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INEICHEN, Pierre

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Reference


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Validation of Models that Estimate the Clear Sky Global and Beam Solar Irradiance

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Abstract

The optimal utilization of solar energy requires a thorough characterization of the solar resource. The most accurate way is to measure that resource in situ. However accurate measurements are not a common commodity, especially over longer time spans. To circumvent the lack of ground based measurements, models can be applied to estimate solar irradiance components. A fundamental component is clear sky irradiance. In particular, clear sky irradiance is used as the normalization function in models that convert meteorological satellite images into irradiance, or in models that decompose global irradiance into diffuse/direct fraction. It is therefore important to evaluate and validate clear sky irradiance models.

This paper presents the results of a validation of hourly clear sky models spanning up to 8 years. The validation relies on high quality measurements at 22 locations in Europe and around the Mediterranean region. Seven models are evaluated. They were selected on the basis of their published performance, their simplicity of use, and/or their computational speed; two different sources of the aerosol load are used as input to the models.

The three best models show a low bias and a standard deviation ranging from 3% to 5%. The standard deviation of the bias across the 22 locations is of the same order of magnitude. The observed bias patterns can be largely traced to inaccuracies inherent to the sources aerosol optical depth. No particular seasonal effects are noted. A consistent limitation across all selected models, even if their direct irradiance performance can be judged satisfactory based on the standard deviation metric, is that they tend to fall short of observations for a given clear sky global clearness index value.

Keywords: clear sky solar irradiance, model validation, daily aerosol optical depth, water vapor column

* ISES member
Anthropogenic activities have become an important factor in climate change. One of the aspects of this activity is an impact on the solar irradiance reaching the ground over the long term. It is essential to understand the impact of such changes on the environment (Cutforth 2007, Stanhill 2001). Unfortunately, the density of quality ground irradiance measurement stations is insufficient, especially for direct irradiance. To circumvent this lack of ground measured data, meteorological satellites can be of great help. Models converting the satellite images into different radiation components such as SolarGIS (Suri 2004, Cebecauer 2011), EnMetSol (Hammer 2009), Helioclim (Blanc 2011), IrSLaV (Zarzalejo 2009), Solemi (Meyer 2003), CM-SAF (Müller 2009) or Heliomont (Stoekli 2013), are becoming increasingly efficient. The clear sky index (global irradiance normalized by the corresponding clear sky irradiance) is often effectively used in lieu of the clearness index (global irradiance normalized by the corresponding extraterrestrial irradiance) to eliminate seasonal effects on stationary time series (Hansen 2010), to derive typical meteorological years (TMY) from long term time series, or for forecasting purposes (Pel-land 2013, Engerer 2014). The capability of these models to estimate the radiation reaching the ground is directly related to the precision of the clear sky model used as normalization function.

When the geographic and geometrical parameters are known (altitude, albedo, solar zenith angle, etc.), the two main input variables of clear sky models are the atmospheric aerosol optical depth ($\text{aod}$) and the total water vapor column ($w$). Whereas parameters like the total atmospheric amount of ozone or the NO2 have a minor impact on solar radiation transmissivity, aerosol optical depth and water vapor have a substantial influence on the absorptivity and transmissivity of the radiation during its atmosphere crossing. Therefore, to obtain good estimates of the clear sky irradiance, these two inputs must be known with the best possible precision and a good time and space granularity. If the water vapor column can be retrieved with relatively low uncertainty from ground temperature ($T_a$) and relative humidity ($\text{RH}$) measurements (Atwater 1976), it is not the case for the aerosol optical depth. Measurements of $\text{aod}$ are scarce, especially over the long term, and their spatial repartition is poor. It is therefore important to understand how the choice of a model and of its input data influence the uncertainties of modeled clear sky irradiance.

