

Article

Applying and Improving Pyranometric Methods to Estimate Sunshine Duration for Tropical Site

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Abstract: The aim of this paper is to apply all the existing pyranometric methods to estimate the sunshine duration from global solar irradiation in order to find the most suitable method for a tropical site in its original form. Then, in a second step, one of these methods will be optimized to effectively fit tropical sites. Five methods in the literature (Step algorithm, Carpentras Algorithm, Slob and Monna Algorithm, Slob and Monna 2 Algorithm, and linear algorithm) were applied with eleven years of global and diffuse solar radiation data. As a result, with regard to its original form, the step algorithm is in the first rank. But in the second step, after improving its main coefficients, the Carpentras Algorithm was found to be the best algorithm for tropical sites in the southern hemisphere.

Keywords: Carpentras method; data fitting; global radiation; sunshine duration; Slob and Monna algorithm; step algorithm; linear algorithm



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1. Introduction

The sunshine duration (SD) for a given period is the sum of sub-periods for which the direct solar beam irradiance exceeds 120 Wm^{-2} . It is an important parameter for climatology, tourism, agriculture, and the solar energy industry. According to the World Meteorological Organization (WMO) in its Guide to Instruments and Methods of Observation in [1], the following two methods can be used to measure the SD. The first is the pyrheliometric method, in which a pyrheliometer with a suitable timer is installed on a two-axis solar tracker that directly measures the direct solar beam irradiance. In the second method, which is an indirect approach, two pyranometers first measure the global and diffuse radiation on a horizontal plane; the difference between them gives the direct irradiance on the horizontal surface; and after dividing this latter measurement by the sine of solar angle elevation, the direct solar beam irradiance can be found.

Due to the high cost of purchase, installation, and maintenance, especially for the pyrheliometer method, it is not always possible to have the requested facilities measure the sunshine duration everywhere. So, several studies have been conducted to estimate the SD by the global radiation (G) on the horizontal surface measured by a pyranometer, which are the most available data on solar radiation. All these methods, called pyranometer methods [2–4], are based on a long period of time comparison of the direct solar beam irradiance measured by a pyrheliometer with the global irradiance on a horizontal surface. The comparison is performed inside a station member of the Baseline Station Radiation Network (BSRN) community because a BSRN station has suitable facilities and is also a reference for solar radiation measurement. The result can be used worldwide or for other locations with similar latitude and/or meteorological conditions.

But most of these algorithms were fitted mainly for the northern hemisphere, and in this study, the question of validity and applicability of these algorithms for the tropics

and southern hemisphere arises. So, the aim of the present paper is to first list all existing pyranometric methods, then apply them to a database for a tropical site in the southern hemisphere in order to estimate their uncertainties and find out the most suitable for tropical sites. In the end, one of these algorithms was optimized for the site's database by improving its main coefficients to effectively fit a tropical location in the southern hemisphere. As mentioned above, the task is to compare the measured reference sunshine duration and the sunshine duration computed by the algorithms. In the present work, the reference was obtained by an indirect method, i.e., computing the solar direct beam radiation by the measure of the global and diffuse radiation on the horizontal plane and the solar elevation angle. The site is located inside the University of Reunion Island, Indian Ocean, in the center of the Saint-Pierre locality (latitude -21.34°). The database of global and diffuse radiation was measured for eleven years. Geographically, the Reunion Island is a member of the community of Indian Ocean Islands, which also includes Madagascar, Mauritius, Seychelles, the Maldives, and Comoros.

This paper is composed of six sections. The Section 1 is the introduction. Then, the methodology section is presented, where the following will be explained: the database, the indirect method to estimate the solar direct beam radiation, all the existing pyranometric methods, the data quality control protocol, and the statistical methods to evaluate the uncertainty and quality of the different algorithms. The Section 3 is about the result where statistical analysis of SD reference versus calculated SD by pyranometric methods, in its original form, is performed. The Section 4 is focused on improving one pyranometric method with its result. The Section 5 is devoted to discussion, and the Section 6 deals with the conclusion.

2. Materials and Methods

2.1. The Database

The database consists of measurements taken over eleven years (2007–2017) and contains times, dates, and global (G) and diffuse (D) irradiance on the horizontal surface, which are based on every minute average recording. The other astronomical data like solar azimuth, elevation angle (el), and declination angle (δ) are calculated by Michalsky's Algorithm in [5], which is the recommended method according to the World Meteorological Organization [1]. The value of the mean extra-terrestrial global irradiance is according to [6].

2.2. The Reference Sunshine Duration

The direct irradiance on a horizontal surface (I_h) is the difference between the global and diffuse

$$I_h = G - D \quad (1)$$

The direct solar beam radiation (I) is obtained by the division of the direct radiation on the horizontal surface and the sine of the solar elevation angle el .

$$I = \frac{I_h}{\sin(el)} \quad (2)$$

So, the reference sunshine duration (SD_{ref}) is estimated per minute; if I is greater than or equal to the threshold of $120 \text{ W}\cdot\text{m}^{-2}$, then $SD_{ref} = 1 \text{ min}$; otherwise, $SD_{ref} = 0$. To avoid an abnormally high value of I for a low elevation angle on sunrise and sunset, a minimum value of the solar elevation angle is posed below which the solar beam is considered inferior to $120 \text{ W}\cdot\text{m}^{-2}$, so the calculus of I is not performed, and SD_{ref} is always zero. This minimum angle is set to 3° to equal the minimum angle for the different pyranometric algorithms, especially for the Meteo France Algorithm [3,4] and the modified Slob and Monna Algorithm [2,4]. The unit of the sunshine duration can be an hour per day [h/day] or an hour per year [h/year].

2.3. Data Quality Control Protocol

This protocol was developed inside the Baseline Station Radiation Network (BSRN) community, as seen in [7]. Some intervals for each parameter (G , D , and I) are analyzed; this is also the case for their combination or ratio. If the data exceed these intervals, they are considered as erroneous and excluded from the study. So, a flag is associated with every minute recording; if the value is good according to the protocol, the flag is set to zero; otherwise, the flag is set to a nonzero number. Only the data with flags equal to zero are used to estimate SD. The same protocol is repeated for the algorithm using 10 min average of global irradiation. The average value of G , D , and I for 10 min is calculated and then the quality control is applied to it.

2.4. The Pyranometric Methods

2.4.1. Step Algorithm (SA)

This algorithm is detailed in [4,8]. The averaged value of global irradiance G per minute is compared with a simplified threshold G_{s1} .

If $G \geq G_{s1}$ then $SDSA = 1$ min, otherwise $SDSA = 0$ min, where

$$G_{s1} = 0.4I_0 \sin(el) \quad (3)$$

I_0 is the solar extra-terrestrial irradiance (solar constant) that value is 1367 W/m^2 according to [3].

The sunshine duration of the step algorithm (SDSA) is calculated every minute, and the sum during a day gives the hour/day sunshine duration.

