two channels in the visible domain, fairly similar to those of the AVHRR sensor aboard the NOAA satellites. It would have been possible to exploit the two channels for a better detection of cloud and assessment of their optical properties using the APOLLO package [30]. For example, the German institute, DLR, now delivers such images of cloud properties (wdc.dlr.de/data_products/ CLOUDS/clouds_seviri.php). However, doing so would have meant efforts and time to implement and validate such techniques and to design, implement and validate a new version of the method Heliosat, integrating these techniques for assessing SSI. Consequently, given our limited resources, we opted for the construction of images that are similar to the images acquired by the MFG sensor in terms of spectral sensitivity. To do so, we used the easy-to-implement and fast-running method [31] that

combines the radiances of the two narrow visible bands of SEVIRI to produce broadband radiances that are almost identical to those observed in the broadband channel of Meteosat-7, the last satellite of the MFG series.

Contrary to MFG, receiving stations for the high-quality signal are cheap and we were able to afford one. Simultaneously, costs of computers and storage capacities were decreasing; therefore, we were able to process and store a large amount of data unlike six years earlier. Since 1 February 2004, we have been acquiring images every 15 min with a pixel of 3 km in size at nadir. Meteosat images are converted into radiances using the calibration coefficients embedded in each image. Each image of radiances is then processed by the Heliosat-2 method and yields an image of the 15-min mean of SSI. It is stored in the HC-3 database which comprises approximately nine million pixels. Unlike HC-1, post-processing is applied to the 15 min outputs from the Heliosat-2 method in order to decrease the overestimation observed for low SSI and the underestimation observed for large SSI. The effect of this post-processing on monthly or yearly means is difficult to predict as it is applied on 15 min values and depends on the SSI itself. As a first approximation, the post-processing yields an increase of approximately 10 W/m^2 (approximately 3% in relative value) at very sunny sites exhibiting very large SSI all year round, such as in Tamanrasset or Aswan. The daily mean of SSI was computed for all images available for this day and pixel.

Like HC-1, a web service in the SoDa Service provides a time-series of SSI for any site, and any period, starting from 1 February 2004. This service performs the temporal aggregation of the data. It is important to note that SSI values supplied by the HC-3 database are for the pixel containing the requested site with the correction of altitude of this particular site relative to the mean altitude of the Meteosat pixel [26]. There is no spatial average at all, following [11]. The current version HC-3v2 was made available in June 2009. It corrected drawbacks observed in the initial version over African deserts and includes altitude correction.

The HC-3 database has gone through extensive validation of 15 min and hourly values. However, no article has yet been published on this validation, though the results for 29 sites—26 in Europe, one in the Middle East, one in North Africa, one in South Africa—are published on the SoDa Service (www.soda-is.com/eng/help/helioclim3_uncertainty_eng.html). These results are of interest here as the bias observed in hourly values should be close to that observed for daily and monthly values because it is a systematic error. These results are referred to as *SoDa validation results* hereafter and will guide our analysis.

Table 5 reports the results of the comparison between the monthly means of SSI measured at the stations listed in Table 3—except Sidi Bou Said which has no data for this period—and those from HC-3. The correlation coefficient is large in all cases; *i.e.*, greater than 0.9, and in several cases greater than 0.99. This means that the month-to-month variations in SSI are well reproduced by the HC-3 database. If we exclude the two stations Bulawayo and Inhamabe, one notes that results are very similar for all sites though they are located in very different climates, spanning from 23 ° to 60 °. This is a very satisfactory result which demonstrates the consistency in space of the quality of HC-3. The SoDa validation results confirm this observation.

The bias is small as well as the RMSD, taking into account the discrepancy expected because of the different natures of the compared data sets and the single pixel used in HC-3. The biases are in full agreement with the SoDa validation results for the sites of Carpentras and Tamanrasset.

Compared to the results for HC-1 in Table 4, Table 5 shows better performances for the northernmost sites, Helsinki, Eskadalemuir, Vienna, Payerne, and Carpentras. For the others: Nice, Aswan, and Tamanrasset, the quality of HC-1 is similar to that of HC-3. This enforces the conclusion that poor performances of HC-1 are related to the low number of images used to construct the daily SSI.

Table 5. Comparison between HC-3 and ground-based measurements of monthly mean of SSI (in W/m²). RMSD: root mean square difference. In brackets, quantities are relative to the mean SSI.