In a previous study (Ineichen 2006), the author presented a short-term (one-year) validation of clear sky models using Linke turbidity (Linke 1922) climatic data banks as an input – Linke turbidity was converted to aerosol optical depth with the help of Ineichen model (Ineichen 2002). In the present paper, a long term validation (up to 8 years) of seven clear sky models is presented. This validation is based on daily aerosol atmospheric content derived from two sources: (1) ground measurements and (2) the MACC-II
2. **Clear sky models**

Seven of the best-performing and/or widely used models are selected for evaluation. The choice of models is based on their performance, their ease of use and their computation speed. Models require aerosol optical depth \(aod\) and water vapor column \(w\) as an input. Two of the models use Linke turbidity coefficient at air mass \(2 (TL_{AM2})\) as an input.

2.1 **McClear model**

The McClear is the most recent clear sky model. It is a fully physical model developed by Mines Paris Tech (Lefèvre 2013). The core of the model consists of look-up tables (LUT) calculated with the help of the LibRadTran radiative transfer model (Mayer and Killing 2005, Mayer et al. 2010) in a 10-dimensions space including aerosol optical depths at two wavelengths, partial aerosol optical depths for the determination of the aerosol type, the water vapor column and the ozone amount. The model also uses the parameters derived from the MACC-II project.

2.2 **Simplified Solis model**

The original Solis model is a spectral clear sky model developed in the frame of the Heliosat-3 project (Mueller 2000, 2004). It is also based on LibRadTran calculations. For application to satellite models, because the large spatial coverage, clear sky calculations should be fast, which is not the case when using LibRadTran. To increase computational speed, a broadband simplified version of Solis was derived by Ineichen (2008a, 2008b). Look-up tables were calculated with LibRadTran for possible ranges of the input parameters, and least-square regressions were then applied to the data from the look-up tables. The second version (2008b) of the model includes rural, urban, maritime and tropospheric aerosol types (Shettle 1989). The model requires panchromatic aerosol optical depth (at 700 nm) and water vapor column as inputs. The model is accurate and computationally fast.

2.3 **CPCR2 model**

CPCR2 is a physical model, parametrized in two solar spectrum bands – UV+visible and infrared. In each band a radiation modeling technique is applied and a transmittance of each extinction layer is parametrized to derive transmission functions for the beam and the diffuse components of the clear sky solar irradiance. The main input parameters to the model are the two Angström coefficients (the exponent \(\alpha\) or the size coefficient, and the turbidity coefficient \(\beta\)) and the water vapor column \(w\). The two Angström coefficients are related to the aerosol optical depth \(aod\) by the Angström relation. Average values for the single scattering albedo are used to differentiate types of aerosols. A complete description is given in Gueymard (1989).

2.4 **REST2 model**

The first version of REST, developed by Gueymard (2003) was limited to the beam component of the clear sky irradiance. REST2 is the two-bands version of the REST model, it uses the general features of CPCR2 with updated transmittance functions calculated with the SMARTS spectral model (Gueymard 2001) and using the latest extraterrestrial spectral distribution and solar constant value. As for CPCR2,
the main input parameters to the model are the water vapor column, the Angstrom turbidity coefficient \( \beta \) and aerosol size parameter \( \alpha \). Average values for the single scattering albedo are used to differentiate between types of aerosols. A complete description is given in Gueymard (2004). Default values of 0.0002 atm-cm are applied for the reduced NO2 scattering, and 340 Dobson units for the O3 vertical path length. REST2 and CPCR2 are the most flexible models in terms of input specificity.

2.5 Bird model

Bird and Hulström (1980) developed a transmittance expression for the different attenuation processes in the atmosphere and based on Radiative Transfer Model (RTM) calculation with SOLTRAN (RTM scheme constructed from LOWTRAN). The description can be found in Bird (1980). The model requires 3 input parameters: the water vapor column (in cm), the broadband aerosol optical depth (at 700 nm or calculated from the spectral attenuation at 2 wavelengths commonly used by meteorological networks: 380 and 500 nm), and the total ozone column considered here as constant and equal to 340 Dobson units. The model is simple to implement and widely used in the solar energy community.

2.6 ESRA model

The ESRA clear sky model was developed in the frame of the European Solar Radiation Atlas (ESRA 2000) and used in the heliosat-2 satellite model (Rigollier 2000, Geiger 2002). Contrary to other models, it derives separately the beam and the diffuse components that are added to obtain the global irradiance. The beam component is based on Kasten's (1996) Rayleigh optical depth parametrization and on the Linke turbidity at air mass 2. The clear sky diffuse irradiance is expressed as the product of a zenith diffuse transmission and a diffuse angular function.

