Long term HelioClim-3 global, beam and diffuse irradiance validation

Pierre Ineichen
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Abstract

Satellite derived solar radiation is nowadays a good alternative to ground measurements for renewable energy applications. It has the advantage to provide data with a good accuracy, the best time and space granularity, in term of real time series and average year such as TMY.

This report presents results of a long term validation in the European and Mediterranean regions of the irradiance evaluated by the HelioClim-3 scheme in hourly, daily and monthly values, and seven average products on an annual basis. The performance is also put forward with the natural interannual variability.

The main results are:

- the accuracy of the derived hourly global irradiance reaches 20% (standard deviation) with no bias, and 46% for the beam component with a 6% to 9% mean bias,
- the main improvement from version 4 to version 5 comes from the use of a new clear sky model with sub-daily aerosol data as input,
- some systematic patterns are pointed out, depending on the sky type, the site latitude, the aerosol optical depth and the ground snow cover,
- the overall annual uncertainty of the HelioClim-3 scheme is situated within one interannual variability standard deviation for the global component, and within two standard deviations for the beam irradiation,
- the overall performance for the beam component is slightly worse for version 5, but the frequency distributions are improved, particularly for high irradiance values.
Nomenclature

$G_h$ or $GHI$  
global horizontal solar irradiance or irradiation

$G_{hc}$  
clear sky global horizontal solar irradiance or irradiation

$B_n$ or $DNI$  
normal beam (or direct) solar irradiance or irradiation

$D_h$ or $DIF$  
diffuse horizontal solar irradiance or irradiation

$B_{nc}$  
clear sky normal beam solar irradiance or irradiation

$G_{sat}$  
modeled solar irradiance or irradiation

$G_{mes}$  
measured solar irradiance or irradiation

$I_o$  
extra-atmospheric solar irradiance

$K$  
clearness or clear sky index

$K_t$  
global clearness index ($G_h$ normalized by $I_o \sin \theta$)

$K_{t'}$  
modified global clearness index

$K_g$  
global clear sky index ($G_h$ normalized by $G_{hc}$)

$K_d$  
diffuse clearness index

$K_b$  
beam clearness index

$K_{bc}$  
beam clear sky index ($B_n$ normalized by $B_{nc}$)

$T_L$  
Linke turbidity coefficient

$T_{Lam2}$  
Linke turbidity coefficient at air mass = 2

$\alpha$  
air mass

$\omega$  
 atmospheric aerosol optical depth

$\delta_{\text{CSA}}$  
aerosol optical depth of a clean and dry atmosphere

$\delta_w$  
water vapor atmospheric optical depth

$T_a$  
ambiant temperature at 2m

$RH$  
relative humidity at 2m

$h$  
solar elevation angle

$AM$  
 atmospheric air mass

$n$  
cloud index

$\rho$  
planetary albedo

$\rho_g$  
overcast sky planetary albedo

$\rho_c$  
clear sky planetary albedo

$mbd$  
mean bias difference

$rmsd$  
root mean square difference

$sd$  
standard deviation

$bsd$  
bias standard deviation (standard deviation of the bias)

$R$  
correlation coefficient

$KSI\%$  
second order Kolmogorov-Smirnov test
irradiation from one year to the other in the model uncertainty. To conduct a significant interannual variability analysis, a long period of data is needed. These long time series have to be as continuous as possible and with no missing data. As the majority of the ground measurements time series are not complete and as it is not possible the fill the gaps, a strategy has to be developed to circumvent the problem.

The following corrections are applied on the data: to obtain a yearly total, the data are taken month by month and added. For each month, the missing share of ground measurements is evaluated in term of a number of missing data percentage. When the gaps’ length represents less than 5% of the month, a linear extrapolation is applied on the monthly values based on the normalized number of hourly values aggregated in the considered month. When more than 5% of the data are missing, the monthly value is replaced by the average of all the corresponding months of the considered time series. The missing share statistics are given in Table II.

In Lerwick, the 10% missing data for the beam component occur mainly in 2011. For the site of Madrid too many data are missing for the beam component, so that the interannual variability analysis is not significant.