	Period	Number of observations (months)	Mean SSI (measured)	Bias (relative)	RMSD (relative)	Correlation coefficient
Helsinki	2004-01–2009-12	70	114	6 (5%)	15 (13%)	0.995
Eskadalemuir	2004-01–2009-12	70	93	3 (3%)	11 (12%)	0.992
Vienna	2004-01–2009-12	72	134	−4 (−3%)	7 (5%)	0.998
Payerne	2004-01–2007-12	48	146	−9 (−6%)	13 (9%)	0.994
Carpentras	2004-01–2009-12	58	180	3 (2%)	10 (6%)	0.997
Nice	2004-01–2009-12	72	180	6 (3%)	11 (6%)	0.999
Aswan	2004-01–2005-12	24	259	−9 (−3%)	13 (5%)	0.986
Tamanrasset	2004-01–2007-12	48	267	9 (3%)	15 (6%)	0.977
Bulawayo	2004-01–2005-12	24	220	27 (12%)	32 (15%)	0.909
Inhamabe	2006-02–2007-10	17	209	18 (9%)	24 (11%)	0.942

The stations Bulawayo and Inhamabe stand apart due to the large bias. Nevertheless, the correlation coefficient is large and the RMSD is close to the bias: the month-to-month variations are well described by HC-3 with few errors, except the bias. We do not have a particular explanation to offer. There are a number of parameters in the Heliosat-2 method that influence its quality [16,17]. The ground albedo, the albedo of the brightest clouds, and the optical properties of the clear atmosphere are the most prominent. The cloud albedo and the optical properties are the same for HC-1 and HC-3. Given the good results observed for HC-1, we can hypothesize that they are not the main cause of the observed discrepancy. Ground albedo is difficult to assess [11] and it is possible that this was not done properly for these particular sites. Another influence is the natural variability of the SSI in space and time as discussed earlier [3,27]. If it is large for a site, then the chances of having a large discrepancy are greater for a small pixel (HC-3) than for a large one (HC-1). Finally, we should not forget that the calibration of the ground-based instrument may also be questioned. For Bulawayo, ground-based measurements are available for a long period, *i.e.*, from 1985 to 2005. We found that the performance of HC-1 are degraded for the years 2004 and 2005 compared to previous years: a bias of 8 W/m² for this two year period with a correlation coefficient of 0.900, compared to 2 W/m² for previous years. It is possible that the ground-based instrument displayed calibration defects during 2004 and 2005, rendering the comparison with HC-3 inappropriate. We do not have such a long time-series for

Inhamabe and could not perform a similar study. However, we found that for 2004 and 2005, the difference between HC-3 and HC-1 is 10 W/m^2. If we combine this with the results of HC-1 for Inhamabe (-10 W/m^2, Table 4), we can expect a bias between HC-3 and ground-based measurements close to 0. This only partly explains the observed bias and it is possible that the station Inhamabe experienced drawbacks in its measurements. Our belief is substantiated by the low relative bias (3%) found in the SoDa validation results for the station De Aar in South Africa, whose latitude and longitude are $-30.66\,°$ and $23.99\,°$.

6. Merging HC-1 and HC-3

We have shown that both HC-1 and HC-3 provided accurate time-series of SSI in their respective periods. Now, we faced a new challenge: can we create a single time-series out of the two databases, spanning from 1985 till now, and offering a consistent description of SSI with time?

Practically, this can be done by creating a first time-series from the HC-1 database, and then by augmenting it by adding the time-series from the HC-3 database. However, when concatenating the time-series, we are merging two data sets of different spatial properties which could create a jump in a time-series of SSI that is solely due to the change in spatial resolution at the junction of the two data sets [27]. The magnitude of the jump would depend on the actual underlying spatial variability of the SSI. The lower this variability, the lower the magnitude of the jump would be. In addition, as already discussed, the resampling in time of the B2 images induces limitations in the description of the daily mean of SSI. An additional jump would be created by this effect, whose magnitude depends on the temporal variability of the SSI [28]. Finally, the images, their calibration and their processing and post-processing, slightly differ between HC-1 and HC-3 which induces a difference in retrieved SSI.

To better understand the change in SSI due to the low number of images used to construct the daily means in HC-1, we studied the difference between HC-3 and HC-1 over the ocean for different latitudes. One can expect the spatial variability to be low over the ocean; studying only ocean pixels should enable us to mostly focus on the effects of the temporal resampling. HC-1 and HC-3 values were extracted for a few pixels over the ocean. We have computed the mean difference between HC-3 and HC-1 for the 23 common months in 2004 and 2005. To study the influence of the type of sky, we have also divided the HC-3 SSI by the corresponding irradiance at the top-of-atmosphere, yielding the clearness index, ranging from 0.4 (cloudy sky) to approximately 0.7 (clear sky). The differences in SSI for all pixels are ordered in three classes of latitudes and drawn as a function of the HC-3 clearness index (Figure 4). One can see that the difference between HC-3 and HC-1 has a tendency to increase with the absolute value of the latitude: this corresponds to the decreasing number of images available to construct the daily means. The difference decreases as the clearness index increases: it means that for a given range of latitude, the error due to the small number of images is smaller in case of clear skies. The difference ranges between 5 W/m²and 40 W/m²found at latitude 55 °. The analysis of the values reveals that the difference between HC-3 and HC-1 is approximately symmetrical between the Northern and Southern hemispheres. The lowest values ($\sim$10 W/m^2, $\sim$3% in relative value) are the typical difference that one can expect between HC-3 and HC-1, as a result of the differences in input images, calibration and processing.