2.7 Kasten model

The basis of the Kasten model is the pyrheliometric formula described in a paper from Kasten (1980). The irradiances are calculated by taking into account the absorption and diffusion at two different altitude levels: 2500m and 8000m (Kasten 1984). The model uses the Linke turbidity coefficient at air mass 2 to parametrize the aerosol load of the atmosphere. The atmospheric water vapor column is included in the Linke turbidity factor. Because the ESRA and the Kasten models are based on Linke turbidity, they are included in the study for comparison purposes.

3. Ground measurements

Hourly data from twenty two measurement sites are used for model validation, with up to 8 years of continuous measurements. Their geographic repartition is shown in Figure 1. The sites' latitude, longitude, altitude and climate characteristics are reported in Table 1 along with the types of measurements available and the institute in charge of these measurements. Except for Skukuza, two or three irradiance components are available. High precision instruments (WMO 2008) such as Kipp and Zonen CM10 and Eppley PSP pyranometers, and Eppley NIP pyrheliometers, are used at each station. Following WMO recommendations, the instruments should be secondary standard pyranometers and pyrheliometers, their respective uncertainty for hourly values should not be higher than 2% and 1.5%. Taking into account the demanding maintenance of the sensors, it is estimated that the resulting data uncertainty under the worst conditions of maintenance can reach twice the WMO recommendation values. Stringent calibration, characterization and quality control have been applied to all data at each
site. In addition, the coherence between the different irradiance components was checked by the author: the redundancy between the three global, diffuse and beam components is verified, and, if only two of them are available, a visual control is applied.

![Map of the ground measurement stations](image)