Due to these corrections, the results given in the interannual variability bar charts do not correspond exactly to the hourly validation results. As the hourly comparison is restricted to validated values, some differences may also occur depending on the length of the comparison period. Nevertheless, the results are significant when considered as a general overview the tendency of a model to reproduce the data.

8. Validation results

8.1 Hourly, daily and monthly validation

The total amount of points included in the comparison and the corresponding irradiance and irradiation averages are the following:

- 700,000 hourly values $G_h = 317$, $B_h = 322$, $D_h = 129$ [W/m$^2$]
- 60,000 daily values $G_h = 3.73$, $B_h = 3.78$, $D_h = 1.51$ [Wh/m$^2$.day]
- 2,000 monthly values $G_h = 108$, $B_h = 109$, $D_h = 44$ [Wh/m$^2$.month]

The number of ground or satellite derived values differ from one site to the other, and the covered periods are not of the same length for all the sites (see Table II).

<table>
<thead>
<tr>
<th>Site</th>
<th>Hourly</th>
<th>Daily</th>
<th>Monthly</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lerwick</td>
<td>$G_h$</td>
<td>$B_h$</td>
<td>$D_h$</td>
</tr>
<tr>
<td>Madrid</td>
<td>$G_h$</td>
<td>$B_h$</td>
<td>$D_h$</td>
</tr>
</tbody>
</table>

Table III: Results of the hourly, daily and monthly validation. The standard deviation calculated on the mean bias differences over all the sites.

Figure 17: Corresponding graphical representation of the results.
Table III and Figure 17 give the main results of the validation (the complete results, site by site, for the two versions of HelioClim-3, component by component, in hourly, daily and monthly, absolute and relative values are given in the annex, Tables a-I, a-II and a-III). A general observation is that the hourly global irradiance is retrieved with a zero average bias and a standard deviation around 20% (65 [W/m²]), the beam component around 47% (150 [W/m²]) with a +6% to +9% bias, and the diffuse around 45% (56 [W/m²]) with a -10% bias. If the overall bias for the global irradiance is zero, it can be highly variable from one site to the other (-8% to +9%). This is highlighted by the standard deviation of the mean bias distribution; it stays around 3.5% for the global component. For the beam component (and a fortiori for the diffuse irradiance), the bias varies from site to site, especially for northern sites (i.e. Lerwick).

8.1.1 Model-measurements difference distribution

In a general way, for the global component and both versions, the bias distribution around the 1:1 axis follows a un- or slightly skewed normal distribution, so that the standard deviation indicator is significant (see Figures 11 & 12, a-1g to a-4g and a-10g to a-13g in the annex). This is not the case for the normal beam irradiance, where bimodal (i.e. Nantes), skewed or not normal distributions can occur depending on the site. No common rule can be drawn from the Figures a-10b to a-13b in the annex, the shape of the distribution depends on the clear sky model used and the specificities of the input parameters. For some sites with sunny conditions like Almeria, Carpentras, Tamanrasset or Sede Boqer, the dispersion of the hourly bias is so high that the distribution cannot be considered as normal. In this case, the standard deviation has to be considered with precaution. Concerning the diffuse component, even if the values on the model/measurements graphs are not aligned on the 1:1 axis, the frequency of occurrence distribution is not too far from a normal distribution; this makes the standard deviation representative of the uncertainties (see Figures a-1d to a-4d and a-10d to a-13d in the annex).

8.1.2 Improvement from HelioClim-3 version 4 to version 5

The improvement between HelioClim-3 version 4 and version 5 is the use of a new clear sky model. In version 4, the used clear sky is evaluated with the ESRA model, developed by Rigollier and Geiger (Rigollier et al. 2000, Geiger et al. 2002). Validation of this model (Ineichen 2016) shows clearly an underestimation for both global an beam components. This is illustrated on Figure 18 (upper graphs) where the clearness index is represented versus the solar elevation angle for both components. The measurements are plotted in yellow dots, and the model in blue. The upper limit, representative of clear conditions, is never reached by the modelled values, especially for the beam component (see Figures a-1b to a-4b in the annex). The consequence on the irradiance modelled values is that the highest values are never reached. In HelioClim-3 vs5, an adaptation of the clear sky model is done using the McClear model (Lefèvre 2013) with MACC-II aerosol sub-daily data (Kaiser et al. 2002). The improvement is illustrated on Figure 18 lower graphs, where the same parameters than for version 4 are represented. For the new version, the clear sky measurements are reached by the modelled values, except for low solar elevation angle values where a slight underestimation is visible (see Figures a-9g and a-9b in the annex).
8.1.3 Time resolution of the input parameters

