Global irradiance: typical year and year to year annual variability

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Abstract

Models converting satellite images into the different radiation components become increasingly performing and give often better estimation of the solar irradiation availability than ground measurements if the station is not situated in the near vicinity of the application. Two different kinds of models are used to circumvent the lack of ground measurements: «average» models based on 10 to 20 years of ground measurements and interpolation between stations, and satellite based models that give «real» time series for specific years. The present study analyzes the interannual variability (variation from one year to the other) of the solar irradiation and compares it to the corresponding annual irradiation obtained from different evaluation models.

Reference

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GLOBAL IRRADIANCE: TYPICAL YEAR AND YEAR TO YEAR ANNUAL VARIABILITY

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1. Introduction

Models converting satellite images into the different radiation components become increasingly performing and give often better estimation of the solar irradiation availability than ground measurements if the station is not situated in the near vicinity of the application.

Two different kinds of models are used to circumvent the lack of ground measurements: «average» models based on 10 to 20 years of ground measurements and interpolation between stations, and satellite based models that give «real» time series for specific years.

The present study analyzes the interannual variability (variation from one year to the other) of the solar irradiation and compares it to the corresponding annual irradiation obtained from different evaluation models.

2. Ground measurements

Data from 21 European and African, and 6 American ground stations were collected to conduct the study. The geographic locations of the stations cover latitudes from 8°N to 58°N, altitudes from sea level to 3000 m and a great variety of climates. For stations part of the SurfRad, BSRN (http://www.gewex.org/bsrn.html) and CIE (CIE 1994) networks, high precision instruments (WMO 2008) such as Kipp and Zonen CM10 and Epplle PSP pyranometers, are used to acquire the data. For the other stations, it was not possible to determine the exact type of instruments. A stringent calibration, characterization and quality control was applied on all the data by the person in charge of the measurements (following IDMP recommendations, CIE 1994), the coherence of the data was verified by the author. The list of the stations is given on Table I.

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Table 1: Ground sites list

ANETZ: Automatisches meteorologisches Mes- und Beobachtungsinstitut
BSRN: Baseline Surface Radiation Network
CIE: Commission International pour l’Eclairage
CSTB: Centre Scientifique et Technique du Bâtiment
DWD: Deutscher Wetterdienst
EMHI: Estonian Meteorological and Hydrological Institute
ICA: Institute of Construction and Architecture, Slovak Academy of Sciences
ENTPE: Ecole Nationale des Mines de Paris
UNIGE: University of Geneva
WRDC: World Radiation Data Center
ZAMG: Zentralanstalt für Meteorologie und Geophysik
NREL: National Renewable Energy Laboratory
SurfRad: Surface Radiation Network
3. Ground data accuracy

Sensor calibration is the key point for precise acquisition in the field of solar radiation. The radiation sensors should be calibrated by comparison against a sub-standard before the beginning of the acquisition period, and then every year. Due to the possible errors and inaccuracies, a post-calibration is difficult to conduct.

The quality control is the first step in the process of using ground data. It detects significant instrumental errors like calibration, orientation, leveling, coherence, etc. An automatic quality control cannot detect all the acquisition inaccuracies, one of the remaining points to be assessed is the sensors’ calibration coefficient used to convert the acquired data into physical values. This can only be done by comparison of redundant or complementary data.

The sensors’ calibration coefficient can be verified for clear sky conditions by comparison. Day by day, the highest hourly value is selected from the measurements and plotted against the day of the year as illustrated on Figure 1. These points are representative of the clearest conditions within the considered day. As the highest value for each day is selected, the upper limit represents the clear sky conditions. On Figure 2, the clearness index $K_i$ (global irradiance $G$ normalized by the corresponding extra-atmospheric irradiance $I_o$) is plotted against the solar elevation angle in hourly values. Here again, two different data sets are represented; the upper limits of the two data sets should lie together if the calibration is coherent. On such graphs, data from different sites or different year for the same site can be compared.

![Figure 1](image1.png)  ![Figure 2](image2.png)

**Figure 1 (left):** highest daily global irradiance value versus the day of the year for two different data sets. **Figure 2 (right):** clearness index versus the solar elevation angle for the same site and two different years.