**Figure 1 Map of the ground measurement stations**

<table>
<thead>
<tr>
<th>Site</th>
<th>GHI</th>
<th>DNI</th>
<th>DIF</th>
<th>Lat</th>
<th>Long</th>
<th>altitude</th>
<th>Climate description</th>
<th>Data source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Almeria (Spain)</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>37.092</td>
<td>-3.364</td>
<td>491</td>
<td>dry, hot summer</td>
<td>PSA</td>
</tr>
<tr>
<td>Bratislava (Slovakia)</td>
<td>x</td>
<td>x</td>
<td></td>
<td>48.166</td>
<td>12.083</td>
<td>195</td>
<td>semi-continental</td>
<td>CIE</td>
</tr>
<tr>
<td>Cagauw (the Netherlands)</td>
<td>x</td>
<td>x</td>
<td></td>
<td>51.920</td>
<td>4.930</td>
<td>70</td>
<td>temperate maritime</td>
<td>BSRN</td>
</tr>
<tr>
<td>Carpentras (France)</td>
<td>x</td>
<td>x</td>
<td></td>
<td>44.083</td>
<td>5.059</td>
<td>100</td>
<td>Mediterranean</td>
<td>BSRN</td>
</tr>
<tr>
<td>Davos (Switzerland)</td>
<td>x</td>
<td>x</td>
<td></td>
<td>46.813</td>
<td>9.844</td>
<td>1586</td>
<td>alpine</td>
<td>PMO/SLF</td>
</tr>
<tr>
<td>Geneva (Switzerland)</td>
<td>x</td>
<td>x</td>
<td></td>
<td>46.199</td>
<td>6.131</td>
<td>420</td>
<td>semi-continental</td>
<td>CIE</td>
</tr>
<tr>
<td>Kassel (Germany)</td>
<td>x</td>
<td>x</td>
<td></td>
<td>51.312</td>
<td>9.478</td>
<td>173</td>
<td>temperate humid</td>
<td>FlhG</td>
</tr>
<tr>
<td>Mt Kenya (Kenya)</td>
<td>x</td>
<td>x</td>
<td></td>
<td>-0.062</td>
<td>37.392</td>
<td>3678</td>
<td>warm humid</td>
<td>GAW</td>
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<tr>
<td>Kishinev (Moldavia)</td>
<td>x</td>
<td>x</td>
<td></td>
<td>47.000</td>
<td>28.317</td>
<td>205</td>
<td>continental humid</td>
<td>GAW</td>
</tr>
<tr>
<td>Lerwick (Great Britain)</td>
<td>x</td>
<td>x</td>
<td></td>
<td>60.133</td>
<td>-1.183</td>
<td>82</td>
<td>cold oceanic</td>
<td>GAW</td>
</tr>
<tr>
<td>Lindenberg (Germany)</td>
<td>x</td>
<td>x</td>
<td></td>
<td>52.210</td>
<td>14.122</td>
<td>125</td>
<td>moderate maritime</td>
<td>BSRN</td>
</tr>
<tr>
<td>Madrid (Spain)</td>
<td>x</td>
<td>x</td>
<td></td>
<td>40.450</td>
<td>-3.730</td>
<td>650</td>
<td>semi-arid</td>
<td>UMP</td>
</tr>
<tr>
<td>Nantes (France)</td>
<td>x</td>
<td>x</td>
<td></td>
<td>47.254</td>
<td>-1.553</td>
<td>30</td>
<td>oceanic</td>
<td>CSTB</td>
</tr>
<tr>
<td>Payrins (Switzerland)</td>
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<td>x</td>
<td></td>
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<td>6.994</td>
<td>490</td>
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<td>BSRN</td>
</tr>
<tr>
<td>Sede Boqer (Israel)</td>
<td>x</td>
<td>x</td>
<td></td>
<td>30.905</td>
<td>34.782</td>
<td>457</td>
<td>dry steppe</td>
<td>BSRN</td>
</tr>
<tr>
<td>Skukuza (South Africa)</td>
<td>x</td>
<td>x</td>
<td></td>
<td>25.020</td>
<td>31.497</td>
<td>365</td>
<td>steppe, hot arid</td>
<td>CSRN</td>
</tr>
<tr>
<td>Tamanrasset (Algeria)</td>
<td>x</td>
<td>x</td>
<td></td>
<td>22.780</td>
<td>5.510</td>
<td>1400</td>
<td>hot, desert</td>
<td>BSRN</td>
</tr>
<tr>
<td>Toravere (Estonia)</td>
<td>x</td>
<td>x</td>
<td></td>
<td>58.254</td>
<td>26.450</td>
<td>70</td>
<td>cold humid</td>
<td>BSRN</td>
</tr>
<tr>
<td>Valencia (Italy)</td>
<td>x</td>
<td>x</td>
<td></td>
<td>51.538</td>
<td>-10.248</td>
<td>14</td>
<td>oceanic</td>
<td>GAW</td>
</tr>
<tr>
<td>Vauex-en-Yalin (France)</td>
<td>x</td>
<td>x</td>
<td></td>
<td>45.778</td>
<td>4.923</td>
<td>170</td>
<td>semi-continental</td>
<td>ENTPF</td>
</tr>
<tr>
<td>Wien (Austria)</td>
<td>x</td>
<td>x</td>
<td></td>
<td>48.250</td>
<td>16.367</td>
<td>203</td>
<td>continental</td>
<td>GAW</td>
</tr>
</tbody>
</table>

4. **Input parameters**

The two main parameters needed to calculate clear sky irradiance are the atmospheric aerosol optical
depth \textit{aod} and the water vapor column \textit{w}. The water vapor column can easily be estimated from the ground measurements of the temperature \(T_a\) and the relative humidity \(RH\) with a relatively good accuracy. However it is not the case for the atmospheric aerosol content which requires specific data sources. In the present study, \textit{aod} and \textit{w} are evaluated in the following manner:

- When ground measurements of the ambient temperature and the relative humidity (or dew point temperature) are available, an approximation of the atmospheric water vapor content is obtained from a correlations derived by Smith (1966) and adapted by Atwater (1976). When no ground measurements are available, monthly averages from Meteonorm or Helioclim are used;
- The atmospheric aerosol content can be obtained either (1) from the MACC-II project that monitors the global distributions and long-range transport of greenhouse gases such as carbon dioxide and methane, aerosols that result from both natural processes and human activities, and reactive gases such as tropospheric ozone and nitrogen dioxide (\url{www.copernicus.eu}), (2) from spectral normal beam measurements with Cimel instruments through the Aeronet network (aeronet), or (3) by retrofit of the normal beam radiation with the help of Molineaux-Ineichen \textit{bmpi} model described below. When the Linke turbidity factor is needed as input for a model, it is derived from \textit{aod} using the conversion function developed by Ineichen (2002, 2008c).