2.4.2. Carpentras or Meteo France Algorithm (MFA)

This method is detailed in [3,4]. Like the step algorithm, the averaged value of global irradiance per minute is compared to a threshold, G_{s2} .

If $G \geq G_{s2}$ and $el \geq 3^\circ$ then $SDMFA = 1$ min, otherwise $SDMFA = 0$ min

$$G_{s2} = 1080F_C (\sin(el))^{1.25} \quad (4)$$

$$F_C = A + B \cos\left(\frac{360d}{365}\right) \quad (5)$$

The argument of the cosine is degrees, and d is the day number for the year. For example, $d = 32$ for February 1st. From [4], Table 1 lists the values for A and B for some BSRN stations.

Table 1. Coefficients for Carpentras or Meteo France Algorithm.

BSRN Station	Latitude	A	B
Momote	-2°	0.68	-0.06
Tamanrasset	22°	0.77	0
Tateno	36°	0.73	0.05
Boulder	40°	0.67	0.06
Carpentras	44°	0.71	0.05
Payerne	47°	0.75	0.06
Palaiseau	48°	0.75	0.04
Cabauw	52°	0.77	0.06
Toravere	58°	0.74	0.06

As can be seen, most of the fitting was performed in the northern hemisphere; only the Momote station is situated in the southern hemisphere, but it is nearer to the equator than the Reunion Island's latitude. However, Momote's coefficients will be used in this study because they are only available for the southern hemisphere. Table 1 shows that B coefficient is positive for positive latitude and seems to be negative for southern hemisphere. At this point, saying that B coefficient is negative for the southern hemisphere is just an intuition because there is only one measuring station for negative latitude in the list, unlike the eight other measuring stations, which confirm that B is positive for the north. By Table 1 also, it can be assumed that B value is inside the interval $[-0.06, 0.06]$. For the A coefficient, it seems that the value is always positive for any hemisphere and inside the interval $[0.6, 0.8]$. Nevertheless, as it can be found later in the improvement section of the present method, these intuitions and assumptions will be helpful. Like SA, the daily SD is determined by the sum of per minute SD_{MFA} .

2.4.3. Slob and Monna Algorithm (SMA)

This method, detailed in [2,9,10], is based on the estimation of direct and diffuse radiation. The daily SD is the sum of 10 min SD. Three values of the 10 min global irradiance are needed: the average G , the maximum G_{max} , and the minimum G_{min} . For each 10 min, a fraction coefficient $f \in [0, 1]$ is calculated, and the SD for SMA is $SDSMA = f * 10$ min. If $f = 0$, there is no sunshine; if $f = 1$, there is sunshine. If $0 < f < 1$, there are intermittent clouds during the 10 min period. The method is based on the estimation of the direct solar beam and diffuse irradiance on a horizontal surface. The direct solar beam is estimated by the following:

$$I = I_0(r_0/r)^2 \exp(-T_L / (0.9 + 9.4 \sin(el))) \quad (6)$$

with

I_0 the solar constant 1366 W/m² by [11]

r_0 , the mean earth-sun distance

r , the actual value of earth-sun distance

T_L , Linke turbidity factor

el , solar elevation angle

and

$$\mu_0 = \sin(el) \quad (7)$$

The extra-terrestrial global irradiance on a horizontal surface is

$$G_0 = I_0 \left(\frac{r_0}{r} \right)^2 \mu_0 \quad (8)$$

It is the normalized value of I , G , and D compared to G_0 that is used. There is sunshine if the global is higher or equal to a limit that is the sum of the estimated direct and diffuse irradiance; it means the following:

$$G/G_0 \geq (G/G_0)_{lim} \quad (9)$$

$$(G/G_0)_{lim} = \mu_0 I/G_0 + D/G_0 \quad (10)$$

$$\mu_0 I/G_0 = \exp(-T_L / (0.9 + 9.4 \mu_0)) \quad (11)$$

Regarding the diffuse D , the value of T_L depends on the solar elevation. The algorithm can be summarized Algorithm 1:

Algorithm 1 Slob & Monna Algorithm

```

if  $\mu_0 < 0.1$                                 then  $f = 0$  (sun too low,  $el < 3^\circ$ )
if  $0.1 \leq \mu_0 < 0.3$ 
     $T_L = 6$ 
     $D/G_0 = 0.2 + \mu_0/3$ 
    if  $G/G_0 \geq (G/G_0)_{lim}$                 then  $f = 1$  else  $f = 0$ 
if  $\mu_0 \geq 0.3$ 
     $T_L = 10$ 
     $D/G_0 = 0.3$ 
    if  $G_{max}/G_0 < 0.4$                         then  $f = 0$  else
    if  $G_{min}/G_0 > (G/G_0)_{lim}$                 then  $f = 1$  else
    if  $(G_{max}/G_0 > (G/G_0)_{lim})$  and  $(G_{max}/G_0 - G_{min}/G_0) < 0.1$  then  $f = 1$  else
     $T_L = 4$ 
     $\frac{D}{G_0} = 1.2G_{min}/G_0$ 
    if  $D/G_0 > 0.4$                             then  $D = 0.4$ 
     $f = (G/G_0 - D)/(\mu_0 I/G_0)$ 

```

2.4.4. Slob and Monna Algorithm 2 (SMA2)

This is an improvement of the SMA, as seen in [2,9]. The algorithm is summarized on the following points:

- The minimum angle is brought down for $\mu_0 = 0.1$ to $\mu_0 = 0.05$
- Estimate the intermittent clouds in the $0.05 \leq \mu_0 < 0.3$ interval
- For $0.05 \leq \mu_0 < 0.3$, $T_L = 4$ and $D/G_0 = 0.02 + 1/(20\mu_0 + 4)$ for limit calculus, then $T_L = 2.5$ to estimate intermittent clouds.
- For $\mu_0 \geq 0.3$, $T_L = 5$ for limit calculus and $D/G_0 = 0.01 + 1/(20\mu_0 + 4)$, then $T_L = 4$ to estimate intermittent clouds.
- $D/G_0 = 0.3$ to estimate intermittent clouds.

2.4.5. Linear Algorithm (LA)

References [2,9] show this method. By always using a 10 min period, this method only needs the 10 min average of the global. It is a direct and linear correlation. The algorithm is summarized Algorithm 2:

Algorithm 2 Linear Algorithm

```

For  $\mu_0 < 0.3$ 
    if  $G/G_0 < l_1$                         then  $f = 0$ 
    if  $l_1 \leq G/G_0 < u_1$                 then  $f = (G/G_0 - l_1)/(u_1 - l_1)$ 
    if  $G/G_0 \geq u_1$                     then  $f = 1$ 
For  $\mu_0 \geq 0.3$ 
    if  $G/G_0 < l_2$                         then  $f = 0$ 
    if  $l_2 \leq G/G_0 < u_2$                 then  $f = (G/G_0 - l_2)/(u_2 - l_2)$ 
    if  $G/G_0 \geq u_2$                     then  $f = 1$ 

```

The value of the different coefficients is in Table 2.