When the atmospheric aerosol optical depth (aod) and the water vapor column ($w$) for the site are known, from an independent network such as aeronet, the sensors’ calibration can be assessed by comparison with the help of a clear sky model. On such networks, the aerosol optical depth is acquired as soon as direct sun is present; the values are then averaged to give a daily value. The water vapor $w$ is evaluated from the ground temperature ($T_g$) and relative humidity ($HR$) by the use of a model such as Atwater model (Atwater 1976). When the temperature and humidity measurements are missing, the data from a neighboring station (if applicable) can be used; the water vapor can also be retrieved from the aeronet network. These $aod$ and $w$ values are then used with the Solis clear sky model (Muller 2004, Ineichen 2008a) to evaluate clear sky hourly $G$ and $G_i$ values and plotted on same graphs than above.

If none of the above method can be applied, the results issued from the use of such data bank should be taken with caution.

4. Derived data

Two different derived data sets are analyzed in this study: average and typical years derived from long-term measurements, and specific years derived hour by hour from satellite images. These two categories of products will be compared separately against the corresponding ground data sets.

3.1. Average and typical years

These sets of data are obtained from 10 to 20 years of measurements, and partially interpolated between
stations. Some of them are corrected with the help of satellite images. For Switzerland and the United States, Design Reference Year (DRY from EMPA, CH) and Typical Meteorological Year (TMY from NREL, USA) are also part of the comparison.

These data are derived within the following networks, programs or softwares:


- **WRDC**: the World Radiation Data Centre Online Archive contains international solar radiation data stored at the WRDC, which is a central depository for data collected over one thousand measurement sites throughout the world (available from [http://wrde-mgo.nrel.gov/](http://wrde-mgo.nrel.gov/)).

- **RetScreen**: the RETScreen Clean Energy Project Analysis Software is a unique decision support tool developed with the contribution of numerous experts from government, industry, and academia. The software, provided free-of-charge, can be used worldwide to evaluate the energy production and savings, costs, emission reductions, financial viability and risk for various types of Renewable-energy and Energy-efficient Technologies (RETs, available from [http://www.retscreen.net](http://www.retscreen.net)).

- **NASA SSE**: a renewable energy resource web site of global meteorology and surface solar energy climatology from NASA satellite data on 1 by 1 degree resolution (available from [http://eosweb.larc.nasa.gov/sse/](http://eosweb.larc.nasa.gov/sse/)).

- **EMPClimate**: this database contains monthly means of solar irradiation (downwelling shortwave irradiation), minima, maxima and mean values of air temperature at 2 m, minima, maxima and mean values of relative humidity at 2 m and covers the whole world. It has been created by data fusion techniques applied to satellite data, meteorological re-analyses from the National Centers for Environmental Prediction and the National Center for Atmospheric Research (NCEP / NCAR USA) and orography for the period 1990-2004 by Mines ParisTech (available from the MeSor³ portal at [http://www.mesor.org](http://www.mesor.org)).

- **Meteonorm**: a comprehensive meteorological reference software, incorporating a catalogue of meteorological data and calculation procedures for solar applications and system design at any desired location in the world. It is based on over 23 years of experience in the development of meteorological databases for energy applications (see [http://www.meteonorm.com](http://www.meteonorm.com)).

- **EMPA DRY and NASA TMY**: Design Reference Year and Typical Reference Year contain hourly climate data for a specific location, arranged as hourly sets of simultaneous climate parameters. The basic requirements for a DRY or a TRY are that it correspond to an average year, both regarding monthly or seasonal mean values, occurrence and persistence of warm, cold, sunny or overcast periods.

- **ESRA**: the European Solar Radiation Atlas is oriented towards the needs of the users like solar architects and engineers, respecting the state of the art of their working field and their need of precise input data. From best available measured solar data complemented with other meteorological data necessary for solar engineering, digital maps for the European continents are produced. Satellite-derived maps help in improving accuracy in spatial interpolation (see [http://www.helioclim.com](http://www.helioclim.com)).

- **Satel-Light**: a Meteosat image based data server developed within a Joule XII European project that provides 5 years of half hourly data of solar irradiance and daylight components with a spatial

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³ MeSor: Management and Exploitation of Solar Resource Knowledge. The MeSor project is a European funded Coordination Action which aims at removing the uncertainty and improving the management of the solar energy resource knowledge. The project includes activities in user guidance (benchmarking of models and data sets; development of a handbook on best practices on how to use solar resource data), unification of access to information (use of advanced information technologies; offering one-stop-access to several databases), connecting to other initiatives (INSPIRE of the EU, POWER of the NASA, SHC and PVPS of the IEA, GMES/GEO) and to related scientific communities (energy, meteorology, geography, medicine, ecology), and dissemination (stakeholders involvement, future R&D, communication).
resolution of 10 km by 10 km. It covers all Europe and part of North Africa (available from http://www.satel-light.com). The average over the years 1996 to 2000 is used here.