From the station list, only three sites are part of the Aerosol Robotic Network (Aeronet): Cabauw, Carpentras and Toravere, and two of them are situated at high latitudes. To circumvent the lack of aerosol optical depth ground measurements, measured irradiance data are used to estimate a daily aerosol optical depth by applying a retrofit on the normal beam irradiance DNI. This is done with a model developped by Molineaux (1998) and referenced as the \textit{bmpi} model:

Based upon numerically integrated spectral simulations from Modtran (Berk, 1996), Molineaux derived the following expression for the panchromatic (broad-band) optical depth of a clean and dry atmosphere with no aerosol loading:

\[
\Delta_{cda} = - 0.101 + 0.235 * AM^{0.16}
\]

He also produced the following expression for the panchromatic water vapor optical depth:

\[
\Delta_{w} = 0.112 * AM^{0.55} * w^{0.34}
\]

where \(w\) is the precipitable water vapor content of the atmosphere in cm and AM the air mass. The precision of these fitted expressions is better than 1% when compared to Modtran simulations in the range \(1 < AM < 6\) and \(0 < w < 5\) cm. The following equation may then be applied to estimate the broad band aerosol attenuation \(\Delta_a\):

\[
DNI = I_o \exp (-AM * (\Delta_{cda} + \Delta_{w} + \Delta_a))
\]

where \(I_o\) is the extraterrestrial normal irradiance.

To retrofit \textit{aod} from DNI observations, the model is applied in the following way: when the atmospheric water vapor column \(w\) is known, the hourly profile of DNI is calculated for each day and for the complete range of considered \textit{aod}. Then, the daily profile with the lowest quadratic difference with the measurements is kept; it is related to the best fit of the daily \textit{aod} value.

The effectiveness of the retrofitting method is illustrated in Figure 2 where the retrofitted \textit{aod} is plotted versus the aeronet retrieved \textit{aod} for the three locations where the latter is available. The mean slope is +5% away from the 1:1 diagonal, with a standard deviation of 0.03 in optical depth units. The correlation coefficient is equal to 0.92.
The resulting impact of the retrofit method’s precision on clear sky model validation is estimated to be of the order of 1% for bias and less than 0.5% for the standard deviation. It is therefore acceptable to apply the retrofit method to obtain daily aod when well calibrated and characterized DNI measurements are available. The precision of derived daily aod is sufficient precision to have only a marginal influence on the validity of the present clear sky model evaluation study. Moreover, all tested models are treated equal in this respect.

5. **Clear Sky models Characteristics**

In order to define physical limits for the measurements, the behavior of the models and the coherence between irradiance components are analyzed. To visualize these characteristics, model trends are represented for four typical values of aerosols optical depths (0.05, 0.1, 0.2 and 0.5) and a range of water vapor column; a value of \( w = 1 \text{cm} \) is kept for the illustrations. The ozone amount is taken constant at a value of 340 Dobson units, the aerosol characteristics is of rural type, with an Angström size coefficient \( \alpha = 1.3 \), and the albedo coefficient at 15%. Figure 3 illustrates the Solis model, for 1 cm of water vapor column and rural aerosol type. The global clearness index \( K_t (\text{GHI}/I_o \cos \theta) \), the modified global clearness index \( K_t' \) (Perez 1990), the beam clearness index \( K_b (\text{DNI}/I_o) \) and the diffuse fraction \( \text{DIF/GHI} \) (or \( D_i/I_o \)) are represented versus the solar elevation angle. The components’ coherence is illustrated by representing the diffuse fraction or the beam clearness index versus the global clearness index.
Figure 3 Trends for the clearness indices and the diffuse fraction against the solar elevation angle and the global clearness index for the Solis model with rural aerosol type, 1cm water vapor column and four values of aerosol optical depths