Figure 4. Difference in the 23-month means of SSI between HC-3 and HC-1 for ocean pixels; ordered in three classes: Low latitude: [−20°, 20°]; Mid-latitude: [−45°, 25°] and [25°, 45°]; High latitude: less than −50° and greater than 50°.
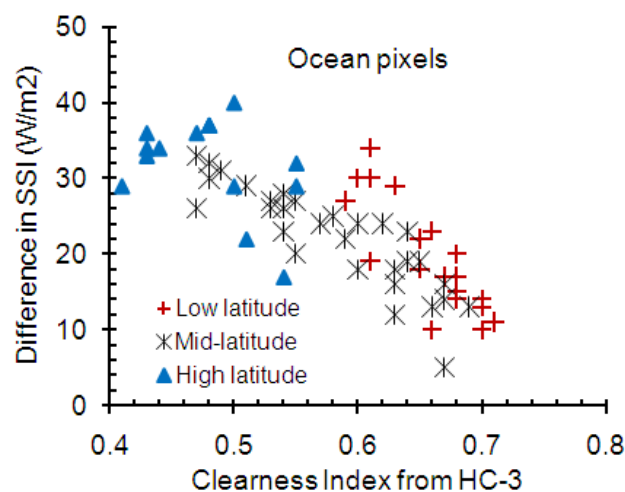
It follows from the above discussion that a discrepancy can be expected when associating time-series of the two databases whose magnitude is a difficult-to-predict function of space and time. We illustrate this conclusion by four examples: Vienna, Nice, Aswan and Bulawayo. We have computed the yearly means of SSI by averaging the twelve monthly means for each year, when available. These yearly means are reported in Figures 5 and 6, which represent ground-based measurements: HC-1 for the period 1985–2005; and HC-3 for 2004–2009, as a function of year. In order to better observe the quality of HC-1 and HC-3 in depicting changes in yearly means of SSI, we have filled the gaps in for July 1986 for HC-1 with ground-based measurements when available and in January 2004 for HC-3 with HC-1 data. We can thus observe the whole time-series as well as the transition between the two databases.

Figure 5. Yearly means of SSI from 1985 to 2009: **(a)** Vienna; **(b)** Nice.