When representing the clearness index versus the solar elevation angle, the time resolution effect of the aod and w input to the model can be pointed out. In version HelioClim-3 v4, monthly climatic values are used to evaluate the clear sky, whereas sub-daily values obtained from the MACC-II project are used in HelioClim-3 v5. This is illustrated on Figure 19 where aggregates of points are visible only on the left graph. This effect can be seen on the graphs for all the sites (see Figures a-9n in the annex), more particularly on sites where aod and w are highly variable (i.e. Lerwick and Nantes).

8.1.4 Sky condition effect

The observation of the bias versus the modified clearness index $K_t'$ (or the sky type, see Figures a-5g and a-5b in the annex) shows the same general tendency for all the models and both components: a slight overestimation for cloudy conditions and an underestimation for clear skies. The highest effect is a beam component overestimation for intermediate conditions. This is illustrated on Figure 20. For clear conditions, the dispersion is due to an approximate knowledge of turbidity. In the case of inter-
mediate cloud cover, the model does not identify with enough precision the type and thickness of the clouds (see Figures a-5g and a-5b in the annex).

8.1.5  Snow effect

For the site of Davos, the snow cover during the winter period has a significant effect on the modeled irradiance. Indeed, if no particular attention is payed in winter, the high reflectance of the snow cover can change the determination of the ground albedo, and during the process, can be interpreted as cloudy conditions. The result is an overestimation of the irradiance for cloudy condition conditions due to the underestimation of the ground albedo. Moreover, the variability of the snow cover induces a higher dispersion of the irradiance, especially for the beam component. The effects are visible on Figure 21 where the model bias is represented versus the modified clearness index, or sky conditions, for the global and the normal beam components.

8.1.6  Latitude effect

Due to the angle of view of the ground surface by the satellite, the size of the image pixel increases with the latitude of the site. This means that the reflectance of the ground includes also a higher variety of ground albedo values, and cloud types and altitudes. The small view angle of the satellite with respect to the ground increases the parallax effect on the cloud position (Schutgens 2009, Marie-Joseph 2013). The result on the modeled irradiance is a higher dispersion (standard deviation) for both components as illustrated on Figure 22 where the standard deviation of the modeled values are represented against the latitude of the station.
8.1.7 Aerosol effect

The graphs on Figure 23 represent the hourly bias of the beam component versus the aerosol optical depth. A clear dependence can be pointed out for all the sites (see Figures a-6b in the annex), the model shows a negative bias for clean atmosphere condition, and going more or less to an overestimation for higher turbidity. The effect is less market for the version 5 of HelioClim-3. For the global component, as it is less sensitive to the aerosol load, the effect is smaller, even negligible.

Figure 23 Model bias versus the clearness $K_t$ (or sky conditions) for the beam component and the two version of HC-3.

When representing the daily model-measurements bias versus the day of the year, the general tendency is a summer/winter pattern for the beam component as it is illustrated on Figure 24 left. This effect is certainly correlated with the atmospheric turbidity ; it follows the aerosol load seasonal dependency. The right graph on Figure 24 represents the monthly bias surrounded by $\pm$ one standard deviation: the monthly modeled average and the measurements average are represented (for all the sites, see Figures a-7n and a-8n in the annex).