Figure 4 is similar to figure 3, but focuses on small inconsistencies noted for each model for some of the considered relationship:

- **McClear (top left)**: because of the reliance of LUT in the derivation of the clear sky radiation, the behavior of the global clearness index trend exhibits a discontinuous derivative for low elevation angles.
- **CPCR2 (top right)**: for low values of the solar elevation angle, the derivative of the global clearness index shows a smooth inversion,
- **REST2 (center left)**: for low solar elevation angles the global clearness index becomes incoherent. This effect is more pronounced for high aerosol load,
- **Bird (center right)**: The distorted diffuse fraction shows that the consistency between the global and the beam components is not verified for global clearness indices lower than 0.4 and low
aerosol optical depths,

- **Esra (bottom left)**: the lowest possible global clearness index is 0.4 whereby the derivative exhibits an inversion,
- **Kasten**: The behavior is similar to the Bird model, but it is more pronounced.
- **Solis** is the only model that shows no inconsistency in any of the trends.

These effects occur mainly at low solar elevation angles and the consequences on the overall model precision is only minor. On the other hand, for some models, the consistency between the global and the beam components is not verified for low values of $K_t$ (lower than 0.4 for the ESRA model).

6. **Model validation**

The first step of the validation process is the selection of clear condition measured data to be paired
with clear sky model output. The validation is then quantified using classical first order statistical indicators: the mean bias difference \( \text{mbd} \) and the standard deviation \( \text{sd} \). Finally, the results are presented graphically for selected and representative sites and radiation components.

### 6.1 Clear conditions selection

To perform the selection, the following criteria are applied:

- The closure equation is the equation connecting together the three solar irradiance components: 
  \[ G_h = D_h + B_h, \] it must be satisfied within \( \pm 50 \text{ W/m}^2 \pm 5\% \),
- The global clearness index \( K_t \) of the measurements is lower than 0.82,
- The modified global clearness \( K_t' \) (Perez 1990) of the measurements is higher than 0.65,
- The stability of the global clearness index \( \Delta K_t' \) is better than 0.01 (\( \Delta K_t' \) is evaluated by difference of the considered hour and the average of the considered hour, the preceding and the following hour),
- The broadband aerosol optical depth is lower than 0.5

This selection is restrictive, but it ensures that only clear and stable conditions are selected. This is particularly important for high latitude sites where the conditions are often cloudy, and where a less restrictive selection can lead to erroneous statistical results biased by a few non-representative outliers. The number of hourly values selected through this procedure is given in Table III (see Section 7).

### 6.2 Statistical indicators and graphical representation

The comparison is done on an hourly basis, the model – measurements difference is computed, so that a positive value of the mean bias difference represents an overestimation of the model. The following indicators are used to quantify model performance:

- First order statistics for a given site: the mean bias (\( \text{mbd} \)) and the standard deviation (\( \text{sd} \)). In addition qualitative visualization is made with the help of model vs. measure scatterplots
- The standard deviation of the bias (\( \text{bsd} \)). It expresses the capability of the model to present a minimum spatial dispersion of the bias for the considered region of validation,
- The seasonal dependence of the bias and its dependence on aerosol optical depth (\( \text{aod} \)),
- The frequency distribution of the model-measure differences and the corresponding cumulated frequencies.