Table 2. Coefficients for linear algorithm.

l_1	u_1	l_2	u_2
0.4	0.5	0.45	0.6

2.5. Statistical Analysis of the Results

The main data are the daily sunshine duration (SD) [h/day]. SD_x means the SD calculated by whichever algorithm; SD_{ref} is the daily SD reference. The following parameters and tasks are calculated or performed;

- N : Number of experimental points (daily SD).

- *totdif* [h]: cumulative difference of daily sunshine duration between the algorithm and the reference in hours

$$totdif = \sum_{i=1}^{i=N} (SDx_i - SDref_i) \quad (12)$$

The closer *totdif* is to zero, the better the algorithm is. If *totdif* is positive, the method overestimates the sunshine duration, and conversely, if it is negative, the method underestimates the sunshine duration.

- *rtotdif* [%]: relative cumulative difference of daily sunshine duration between the algorithm and the reference.

$$rtotdif[\%] = 100 \frac{\sum_{i=1}^{i=N} (SDx_i - SDref_i)}{\sum_{i=1}^{i=N} SDref_i} \quad (13)$$

rtotdif can be positive or negative like *totdif*; the best method is the one whose *rtotdif* is close to zero.

- *nrmse* [%]: the normalized root mean square error of each algorithm

$$nrmse[\%] = 100 \frac{rmse}{SDref_0} \quad (14)$$

where *SDref₀* is the mean value of the daily sunshine duration for the reference and *rmse* is the algorithm's root mean square error. These are shown below.

$$SDref_0 = \frac{\sum_{i=1}^{i=N} SDref_i}{N} \quad (15)$$

$$rmse = \sqrt{\frac{1}{N} \sum_{i=1}^{i=N} (SDx_i - SDref_i)^2} \quad (16)$$

The best method has the smallest *nrmse*.

- *mdd* [h/day]: mean value of the daily differences between the algorithm and the reference.

$$mdd = \frac{\sum_{i=1}^{i=N} SDx_i - SDref_i}{N} \quad (17)$$

mdd can be positive or negative; the best method is the one whose *mdd* is close to zero.

- *sdd* [h/day]: standard deviation of the daily differences between the algorithm and the reference.

$$sdd = \sqrt{\frac{1}{N-1} \sum_{i=1}^{i=N} (SDx_i - SDref_i - mdd)^2} \quad (18)$$

The smaller the standard deviation is, the better the method is.

- *U95* [h/day]: uncertainty interval that contains 95% of daily differences.
- Scatter plot SDx versus SDref with linear fitting.
- Plot of cumulative differences for the eleven years with *totdif* and *rtotdif*.
- Plot of the histogram of daily differences with skewness.

3. Results

3.1. Scatter Plot with Linear Fitting

Figures 1–3 show the scatter plot of SDx versus SDref. Linear fitting is also calculated and plotted in the red line, whereas the diagonal is in the black line. The number of measuring points is *N* = 4018.

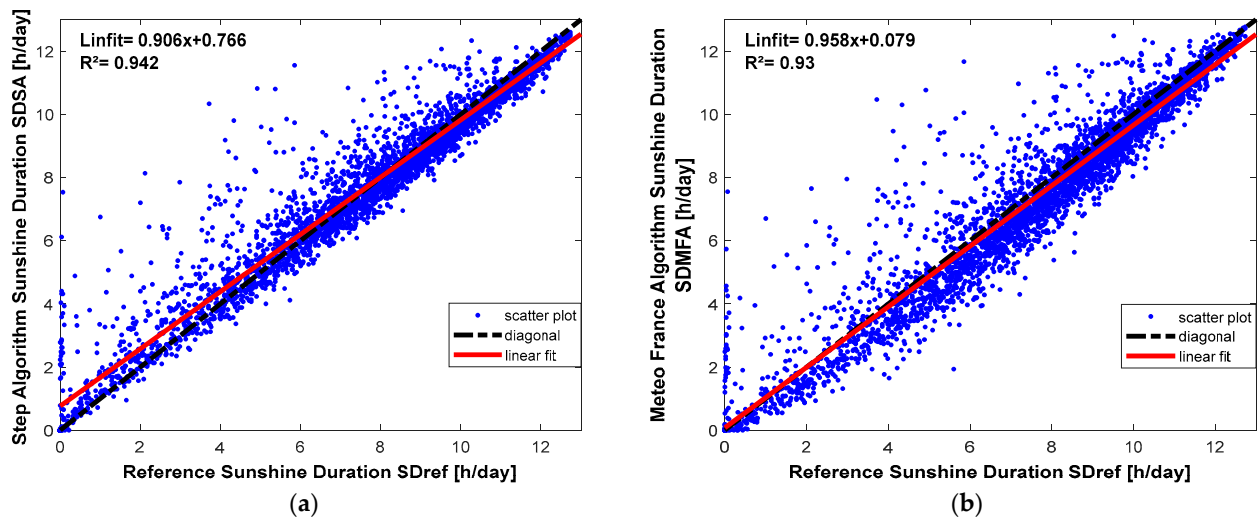


Figure 1. Scatter plot with linear fitting: (a) Step algorithm vs. reference; (b) Meteo France Algorithm vs. Reference.

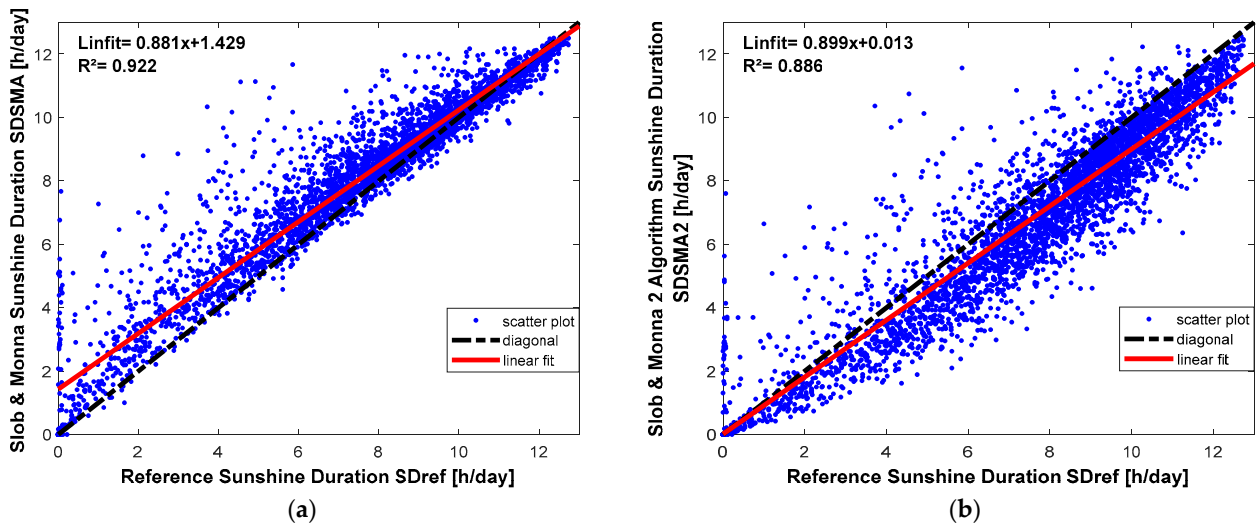


Figure 2. Scatter plot with linear fitting: (a) Slob and Monna Algorithm vs. Reference; (b) Slob and Monna 2 Algorithm vs. Reference.