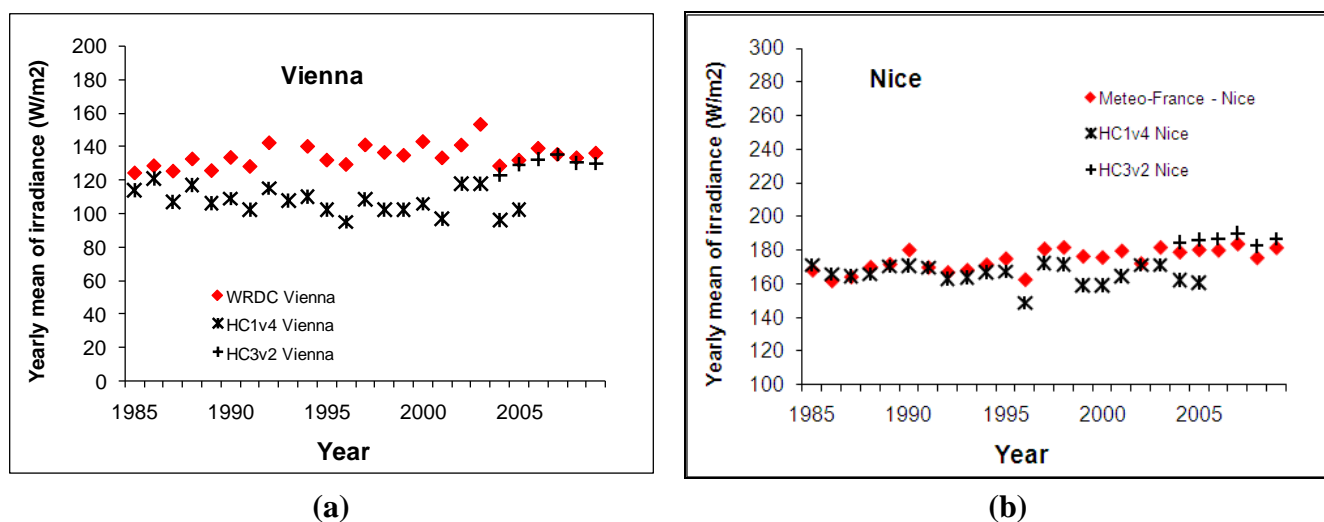**(a)**   **(b)**

Figure 5 depicts the yearly means for the Vienna and Nice sites. Ground-based measurements were available in Vienna for the whole period, except 1993. One can see that except in 1985 and 1986, HC-1

underestimates the SSI. There is a positive trend in Vienna: the ground-measured SSI increases from 1985 to 2003, then a sort of plateau follows. The HC-1 time-series does not reproduce these changes; on the contrary, it has a tendency to decrease as the years increase. However the HC-3 time-series are in agreement with the ground-based measurements. The transition between HC-1 and HC-3 in 2004 and 2005 is marked, and the differences are identical (27 W/m^2). Similar observations on transitions are made for Helsinki, Eskadalemuir, and Payerne: a marked difference constant with year. We believe that the temporal resampling is the main cause for the transition.

Ground-based measurements at Nice show a positive trend over the years: the SSI increases from 1985 to 2009. The HC-1 time-series is in good agreement with ground measurements from 1985 to 1995. In the following period, HC-1 underestimates the SSI. HC-1 does not reproduce the positive trend of the SSI. We do not have any explanation for the turning point 1996: it corresponds to a change in satellite but the other sites do not show a similar behavior. It is more likely related to a change in cloud cover that cannot be reproduced correctly because of the temporal sampling in the B2 data set. Looking at data in more detail, we observe that after 1995, HC-1 underestimates the SSI for all months with unstable climate, *i.e.*, in spring and autumn, yielding an underestimation of the yearly mean. However, the HC-3 time-series is in good agreement with the ground-based measurements. It reproduces the positive trend observed in Nice from 2005 to 2009. The transition between HC-1 and HC-3 in 2004 and 2005 is marked (24 W/m^2). It does not vary by year as in Tamanrasset, and unlike Carpentras (22 W/m^2 in 2004 and 14 W/m^2 in 2005). We believe that the main cause of the jump in Tamanrasset is the post-processing in HC-3. The situation is more complex in Nice and Carpentras where we should add effects on the time sampling and spatial variability to explain the magnitude of the transition.

Figure 6. Yearly means of SSI from 1985 to 2009: **(a)** Aswan. **(b)** Bulawayo.

(a)   **(b)**
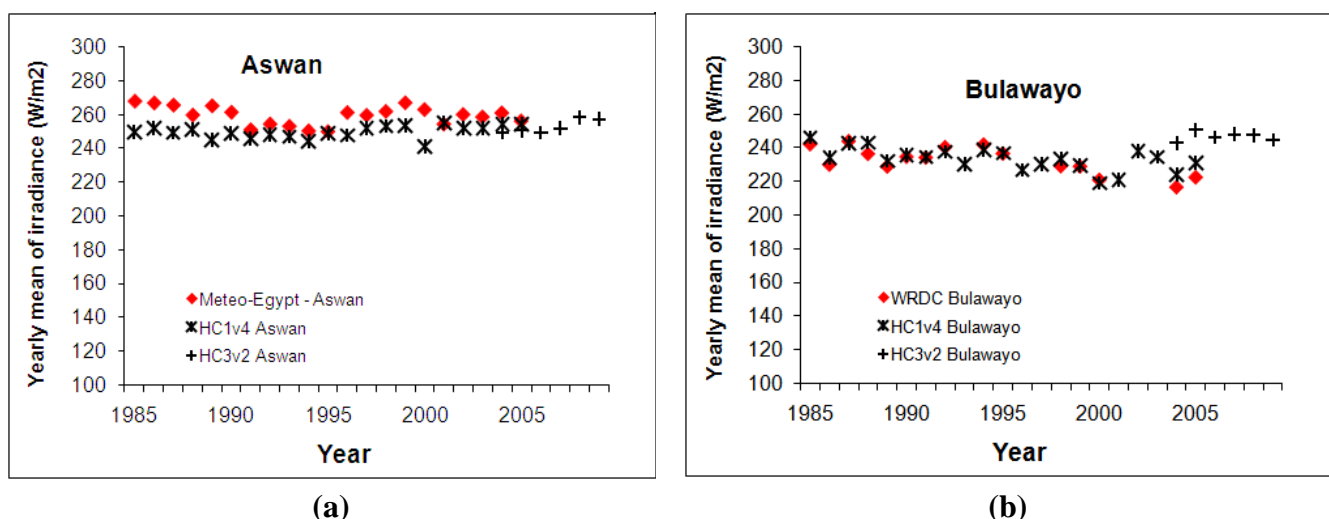
Figure 6 depicts the yearly means of SSI for the sites Aswan and Bulawayo. Ground measurements for Aswan show a negative trend from 1985 to 1995 then a slight increase; this finding was reported by [26]. These trends are not evidenced in the HC-1 time-series though they can be faintly observed. From 1985 to 1990, HC-1 underestimates the SSI. From 1991 to 2005, the underestimation is still there, but the agreement is much better. The HC-3 time-series is in agreement with the ground