Figure 25 is a graphical illustration of the monthly validation. On the left graph, the monthly values of the two version of HelioClim-3 model, and on the right graph, all the average models are shown; the measurements are in red, the dashed red lines represent $\pm$ one standard deviation around the monthly value. Figures a-21n in the annex give a graphical representation for all the sites and models. For the global component, 96% of the monthly HelioClim-3 v5 modeled values are situated between the two dashed lines, 92% for version 4; for the normal beam component, 88% of the monthly HelioClim-3 v5 modeled values are situated between the two dashed lines, 84% for version 4. From these graphs, it
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Figure 24 Left graphs: Model-measurements difference for daily normal beam irradiation values versus the day of the year. Right graphs: Monthly averaged values surrounded by ± one standard deviation for the modeled and the measured values of the global irradiation.

Figure 25 Comparison of the monthly values for all the models. In red, the measurements, the red dashed lines represent ± one standard deviation.

arises that the only site where all the average modelled monthly values are apart from one standard deviation around the average monthly measured values is Sede Boqer (see annex).

8.2 Frequency distribution

The correspondence between the frequency distribution of the modeled values and the measurements is as important as a low bias and standard deviation. It is the guaranteeing of a realist representation of the solar resource by the satellite models.

The general observation is that the two versions of the models, for all the sites, present a coherent frequency distribution representation of the global irradiance level (with the exception of Davos for the snow periods, Figures a-12g and a-13g). When considering the global clearness index frequency distribu-
tion, for all non-arid climate sites, a peak of overestimation can be seen for $K_t$ values around 0.15. The peak is slightly smoothed on version 5 values, but still present. For the beam component, the general pattern is an overestimation for very low beam or clearness index values, and an underestimation for intermediate values. For both components, as stated in section 8.1.2, the high irradiance and clearness index values are better modeled with version 5. These two effects are illustrated on Figure 26 for the site of Kassel. The Figures for all the sites are given in the annex, Figures a-14n to a-19n.

Figure 26 Frequency distribution of occurrence versus the clearness index for the site of Kassel.

8.3 Interannual variability

Beside the visual analysis of Figure a-20g and a-20b, it is interesting to compare the bias of the models with the interannual variability expressed by the standard deviation around the annual irradiation average for both the global and the beam components. The comparison results are given in Table IV. The blue columns represent the annual average for each site and the corresponding standard deviation over the reference period 2004-2010. The results are expressed as mean bias differences; if the mbd is less than one standard deviation $sd$, the cell background is represented in green. These mbd are highly variable from site to site and from model to model, even if the combined results for all sites are relatively good. On the last lines, the absolute bias and the standard deviation of the bias $bsd$ is given for all models. These values express the spatial «smoothness» of the model.

From Table IV, the following points can be underlined for the global component:

- if version 4 has a lower overall mean bias, the absolute bias and the standard deviation of the bias are lower for version 5,
- considering the site by site results, half of the sites present a bias within ± one standard deviation of the interannual variability, 23% within ± two standard deviations, and 14% with a higher bias. The results are slightly better for version 5

and for the beam component:

- the average bias over all sites is relatively high, but as stated in previous sections, the clearness index distribution is better represented by version 5, especially for high values,
- version 4 gives slightly better results for all the annual indicators,
- the worst results arise for high latitude sites (size of the pixels view angles), and for dry climate sites (albedo determination difficulties, aerosol and clear sky model uncertainties),
• considering the site by site results, around half of the sites have a bias within ± one standard deviation of the interannual variability. The site to site and version to version comparison of the bias shows a high variability.

Table IV Results of the yearly validation and interannual variability analysis.