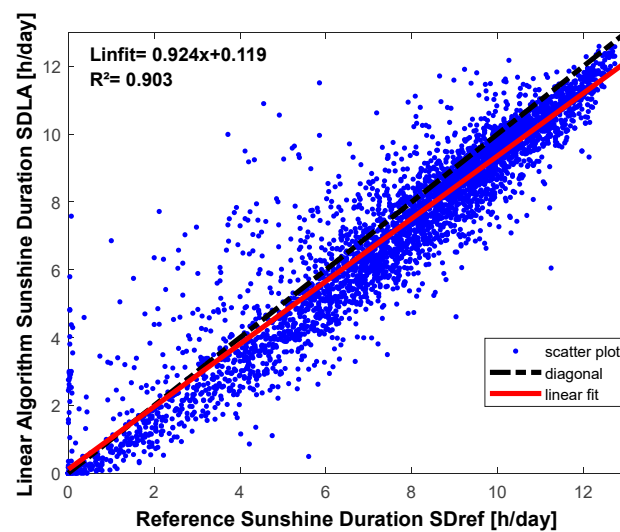


Figure 3. Scatter plot of linear algorithm vs. reference with linear fitting.

By Figure 1a, for the step algorithm, there is, on average, an overestimation for sunshine duration of less than 8 h/day, and conversely, there is an underestimation for sunshine duration of more than 8 h/day. For the Meteo France or Carpentras Algorithm, as seen in Figure 1b, the linear fitting practically overlaps on the diagonal for SD less than 4 h/day, and for higher values, there is underestimation. So, in general, the Meteo France Algorithm underestimates the sunshine duration. Figure 2 shows the two Slob and Monna Algorithms.

Figure 2 shows that Slob and Monna Algorithm overestimates the sunshine duration, whereas the Slob and Monna 2 Algorithm underestimates it. Finally, Figure 3 gives the situation for the linear algorithm.

By Figure 3, it can be concluded that the linear algorithm also underestimates the sunshine duration.

3.2. Plot of Total and Relative Cumulative Differences

Figure 4 shows the total cumulative differences in hours (*totdif*), the total relative cumulative differences in percentage (*rtotdif*) between algorithms and the reference for the eleven years, and a zoom for the first three years.

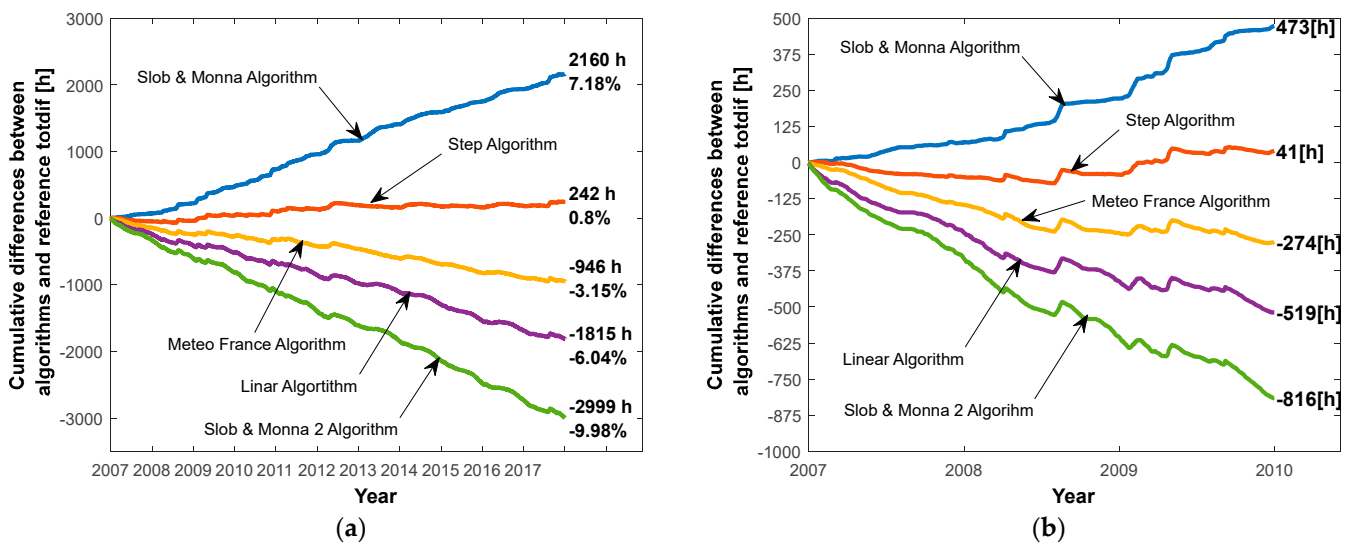


Figure 4. Total and relative cumulative differences between algorithms and the reference: (a) For the eleven years; (b) Zoom for the first three years.

Regarding Figure 4a, the step algorithm gives the best result with 0.8% of the total relative difference, followed by the Meteo France Algorithm with −3.15%. As already shown in Figures 1–3, Figure 4a confirms that the Meteo France Algorithm, Slob and Monna 2 Algorithm, and linear algorithm underestimate the SD, whereas the Slob and Monna Algorithm overestimates. The zoom in Figure 4b gives the behavior of the different curves for the first three years. For the step algorithm, the cumulative difference is negative for the two first years, 2007 and 2008. From the third year, 2009, the cumulative differences for the step algorithm became positive. For the other methods, the tendency or behavior of the cumulative difference curve is the same, whether it is for the first three years or for the first eleven years. The following plots are for the histogram of daily differences for each method with the experimental mean of daily differences (*mdd*) and standard deviation of daily differences (*sdd*). The skewness (*skw*) of the histogram is also shown, and its formula is the one used in [6]. If x_i is the daily difference between SDx and SD_{ref} , the skewness is

$$skw = \frac{N}{(N-1)(N-2)} \frac{\sum_{i=1}^N (x_i - mdd)^3}{sdd^3} \quad (19)$$

The last information with the histogram is the U95 interval that holds 95% of the value of x_i . So, it represents the uncertainty interval for the method. Thus, Figure 5 gives the histogram for the Step Algorithm and Meteo France Algorithm. Figure 6 shows the histogram for Slob & Monna Algorithm and its revised version. Finally, Figure 7 shows the histogram for the Linear Algorithm.