measurements. The magnitude of the jump between HC-1 and HC-3 is constant in 2004 and 2005 yet small: 5 W/m ²and 4 W/m ², because of the counter-balancing of two following effects. The influence of the change in spatial resolution can be assessed by computing the yearly means of SSI from HC-3 for an area of 20 km in radius around the measuring site. The difference between the SSI for a single pixel and the spatial average is approximately -10 W/m^2. Therefore, one expects the HC-1 value to be larger than HC-3. However, the post-processing in HC-3 increases the very large SSI found in Aswan in summer by 10 W/m^2, thus counter-balancing the effect of spatial resolution. The situation is the same in Sidi Bou Said: -1 W/m^2 in 2004 and 1 W/m^2 in 2005.

As for Bulawayo, we have already questioned the ground-based measurements in 2004 and 2005. Not taking these two years into account, one observes a negative trend over the years: *i.e.*, the SSI decreases from 1985 to 2000. The HC-1 time-series is in good agreement with these measurements and clearly depicts the trend. The agreement with the HC-3 time-series is fairly good. Change in spatial resolution and post-processing may explain the jump between HC-1 and HC-3, which is the same in 2004 and 2005: 19 W/m^2. The station Inhamabe offers the same situation with a jump of 11 W/m^2 for both years.

The graphs above show that no simple and universal relationship exists between HC-1 and HC-3. Nevertheless, in many cases, the bias between HC-3 and HC-1 is small and acceptable given the current state of knowledge on SSI, especially in Africa. Therefore, one can fuse HC-1 and HC-3 by a concatenation of values provided caution is taken when analyzing the resulting time-series. For a given site, it may be possible to derive a statistical relationship between daily values of HC-1 and HC-3—e.g., a relationship between the clearness indices—and thus to reconstruct a time-series, consistent with HC-3.

7. Conclusions

We have discussed several challenges that one has to face when creating long-term databases of daily means of SSI: changes in sensors, changes in calibration for a given sensor, changes in space and time sampling, and resolution of the sensors and used images. Such issues are not new [4,5,8]. We coped with them by doing our best within our limited resources.

Consistency in time was a keyword in the HelioClim Project for all aspects, from input data to dissemination. The processing method, Heliosat-2, and the dissemination tool, SoDa Service, were two pillars in our project that we borrowed from other research initiatives, allowing us to concentrate on (i) the calibration and pre-processing of images to create consistent series of images of radiance, (ii) the assessment of the quality of the retrieved SSI, and (iii) operational aspects. The latter has not been discussed here as it does not offer any particular scientific interest though setting up and running such operations is very demanding. The efforts made have been rewarded by the large number of requests made for our databases: approximately 10,000 time-series of daily and monthly time-series of SSI are supplied per year.

We have shown that the HC-3 database provides accurate values of SSI for Africa, Europe, and the Atlantic Ocean. Due to its use of B2 images of reduced spatial and temporal resolutions, the HC-1 database offers good quality only for Africa, the Mediterranean Basin, the Central Atlantic Ocean, and more generally for latitudes comprised between $-45°$ and $45°$. We have shown that it is possible to

easily construct time-series of daily, monthly or yearly means of SSI, from 1985 up to date. However, caution should be taken in the analysis of such time-series, as the difference in processing, spatial and temporal resolutions, between HC-1 and HC-3, may lead to a jump between the period covered by HC-1 (1985–2005) and that of HC-3 (since 2004). The common period (2004–2005) may help in detecting such cases.

Even if uncertainty is currently too great for accurate analyses of climate, the availability of these time-series for virtually any location in the field-of-view of the Meteosat satellites should help any community interested in climate applications to perform steps towards a better knowledge of the SSI and its variation over recent years.

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