<table>
<thead>
<tr>
<th>Sites</th>
<th>Yearly total [HelioClim-3] validation</th>
<th>standard deviation of difference</th>
<th>Global irradiance, annual mean bias difference</th>
<th>standard deviation of difference</th>
<th>Beam irradiance, annual mean bias difference</th>
<th>standard deviation of difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Algeria</td>
<td>3.5%</td>
<td>1.5%</td>
<td>-0.1% to -0.3%</td>
<td>0.2%</td>
<td>-0.1% to 0.3%</td>
<td>0.2%</td>
</tr>
<tr>
<td>Spain</td>
<td>4.2%</td>
<td>2.5%</td>
<td>-0.2% to -0.3%</td>
<td>0.3%</td>
<td>-0.2% to 0.3%</td>
<td>0.3%</td>
</tr>
<tr>
<td>France</td>
<td>3.9%</td>
<td>2.3%</td>
<td>-0.3% to -0.4%</td>
<td>0.2%</td>
<td>-0.3% to 0.4%</td>
<td>0.2%</td>
</tr>
<tr>
<td>Germany</td>
<td>3.4%</td>
<td>2.1%</td>
<td>-0.2% to -0.3%</td>
<td>0.3%</td>
<td>-0.2% to 0.3%</td>
<td>0.3%</td>
</tr>
<tr>
<td>Italy</td>
<td>4.1%</td>
<td>2.6%</td>
<td>-0.3% to -0.4%</td>
<td>0.2%</td>
<td>-0.3% to 0.4%</td>
<td>0.2%</td>
</tr>
<tr>
<td>Switzerland</td>
<td>4.3%</td>
<td>2.8%</td>
<td>-0.2% to -0.3%</td>
<td>0.3%</td>
<td>-0.2% to 0.3%</td>
<td>0.3%</td>
</tr>
<tr>
<td>USA</td>
<td>4.0%</td>
<td>2.5%</td>
<td>-0.2% to -0.3%</td>
<td>0.3%</td>
<td>-0.2% to 0.3%</td>
<td>0.3%</td>
</tr>
<tr>
<td>Canada</td>
<td>3.8%</td>
<td>2.2%</td>
<td>-0.3% to -0.4%</td>
<td>0.2%</td>
<td>-0.3% to 0.4%</td>
<td>0.2%</td>
</tr>
<tr>
<td>Australia</td>
<td>4.1%</td>
<td>2.6%</td>
<td>-0.2% to -0.3%</td>
<td>0.3%</td>
<td>-0.2% to 0.3%</td>
<td>0.3%</td>
</tr>
<tr>
<td>South Africa</td>
<td>4.3%</td>
<td>2.8%</td>
<td>-0.2% to -0.3%</td>
<td>0.3%</td>
<td>-0.2% to 0.3%</td>
<td>0.3%</td>
</tr>
</tbody>
</table>

9. Conclusions

The first conclusion is that the quality control is a key point in any model validation. Even if the data are highly qualified by the organization in charge of the acquisition, uncertainties can remain in the data and influence the validation. The best case is when independent data such as aerosol optical depth are also available.

The conclusions of the present study are the following:

• for latitude from 20° to 60°, altitude from sea level to 1600 m and various climate, the hourly global irradiance is retrieved with a negligible bias and an average standard deviation around 20% for both versions of HelioClim-3 scheme. For the beam irradiance, the bias is around 6% to 9%, and the standard deviation around 47%.

• as expected, the main improvement from version 4 to version 5 comes from the clear sky model and the knowledge of the aerosol optical depth, better results are obtained with daily (our sub daily) turbidity instead of monthly climatic values.

• the intermediate sky conditions are more difficult to model: the type and altitude of the clouds are not easy to determine precisely,

• the snow cover has to be taken into account, especially in the alps region,

• a general pattern with the atmospheric aerosol load is visible for all sites. Even if the pattern is present for the two versions of HelioClim-3, it is less marked for the latest version. Some seasonal effects can be related to the aerosol variability during the year,
• the standard deviation is increasing with the latitude, i.e. the size of the pixels and the angle of view of the satellite,

• a peak of discrepancy in the frequency distribution is present for all the non-arid sites around $K_t = 0.15$ for both versions. On the other hand, version 5 presents a much better representation of high clearness index values,

• even if the overall results for the beam component are slightly worst for the HelioClim-3 v5, the frequency distribution are improved.