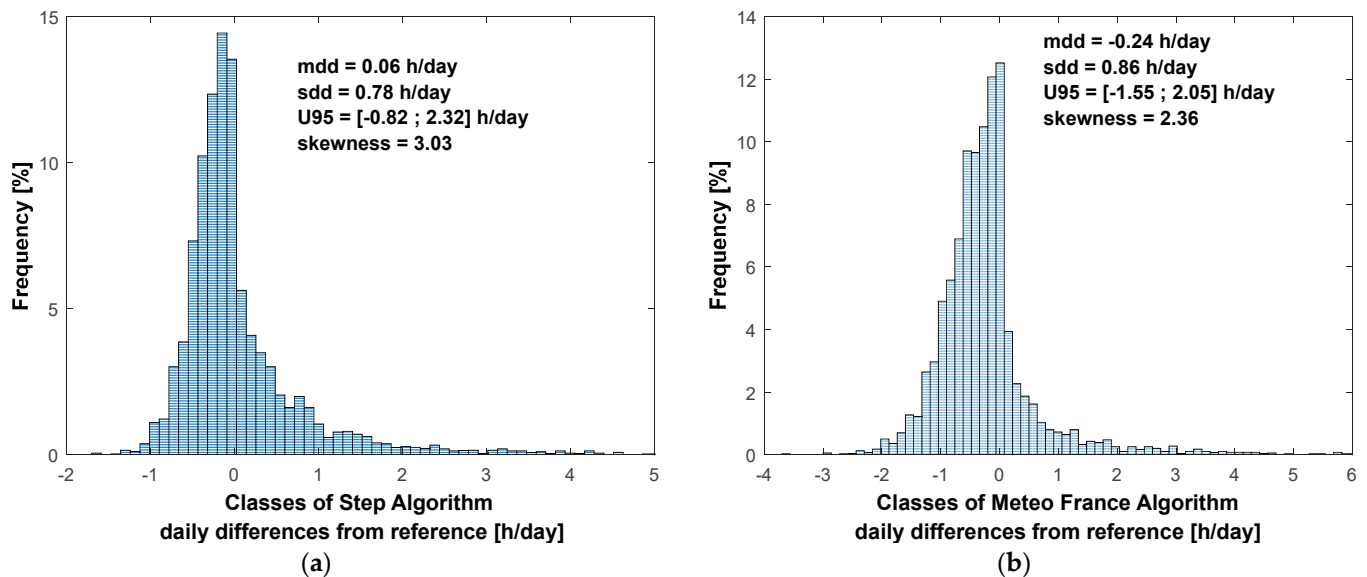


Figure 5. Histogram and statistical parameters: (a) Step algorithm; (b) Meteo France Algorithm.

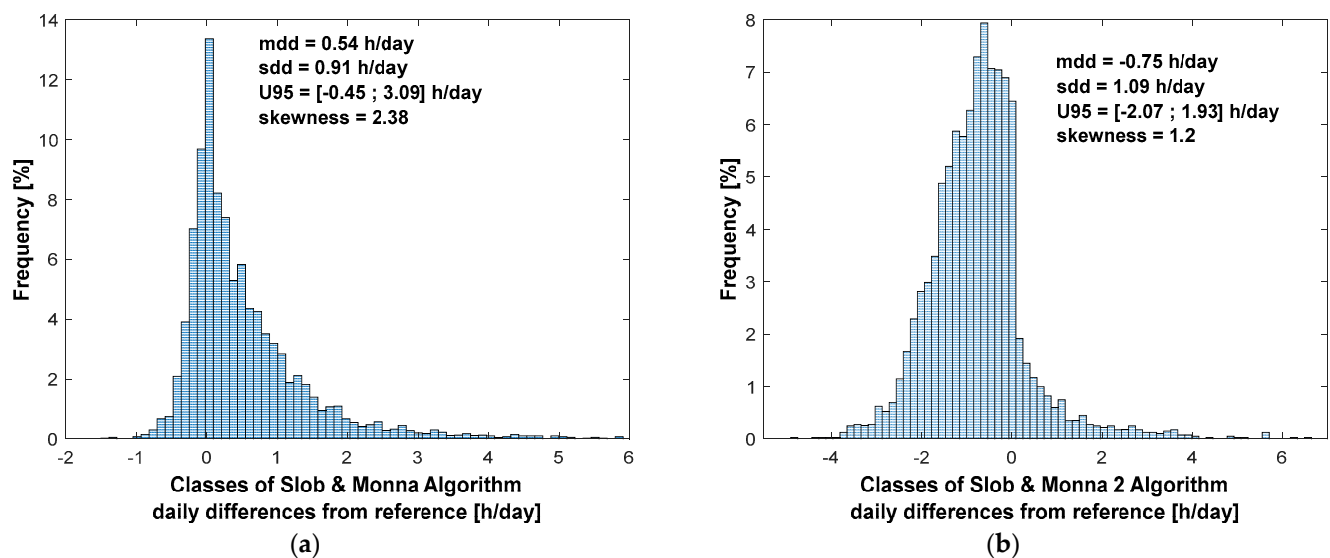


Figure 6. Histogram and statistical parameters: (a) Slob and Monna Algorithm; (b) Slob and Monna 2 Algorithm.

Table 3 summarizes the statistical performance indicators of the five methods. The *spanU95* datum is the length or size of the U95 uncertainty interval that holds 95% of the daily differences value between algorithms and the reference. As mentioned in Section 2.5, for each parameter, the best method is the one whose parameter value is the smallest or close to zero.

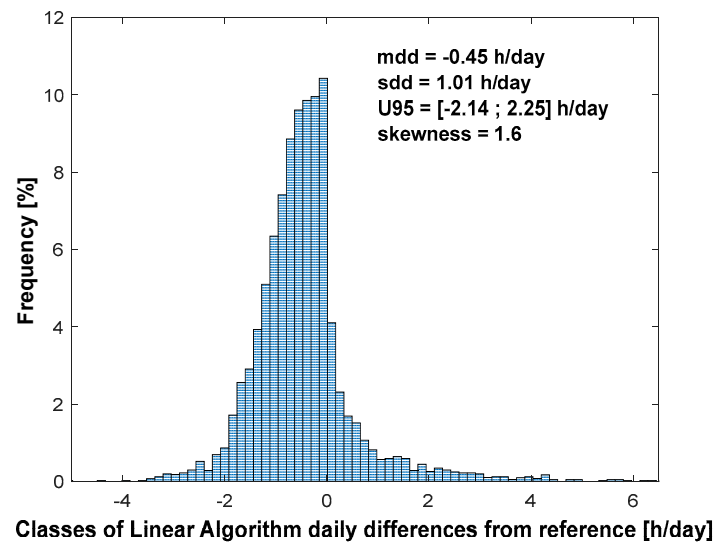


Figure 7. Histogram and statistical parameters for linear algorithm.

Table 3. Statistical performance indicators for each algorithm.