- SolarGis from GeoModel: a modified Heliosat-2 algorithm is used to calculate irradiance from 15-minute MSG data, adapted for multispectral MSG data, with improvements of snow classification and cloud index determination and a terrain disaggregation (see http://www.geomodel.eu and below)

3.2. Specific satellite derived years

The second set of data is obtained from satellite images, and is representative of data for specific years:

- The Helioclim-3 data bank (http://www.soda-is.com) is produced with the Heliosat-2 method that converts observations made by geostationary meteorological satellites into estimates of the global irradiation at ground level. This version integrates the knowledge gained by various exploitations of the original Heliosat method and its varieties in a coherent and thorough way. It is based upon the same physical principles, but the inputs to the method are calibrated radiances, instead of the digital counts output from the sensor. This change opens the possibilities of using known models of the physical processes in atmospheric optics, thus removing the need for empirically defined parameters and of pyranometric measurements to tune them. The ESRA models (ESRA 2000, Rigollier 2000 and 2004) are used for modeling the clear-sky irradiation. The assessment of the ground albedo and the cloud albedo is based upon explicit formulations of the path radiance and the transmittance of the atmosphere. The turbidity is based on climatic monthly Linke Turbidity coefficients data banks.

- SolarGis (http://www.geomodel.eu): the irradiance components are the results of a five steps process: a multi-spectral analysis classifies the pixels (normalized difference snow index (Ruyter 2007), cloud index (Derrien 2005), and temporal variability index), the lower boundary (LB) evaluation is done for each time slot (based on the original approach by Perez (2002)), a spatial variability is introduced for the upper boundary (UP) and the cloud index definition, the Solis clear sky model is used as normalization [simplified version (Ineichen 2008a), as inputs, the climatology values from the NVAP water vapor database (Randl 1996) and Atmospheric Optical Depth data by (Remund 2008) assimilated with Aeronet and Aerocom datasets are used], and a terrain disaggregation is finally applied [based on the approach by Ruiz-Arias (2010), with a spatial resolution of 100 m].

- Satel-Light (http://www.satel-light.com): the only parameter directly computed from the satellite image is the global horizontal irradiance. All other parameters are computed from it. The global horizontal irradiance is estimated from the pixel value of the satellite image using the concept of the Heliosat method, proposed by Cano (Cano, 1986). This method was modified by Beyer (Beyer, 1996) and further improvements have been made to it for Satel-Light. The Heliosat method is based on the assumption that the albedo of a cloudy atmosphere will usually be larger than the albedo of the ocean or the earth surface (this is not true if the ground is covered with snow). Thus, the increase of the albedo gives a measure of the cloud cover. Then, the albedo is used to compute the cloud index, which is representative of the cloud cover.

The presence of snow increases significantly the albedo, making the detection of cloudless situations almost impossible when using only the satellite visible channel. Unfortunately, the generation of Meteosat satellites used at the time of the project did not offer channels which could be used to make the distinction between snow cover and cloud cover. This means that a pixel overlooking an area covered with snow during part of the month is considered as a pixel overlooking an area covered with clouds during that same period of time. The solar radiation for this pixel will then be underestimated (Ineichen 1999).

- Suny model (State University of New York at Albany): the semi-empirical model producing global Irradiance (G) and direct irradiance (Gd) from geostationary satellite images (visible channel) has been described in detail in two previous articles (Perez 2002, Perez 2003).

The cloud index determination is individualized for each ground (pixel) location. It is determined
from the location-specific relative normalized pixel brightness -- i.e., the brightness of a pixel in relation to its maximum and minimum possible value, the latter representing clear conditions (brightness of ground) and the former representing cloudy conditions (brightness of thick cloud top). Because it is individualized for each pixel, this process accounts for ground reflectivity differences over space and time and does not require an absolute knowledge of satellite sensors calibration. The model also accounts for site-specific ground bi-directional (specular) reflectance characteristics and for snow cover when present (Perez 2002, Perez 2003).