### 7. Results

The overall first order statistics for all the sites are presented in Table II for two aerosol sources: MACC-II project and \textit{bmp} retrofit. The table reports the total number of clear sky hourly values included in the validation, the hourly average irradiance value, the mean bias difference, the standard deviation and the standard deviation of the biases for the GHI and the DNI. The best ranked results are shaded.
Table II Statistics (mbd, sd and bias standard deviation bsd) for all the sites, models and 2 aerosol sources. The best ranked results are shaded.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>McClear</td>
<td>31'824</td>
<td>629</td>
<td>2.9%</td>
<td>3.1%</td>
<td>3.4%</td>
<td>4.8%</td>
<td>2.5%</td>
<td>4.6%</td>
</tr>
<tr>
<td>REST2</td>
<td>33'334</td>
<td>632</td>
<td>-4.5%</td>
<td>4.3%</td>
<td>5.4%</td>
<td>0.5%</td>
<td>2.6%</td>
<td>1.3%</td>
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<td>CPCR2</td>
<td>33'799</td>
<td>635</td>
<td>0.6%</td>
<td>3.0%</td>
<td>3.0%</td>
<td>3.5%</td>
<td>2.7%</td>
<td>3.7%</td>
</tr>
<tr>
<td>Solis 2008</td>
<td>33'134</td>
<td>633</td>
<td>-0.2%</td>
<td>3.4%</td>
<td>2.8%</td>
<td>2.9%</td>
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</tr>
<tr>
<td>Bd1</td>
<td>33'146</td>
<td>633</td>
<td>3.0%</td>
<td>3.4%</td>
<td>4.2%</td>
<td>6.4%</td>
<td>3.4%</td>
<td>6.6%</td>
</tr>
<tr>
<td>ESRA</td>
<td>34'062</td>
<td>634</td>
<td>-7.1%</td>
<td>5.7%</td>
<td>8.1%</td>
<td>0.8%</td>
<td>3.4%</td>
<td>1.5%</td>
</tr>
<tr>
<td>Kasten</td>
<td>33'146</td>
<td>633</td>
<td>-0.6%</td>
<td>3.6%</td>
<td>2.7%</td>
<td>2.8%</td>
<td>2.8%</td>
<td>3.4%</td>
</tr>
</tbody>
</table>

The mains results are the following:

- For the MACC-II aerosol source, the best results are produced by the Solis model for the global component and by McClear for the beam component,
- For the bmpi aerosol source, respectively REST2 and CPCR2 give the best statistics.

The McClear model was developed with MACC-II aerosol data as its input; it has to be noted that, when using MACC aerosol inputs, all the other models present a high negative bias and a high dispersion of the biases for the beam component. This expresses the fact that the MACC-II data presents some weaknesses in representing correctly the aerosol amount and/or the aerosol type. On the contrary, when using bmpi data as input, which are ground based measurements, the three REST2, CPCR2 and Solis give better results. Figure 5 is an illustration of these results.

![Figure 5](image)

A deeper analysis of the results leads to the following general observations:

- when representing on the same graph the measurements and the modeled values for the selected clear sky conditions, it can be seen for all models and all sites that for a given global clearness index, the highest beam measurements, and consequently also the lowest diffuse values, are never reached by the modeled values (see the green points on the graphs in Figure 6).

This is illustrated for the site of Kishinev and the McClear model in Figure 6 where the diffuse fraction is plotted against the global clearness index on the left graph, and the beam clearness index against the global clearness index on the right graph. The same pattern is visible regardless the aod values used as input to the models.
• The trend of the bias as a function of the aerosol optical depth exhibits a similar pattern for all the sites and models: when using MACC \textit{aod} as input, the models’ bias decreases with the optical depth for both the global and the beam components as illustrated in Figure 7 for the site of Kishinev and the McClear model.

When the \textit{bmpi} aerosol optical depth values are used, no specific pattern can be detected. It has to be noted that unlike the MACC values that are retrieved by a model, the \textit{bmpi} values are retrieved from ground measurements; therefore, better results are expected for the latter input.

• The seasonal dependence of the bias for both the global and the beam irradiance components shows no specific pattern. It differs slightly from one site to the other regardless of the model and the aerosol input. An illustration is given on Figure 8 for the site of Kishinev, for hourly values of the McClear model with MACC input.
• To the exception of a few specific sites like Davos or Mt Kenya, the distributions of the bias around the 1:1 model-measurements axis are near normal; for this reason the first order statistics represented by the mean bias and the standard deviation can be considered as reliable. An example is given in Figure 9 for the site of Kishinev, with the McClear model with MACC input. The figure displays the hourly bias frequency distribution for both GHI and DNI irradiance components. The cumulated frequencies (red curve) are also represented.