Statistical Parameters	Step Algorithm	Meteo France Algorithm	Slob and Monna Algorithm	Slob and Monna 2 Algorithm	Linear Algorithm
Mean daily differences <i>mdd</i> [h/day]	0.06	−0.24	0.54	−0.75	−0.45
Standard deviation of daily differences <i>sdd</i> [h/day]	0.79	0.86	0.91	1.09	1.01
Span <i>U95</i> [h/day]	3.13	3.6	3.54	4.64	4.4
Total cumulative differences <i>totdif</i> [h]	242	−946	2160	−2999	−1815
Relative cumulative differences <i>rtotdif</i> [%]	0.8%	−3.15%	7.18%	−9.98%	−6.04%
Normalized Root Mean Square Error <i>nrmse</i> [%]	10.57%	11.96%	14.17%	17.71%	14.82%

Obviously, the step algorithm is the best among the existing methods on their original form. It has the lowest total (242 h) nearest to zero, the lowest relative cumulative differences (0.8%), and the lowest normalized root mean square error (10.57%). The step algorithm also has the mean daily differences nearest to zero (0.06 h/day) with the lowest dispersion value because it has the smallest standard deviation for the mean (0.79 h/day), and of course, the step algorithm has the smallest length of the interval containing 95% of the daily difference values. On the second rank is the Carpentras or Meteo France Algorithm, with −3.15% of relative cumulative differences and almost 12% as normalized root mean square error, followed by the linear algorithm and the two Slob and Monna Algorithms. The next step is to identify the method that can be improved for tropical sites. It can be seen that the Meteo France Algorithm is in the second rank and that its uncertainties are not too high; it is a suitable candidate to be improved.

4. Improving the Meteo France Algorithm

The improvement is to adjust the method for the local database. Practically, it means finding the proper value for *A* and *B* coefficients. Table 1 shows already that these coefficients should be adjusted following the latitude, and the coefficients for Momote's station are the starting points because this site is in the southern hemisphere. As indicated by [5–7], the determination of *A* and *B* coefficients is an empiric approach. Following the intuitions and assumptions in Section 2.4.2, seen that the site's latitude is further south than Momote's

station, it is quite plausible to think that A coefficient will have a positive value lower than the coefficient of Momote's station (0.68) and B coefficient will be negative around the value of Momote's station (-0.06).

After many trials, two intervals for the two coefficients were set up as $[0.59, 0.65]$ for A and $[-0.09, 0]$ for B . Then, the cumulative difference for the eleven years, for all possible combinations of A and B values by step of 0.01 inside the two above-mentioned intervals, were calculated in order to find the couple of values that minimize the cumulative error. So, by step of 0.01, there are seven possible values for A and ten values for B . In total, there are 70 combinations of A and B values. Figure 8 gives the plot of the relative cumulative error for eleven years for each combination. On the horizontal axis is the order number of the combination, and on the vertical axis is the relative total cumulative difference.

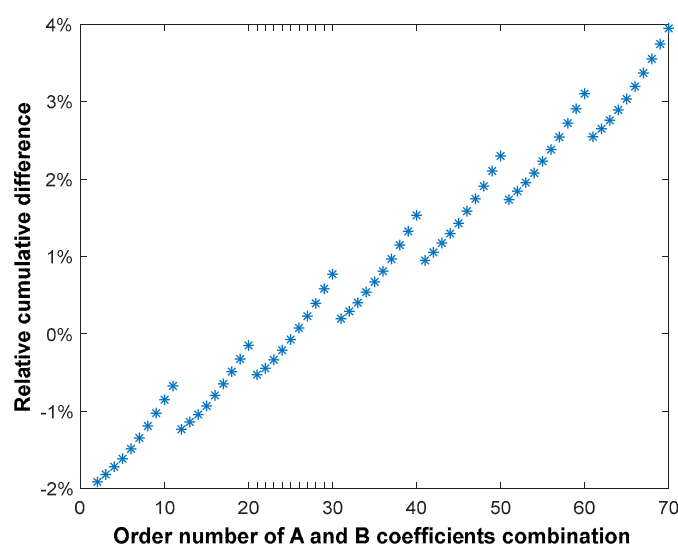


Figure 8. Relative cumulative differences for the 70 possible combinations of A and B values.

The best combination is the one whose relative cumulative difference is close to zero. According to Figure 8, it is for the 25th and 26th combination. For the 25th, the result is -0.0735% , and for the 26th, it is 0.082% , so the best combination is the 25th, for which $A = 0.63$ and $B = -0.05$. So, the result confirms all aforementioned intuitions and assumptions. The notation of the improved Meteo France Algorithm is *MFAi* in this paper. Seen that in their original form, the step algorithm is the best followed by the Meteo France Algorithm, these last two methods will be mainly used as a comparison to evaluate the performance of the present improved method. So, Table 4 shows the performance indicators of the present improved method compared to the step algorithm and the Meteo France Algorithm. This comparison continues in Figure 9, where the variation over the eleven years of the total and relative cumulative differences for the improved method is plotted with the other methods.

From Table 4 and Figure 9, it can be concluded that the *MFAi* gives a better result than the SA. The total and relative cumulative differences are reduced from 242 h (0.8%) to -22 h (-0.07%) over the eleven years. The mean daily difference is very close to zero (-0.0055 h/day), and even the standard deviation of the mean, the normalized root mean square error, and the length of the U95 interval are a little bit higher than the step algorithm. *MFAi*, in the long term, underestimates the SD following the behavior of its origin, which is the Meteo France Algorithm. Figure 9b gives the zoom for only SA and *MFAi*. As mentioned above, the cumulative difference for the step algorithm is negative for the first two years; for *MFAi*, it is also negative, but *MFAi* is more negative than the step algorithm. From the third year on, it becomes positive for the step algorithm, and for *MFAi*, the cumulative difference is approaching zero. Then, the cumulative difference increases

over the years for the step algorithm, while for MFAi, it oscillates around and near zero. Figure 10 shows the scatter plot and histogram of MFAi.

Table 4. Comparison of the performance indicators for the Improved Meteo France Algorithm, the step algorithm, and the Meteo France Algorithm.