The clear sky envelopes (Bird model adapted by Maxwell 1998) represent the upper limit of irradiances generated by the model. These envelopes are functions of ground elevation and atmospheric turbidity as quantified by atmospheric precipitable water w and by atmospheric optical depth (aod). In its operational version, the model uses monthly site-specific climatological estimates of w and broad-band aod traceable to (Randall 1996, Mischenko 1999, Yu 2003).

The model enhances its performance in complex terrains, via a systematic internal calibration of its output to modeled clear sky profiles (Perez 2003).

5. Evaluation method

A reference period covering the years 1999 to 2006 will guide the evaluation of the products. The average yearly total H is determined by the mean value over the reference period and is used as normalization for the yearly totals. This normalized average (=100%) is represented on the Figure 3 by the first blue bar from the left and labeled 1999-2006 average. The corresponding 100% dashed line is surrounded by ± one standard deviation (estimated over the 8 years of the reference period) in light orange on the graph. The following values are given on the Figure 3:

(1) first left blue bar: average annual irradiation on the reference period (1999-2006 => 100%),
(2) blue bars: relative annual ground measurements,
(3) yellow bars: average data banks, satellite based or average ground measurements,
(4) orange bars: year by year SolarGis irradiation (European sites),
(5) green bars: year by year Helioclim 3 irradiation (European sites),
(6) light blue bars: year by year Satel-Light data for the 1996 to 2000 period (European sites),
(7) grey bars: year by year Suny irradiation (for United States sites),
(8) red bars: average data banks annual deviation from the 1999-2006 reference average,
(9) brown bars: ground measurements annual deviation from the 1999-2006 reference average.

![Figure 3: Relative total annual irradiation normalized to the average annual value over the reference period (1999-2006) for the site of Geneva airport. The mean bias deviation is also given.](image-url)
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<td>1162</td>
<td>1162</td>
<td>1162</td>
<td>1991-2000</td>
</tr>
</tbody>
</table>

**Table 11:** Variability of the annual total global irradiance, and deviation from the reference average.
6. Results

5.1. Interannual variability

The interannual variability of the global irradiation $H$ for the European stations is given in Table II. The reference period average, mean bias difference and fluctuation (root mean square difference) values are given in the most left column, while the values over the whole measurements period are given in the most right column.

The first established fact is that even if the standard deviations don’t exceed some percents, specific years can be more that 10% away from the average.

The European sites can be separated in 2 groups. For some stations, there is a tendency to have higher yearly total global irradiation in the last years, while a diminution can be seen for other sites. This is illustrated on figure 4 where a 14 year reference sequence (1996-2009) is used for normalization. The opposite tendency can clearly be seen on data from Geneva and Berlin, and from Vaulx-en-Velin for example. For Geneva and Vaulx-en-Velin, with relatively similar climates and situated at only 100 km one from the other, this cannot be attributed to a regional effect, but can come from a turbidity change that could not be investigated due to a lack of aerosol optical depth knowledge.

![Figure 4: Yearly total global irradiation deviation from the 1996 to 2009 average for two groups of sites.](image-url)
important differences can be seen between the two Geneva and the two Payerne data sets. If the general
tendency is the same for all the curves, there are significant differences, not always of the same sign. This
has to be underlined, particularly for the site of Payerne where the acquisition is done side by side; the
difference can be attributed to the sensors’ calibration. These two data sets are analyzed and corrected
following section 3.

Figure 5: Total annual global irradiation for the two data sets of Geneva and Payerne before and after correction.

5.2. Average and typical years
EMP Climate obtained from the MeSor portal is a prototype; the results are highly variable, and, even if
given on the graphs and in the Tables, the values should not be used.

For Meteonorm, three different possibilities are investigated: monthly values obtained from the MeSor portal
(http://www.mesor.org), product based on average ground measurements acquired from 1983 to 1992, and
over a longer period, i.e. from 1981 to 2000. The results are very similar for all the Meteonorm products.

It can be seen on Figure 3 for the site of Geneva that except for EMPClimate (see above remark),
the different products give values near or within ± one standard deviation around the considered reference
period. The evaluated products can therefore be used with a good precision for photovoltaic power plant
sizing (only the annual total is relevant in that case).

On Figure 6, the seasonal evolution of the monthly global irradiation obtained from the different products is
represented for the site of Payerne, data from the BSRN network. In most of the cases, when a model over-
or underestimates the irradiation, it does it over the whole year, i.e. the bias is not linked to a seasonal effect
as for example the albedo variation.