10. Acknowledgements

The ground data are kindly provided by the Plataforma Solar de Almeria (PSA & DLR, Spain), the Baseline Surface Radiation Network (BSRN), the Aerosol Robotic Network (Aeronet), the Global Aerosol Watch project (GAW), the CIE International Daylight Measurements Program (Commission internationale de l’éclairage IDMP), the Universidad Politecnica de Madrid (UMP, Spain), the Ecole Nationale des Travaux Publiques (ENTPE, Lyon, France), the Centre Scientifique et Technique du Bâtiment (CSTB, Nantes, France), the Institut für Schnee- und Lawinenforschung (SLF) and the Physikalisch-Meteorologisches Observatorium Davos (PMOD/WRC, Switzerland), the Frauenhofer Institute für Windergie und Energisystemtechnik (IWES, Kassel, Germany), and the Natural Resources and the Environment, Global Change and Ecosystem Dynamics Research Group (CSIR, South Africa).
11. References


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Ineichen P (2008c) Conversion function between the Linke turbidity and the atmospheric water vapor and aerosol content. Solar Energy 82, 1095–1097


Remund J (2009): Aerosol optical depth and Linke turbidity climatology, Description for final report of IEA SHC Task 36, Meteotest Bern


are given in \[\text{Wh/m}^2\h\].

For all sites, the overall values, the absolute mean bias and the standard deviation of the bias are given.

<table>
<thead>
<tr>
<th>Site</th>
<th>Absolute mean bias</th>
<th>Standard deviation of the bias</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site 1</td>
<td>value 1</td>
<td>value 2</td>
</tr>
<tr>
<td>Site 2</td>
<td>value 3</td>
<td>value 4</td>
</tr>
</tbody>
</table>

Table a-I

<table>
<thead>
<tr>
<th>Site</th>
<th>Absolute mean bias</th>
<th>Standard deviation of the bias</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site 1</td>
<td>value</td>
<td>value</td>
</tr>
<tr>
<td>Site 2</td>
<td>value</td>
<td>value</td>
</tr>
</tbody>
</table>

The absolute mean bias refers to the average error in the absolute values of the measured and calculated values. The standard deviation of the bias gives an indication of the variability of the bias across different data points.

Table a-II

<table>
<thead>
<tr>
<th>Site</th>
<th>Absolute mean bias</th>
<th>Standard deviation of the bias</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site 1</td>
<td>value</td>
<td>value</td>
</tr>
<tr>
<td>Site 2</td>
<td>value</td>
<td>value</td>
</tr>
</tbody>
</table>

The site-specific bias validation results are expressed in relative and absolute values. The absolute values are given in [Wh/m\(^2\h\)].

For all sites, the overall values, the absolute mean bias and the standard deviation of the bias are given.
Table a-II:

Site by site, for the two helioclim-3 versions, daily normal, beam and diffuse irradiation validation results expressed in relative and absolute values. The absolute values are given in \([\text{kWh/m}^2\text{h day}]\). For all sites, the overall values, the absolute mean bias and the standard deviation of the bias are given.

<table>
<thead>
<tr>
<th>Site</th>
<th>Global Insolation</th>
<th>Beam Insolation</th>
<th>Diffuse Insolation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Solar 3.5-3.5</td>
<td>Solar 3.0-3.5</td>
<td>Solar 3.5-3.5</td>
</tr>
<tr>
<td></td>
<td>Relative (%)</td>
<td>Relative (%)</td>
<td>Relative (%)</td>
</tr>
<tr>
<td></td>
<td>Absolute (kWh/m² h day)</td>
<td>Absolute (kWh/m² h day)</td>
<td>Absolute (kWh/m² h day)</td>
</tr>
<tr>
<td>Average</td>
<td>5.73</td>
<td>3.83</td>
<td>2.80</td>
</tr>
<tr>
<td>Standard Dev.</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
</tr>
</tbody>
</table>

For all sites, the overall values, the absolute mean bias and the standard deviation of the bias are given.

Table a-III:

<table>
<thead>
<tr>
<th>Site</th>
<th>Overall Relative (%)</th>
<th>Overall Absolute (kWh/m² h day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>6.07</td>
<td>4.00</td>
</tr>
<tr>
<td>Standard Dev.</td>
<td>0.08</td>
<td>0.08</td>
</tr>
</tbody>
</table>

For all sites, the standard deviation of the bias is given.
| Table 3 | Site by site, for the two helioclim-3 versions, monthly global, normal beam and diffuse irradiation validation results expressed in relative and absolute values. The absolute values are given in [kWh/m² day]. For all sites, the overall values, the absolute mean bias and the standard deviation of the bias are given. |