Statistical Parameters	Improved Meteo France Algorithm	Step Algorithm	Meteo France Algorithm
Mean daily differences mdd [h/day]	−0.0055	0.06	−0.24
Standard deviation of daily differences sdd [h/day]	0.81	0.79	0.86
Span U95 [h/day]	3.38	3.13	3.6
Total cumulative differences $totdif$ [h]	−22	242	−946
Relative cumulative differences $rtotdif$ [%]	−0.07%	0.8%	−3.15%
Normalized Root Mean Square Error $nrmse$ [%]	10.9%	10.57%	11.96%

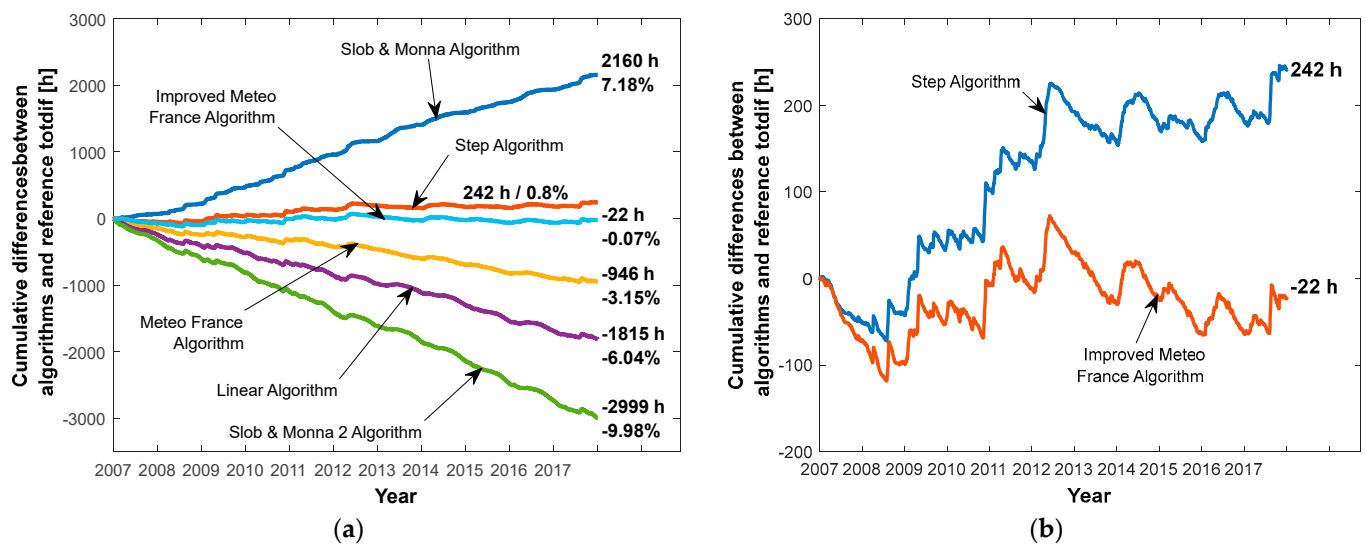


Figure 9. Total cumulative differences for the Improved Meteo France Algorithm compared to the other models: (a) All methods over the eleven years; (b) Zoom for the step algorithm and Improved Meteo France Algorithm.

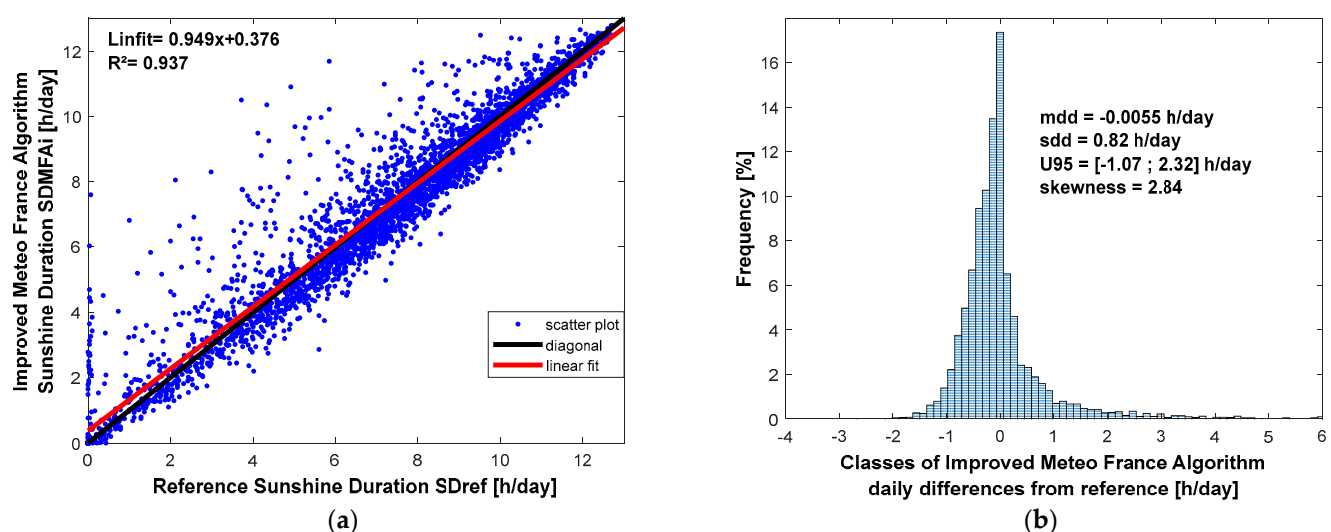


Figure 10. Improved Meteo France Algorithm: (a) Scatter plot and linear fit; (b) Histogram.

The behavior of MFAi is similar to the step algorithm; for SDs less than 7 h/day, there is overestimation, and conversely, there is overestimation for SDs higher than 7 h/day. But the maximum distance between the linear fit and the diagonal is less than that for the Step Algorithm.

5. Discussion

5.1. About the Reference

Obviously, the ideal way to obtain the reference is through the pyrheliometric method; all the pyranometric methods were fitted by this approach. But the unavailability of this costly equipment, and especially the fact that the indirect method was approved by the World Meteorological Organization [1], made it possible for the local facilities to do the comparison. As described in the Introduction section, the sunshine duration for a given period is the sum of the sub-periods for which the direct solar beam irradiance exceeds 120 Wm^{-2} . For the present work, the sub-period is 1 min averaging, which permits the use of all existing pyranometric methods because they need either 1 min or 10 min of averaging data. The limit of 3° , which is around the solar elevation angle, is necessary to avoid the constraints and uncertainties of low solar elevation angle and atmospheric refraction during sunset and sunrise, principally by the indirect method that implies division by the sine of the above-mentioned angle. This latter can produce abnormal results if its value is too small. This limit corresponds to the limits used by the different pyranometric algorithms; it is exactly 3° for Meteo France Algorithm, 5.74° ($\mu_0 = 0.1$) for Slob and Monna Algorithm and 2.87° ($\mu_0 = 0.05$) for the modified Slob and Monna Algorithm. So, the reference and the tested models use the same basic parameters.

5.2. About the Pyranometric Methods

Five algorithms were presented here, from the simplest to the most complicated. The step algorithm is the simplest and can be considered to be like an empiric method. There is sunshine if the solar global radiation exceeds a certain fraction of the extra-terrestrial radiation. For the Meteo France Algorithm, the global radiation is always compared to a threshold that depends on a fraction of global irradiance in the clear sky in mean conditions of atmospheric turbidity. The sub-period to sum for the step algorithm and Meteo France Algorithm is one minute. The linear algorithm, whose sub-period is ten minutes, is a direct and linear correlation between pyrheliometric sunshine duration and global radiation, and at the end, the algorithm gives the fraction of the ten minutes that complies with the sunshine definition. The Slob and Monna Algorithm, which also uses a ten-minute averaging as a sub-period, is based on the measure of the global radiation and estimation of the solar direct beam radiation and diffuse radiation. Then, the normalized values of these three radiations data are used in the algorithm to estimate the sunshine duration every ten minutes. In its Guide to Meteorological Instruments and Methods of Observation [1], the World Meteorological Organization recommends the Slob and Monna Algorithm and the Meteo France Algorithm.