Figure 6: Seasonal evolution of the monthly global irradiation for the site of Payerne.

The results for the European sites and the average products are given in Table III, where the deviation from
the average over the reference period is given in absolute and relative values. In the first column, the1999-
2006 average is given with its the standard deviation over the. The results for the products that are within
± one standard deviation over the reference period are given in blue in the Table. The corresponding Table
for the stations situated in the United States can be found in the Annex on http://www.cuepe.ch.

5.3. Specific satellite derived years
Over Europe, Satel-Light data are evaluated from 1996 to 2000, Helioclim 3 and SolarGis products are
<table>
<thead>
<tr>
<th>Country (Region)</th>
<th>Yearly total (kWh/yr)</th>
<th>Deviation from average</th>
<th>Deviation %</th>
<th>Average deviation</th>
<th>Deviation [%]</th>
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<tr>
<td>Berlin Dahlem (D)</td>
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<td>74</td>
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<td>1053</td>
<td>-6%</td>
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<tr>
<td>Bratislava (Slovakia)</td>
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<td>Carpentras (F)</td>
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<td>1592</td>
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<tr>
<td>Davos (CH)</td>
<td>1344</td>
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<tr>
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</tr>
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<tr>
<td>Sion (CH)</td>
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<td>1155</td>
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</tr>
</tbody>
</table>

**Table III: Products comparison and annual variability for the European stations.**

In the average column, the standard deviation calculated on the reference period is given in absolute and relative values.

The results for products situated within ± one standard deviation are given in blue.
available since the year 2004. For the six American sites, data for 10 to 14 years sequences are available, including satellite product derived by Suny. The comparison is done year by year as described on Figure 3 for the site of Geneva. The yearly total global irradiation is normalized to the 1999-2006 reference period average.

The results for the United States stations are illustrated with data from Table Mountain (CO) on Figure 7. The color codes are the same than on Figure 1.

From all the graphs given in the Annex (see http://www.cuepe.ch), the following conclusions can be drawn:

- even if the satellite derived data present some bias, the derived data interannual variation follows satisfactorily the ground measurements variation,
- the sites with potential snow cover (Davos, Sonnblick and Sion) show an important overestimation by Helioclim data, and an underestimation by SolarGis data,
- In Locarno, the year by year higher bias can be induced by the nearby mountains and lake,
- in Ilorin, the bias is probably due to a too low turbidity value used in the models. The turbidity measurements are not dense enough on the African continent.

For the American sites, the 1995 to 1998 period has to be considered separately, the deriving algorithm has changed in 1998. This can be seen on Figure 8 for the site of Table Mountain, where the 12 monthly averages are plotted separately for each year, derived data against ground measurements. Two linear best fits are also represented for the data before and after 1998. A higher dispersion and a different bias can clearly be seen on the figure for the beginning period.

![Figure 7: Relative total annual irradiation normalized to the average annual value over the reference period (1999-2006) for the site of Table Mountain (CO). The mean bias deviation is also given.](image)

![Figure 8: Derived monthly global irradiation versus the corresponding measurements, year by year for the station of Goodwin Creek and Table Mountain. A best fit is represented for two separate periods: before and after 1998.](image)

In conclusion, except for some sites with specific ground or snow cover, an annual bias can be present,
depending on the site and the product. This could mainly be an aerosol optical depth and/or surface albedo effect. All the 4 tested products follow in a satisfactorily manner the year to year variability.

7. Conclusions

10 to 30 years of ground data acquired at 27 different sites are used to analyze the interannual variability of the solar irradiation and to compare it to average and/or interpolated data, software generated typical years and satellite derived data.

The main results are that the majority of the tested state of the art products give yearly values within the natural interannual variability of the solar irradiation. When dealing with specific year and «real» satellite derived data, their interannual variability follows in a satisfactorily manner the ground measurements, especially with the newest algorithms.

8. Acknowledgements

This comparative study could be performed thanks to the data provided by the MeteoSwiss (Swiss office of Meteorology and Climatology, http://www.meteoswiss.ch), FluxNet community (http://www.fluxdata.org) for the Spain sites, the BSRN network (http://www.gewex.org/bsrn.html) for Europe and part of Tamanrasset, the WRDC data set for Thessaloniki, Sonnblick, Wien and part of Tamanrasset (http://wrdc.mgo.rsi.ru), and the SurfRad network for the American sites (http://www.srrb.noaa.gov/surfrad).

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