5.3. About the Best of the Existing Pyranometric Methods

In their original form, the method that gives the best result is the step algorithm. So according to the cumulative difference, for example, the ranking in descending order is as follows: step algorithm, Meteo France Algorithm, linear algorithm, Slob and Monna Algorithm, and finally, the second version of the Slob and Monna Algorithm. Of course, the first question is why the simplest and most empirical method gives the best result compared to those of the others, which are more sophisticated. The main answer is that the other methods were mainly fitted by pyrheliometric data from the BSRN station in the northern hemisphere or for latitudes far from Reunion Island's latitude. The Slob and Monna Algorithm and linear algorithm were fitted in the BSRN station of Cabauw, Netherlands (latitude = 52°), and the coefficients for the Meteo France Algorithm come from Momote's BSRN station whose latitude (-2°) is far from the site in Reunion Island

(-21.34°). But the Meteo France Algorithm is in second place, and its relative cumulative difference is -3.15% , which is practically acceptable. Even though the Slob and Monna Algorithm is recommended by the World Meteorological Organization, this method and its revised version are the worst in the present study. Another remark from this study is that methods using a one-minute sub-period are better than the others with a ten-minute sub-period.

5.4. About the Improvement of the Meteo France Algorithm

The method that was chosen to be improved is the Meteo France Algorithm. This does not mean that the others cannot be enhanced, but the Meteo France algorithm is the easiest. The improvement is an empiric approach, searching two coefficients to minimize the cumulative error. Following intuitions and after some trials, two intervals that were supposed to include the best value of the coefficients were defined. With a step of 0.01, the algorithm was run for each possible couple of values of the coefficients inside the two intervals, and the couple that gives the minimum cumulative error is the best. The result is really satisfying because the relative cumulative error decreases to -0.07% for the eleven years of measurement. The curve of the cumulative difference for MFAi oscillates near and around zero over the long time period of measurement, while for the other methods, it is continuously increasing or decreasing. So, the Improved Meteo France is by far the best method followed by the step algorithm. As mentioned above, the Slob and Monna Algorithm is the worst, even though it is recommended by the World Meteorological Organization.

As reported in [4,5], an inter-comparison program with pyr heliometric data is performed inside BSRN stations in France and Italy and shows that the best method is the Meteo France Algorithm followed by the step algorithm, as in the present work. The Slob and Monna Algorithm, in this inter-comparison program, was in the third position, but the linear algorithm was not tested during this measurement campaign. Reference [11] emphasizes that if well-adjusted by pyr heliometric data, the Meteo France Algorithm is the best with the lowest uncertainties. So, the Meteo France Algorithm is on the first rank, but the proper values of the A and B coefficients need to be found to fit the latitude and the local weather parameters. The present work also shows that the step algorithm is a good, simple, and globally suitable alternative that can give acceptable practical uncertainties without the need to adjust the method to the local database or latitude every time.

5.5. Future Works

For further confirmation, the study will be extended to other Indian Ocean Islands. Then, cooperation with BSRN stations around the tropics will be necessary to obtain pyr heliometric data in order to have a better quality of reference. Besides the empiric approach, an algorithm or method should be designed to calculate the suitable values for A and B coefficients for the Meteo France Algorithm. The last objective is to find a way to improve the Slob and Monna Algorithm to fit the tropics well.

6. Conclusions

For Reunion Island, the best method for estimating the sunshine duration from global irradiation is the Carpentras or Météo France Algorithm, especially with the appropriate coefficients that were computed by the present work. This method is also the easiest to improve or to adjust among the existing algorithms. The step algorithm in the second position is a simple and suitable alternative for practical use. The other algorithms give uncertainties that are too high for tropical sites. The present result can be applied to any tropical site whose latitude is similar to Reunion Island, especially the islands inside the Indian Ocean.

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Nomenclature

SD	Sunshine duration in minutes or hours
G	Global radiation on horizontal surface [$W \cdot m^{-2}$]
D	Diffuse radiation for horizontal plane [$W \cdot m^{-2}$]
el	Solar elevation angle in degree
δ	Solar declination angle in degree
I_h	Solar direct radiation on horizontal surface [$W \cdot m^{-2}$]
I	Solar direct beam radiation [$W \cdot m^{-2}$]
SD_{ref}	Reference sunshine duration in minutes or hours
G_{s1}	Global radiation threshold for step algorithm [$W \cdot m^{-2}$]
I_0	Solar direct beam extra-terrestrial radiation [$W \cdot m^{-2}$]
$SDSA$	Sunshine duration for step algorithm
G_{s2}	Global radiation threshold for Meteo France Algorithm [$W \cdot m^{-2}$]
SD_{MFA}	Sunshine duration for Meteo France Algorithm
F_C	Fraction of global irradiance in clear sky in mean conditions of atmospheric turbidity for Meteo France Algorithm
A, B	Coefficients used in the Meteo France algorithm
d	Day number
$SDSMA$	Sunshine duration for Slob and Monna Algorithm
r_0	Mean earth-sun distance
r	Actual value of earth-sun distance
T_L	Linke turbidity factor
μ_0	Sine of the solar elevation angle
G_0	Extra-terrestrial global irradiance on horizontal surface [$W \cdot m^{-2}$]
f	Time fraction of a sub-period of 10 min, where there is sunshine
$SDLA$	Sunshine duration for linear algorithm
l_1	First relative minimum threshold for linear algorithm
u_1	First relative maximum threshold for linear algorithm
l_2	Second relative minimum threshold for linear algorithm
u_2	Second relative maximum threshold for linear algorithm
SDx	Sunshine duration for whichever algorithm
N	Number of daily sunshine duration points
$totdif$	Total cumulative daily sunshine duration difference between the algorithms and the reference in hours per day
$rtotdif$	Relative daily sunshine duration cumulative difference between the algorithms and the reference in hours per day
mdd	Mean value of daily sunshine duration difference between algorithm and the reference in hours per day
sdd	Standard deviation of daily sunshine duration difference between algorithm and the reference in hours per day
$SDMFai$	Sunshine duration for improved Meteo France Algorithm

<i>rmse</i>	root mean square error
<i>nrmse</i>	normalized root mean square error
SD_{ref0}	Average value of the daily sunshine duration for the reference

Acronyms

WMO	World Meteorological Organization
BSRN	Baseline Station on Radiation Network
SA	step algorithm
MFA	Meteo France Algorithm
SMA	Slob and Monna Algorithm
LA	linear algorithm
MFAi	Improved Meteo France Algorithm

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