Figure 9 Frequency of occurrence of the bias around the 1:1 axis for both components, for the site of Kishinev, the McClear model with MACC aerosol input

To avoid displaying too many tables, detailed results are presented for only two models in Table III. The table reports the number of hourly values used for the validation, the average measured irradiance, the absolute and relative mean bias difference, and the standard deviation. Results are provided for the three irradiance components and all sites. The overall statistics across all sites including the lowest and the highest mean bias, absolute bias, and standard deviation of the biases, are presented at the end of the table. The number of data from Mt Kenya (identified in gray in Table III) is very low; therefore the site is not included in the overall results.

Because of the retrieval methodology, unlike the bmpi aerosol optical depths, the MACC aerosol data can be evaluated for any sky conditions. Therefore, the number of selected hourly values is twice higher for MACC than for bmpi input. In order to have comparable results, the statistics are given for all the models based on the same set of data. Nevertheless, the statistics obtained for the McClear model applied on the complete set of data are comparable.

8. Conclusions

A long term validation of seven hourly clear sky models has been conducted with benchmarking data from 22 sites across Europe and around the Mediterranean region. Validation data cover over up to 8 years. Two sources of input aerosol optical depth input data were used. The main results of this investigation are the following:

• The Solis model is the only model that shows coherent relationships between irradiance components for the complete range of solar elevation angles;
• The distributions of the model-measurements bias can be considered as normal distributions. Therefore first order benchmarking statistics such as mean bias error and standard deviation can be considered as reliable metrics.
• Three models exhibit roughly the same level performance and stand above the other models. These models are: McClear, REST2 and Solis. The standard deviations for these models are of the order of 3% for the global component and 4 to 5% for the beam component. The standard deviations of the bias are also respectively 3% and 4 to 6%. Considering that the measurements uncertainties are respectively around 4% and 3% for the global and the beam components, the validation results show that roughly all the models stay within this value for the global component whatever the aerosol input data set is, but none for the beam component with MACC aerosol input. When using bm6 aerosol input, the standard deviations of all the models stay around the measurements uncertainty.

• For a given global clearness index, none of the models can reproduce the highest measured direct irradiance values. This is observed for all locations.

• The bias dependence upon aerosol optical depth shows the same pattern for all models and locations.

• No specific model seasonal dependence was observed.
Table III Validation results for all the site, MacClear and Solis model, MACC and bmpi aerosol inputs. Mt-Kenya is not included in the overall statistics. The shaded values are the best (green) and the worst (orange) results.

<table>
<thead>
<tr>
<th>Site</th>
<th>Average GHI mbd</th>
<th>Average GHI sd</th>
<th>Average DNI mbd</th>
<th>Average DNI sd</th>
<th>Average DIF mbd</th>
<th>Average DIF sd</th>
</tr>
</thead>
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<tr>
<td>Almeria 2004 - 2011</td>
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<td>1.8%</td>
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<td>854</td>
</tr>
<tr>
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<td>548</td>
<td>53</td>
<td>9.6%</td>
<td>23</td>
<td>4.3%</td>
<td>740</td>
</tr>
<tr>
<td>Cabauco 2005 - 2011</td>
<td>543</td>
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<td>2.3%</td>
<td>17</td>
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<td>3.0%</td>
<td>820</td>
</tr>
<tr>
<td>Davos 2004 - 2011</td>
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<td>13</td>
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<td>956</td>
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<tr>
<td>Geneva 2004 - 2011</td>
<td>622</td>
<td>42</td>
<td>6.7%</td>
<td>18</td>
<td>2.9%</td>
<td>814</td>
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<tr>
<td>Kaskel 2004 - 2011</td>
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<tr>
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<tr>
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<tr>
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<tr>
<td>Madrid 2004 - 2011</td>
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<tr>
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<tr>
<td>Payern 2004 - 2011</td>
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<td>Sede Bager 2004 - 2011</td>
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<td>Tammarassett 2004 - 2011</td>
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<td>16</td>
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<tr>
<td>Torrevieja 2004 - 2011</td>
<td>984</td>
<td>50</td>
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<tr>
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<td>618</td>
<td>12</td>
<td>2.0%</td>
<td>23</td>
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<td>855</td>
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<tr>
<td>Vaide 2004 - 2011</td>
<td>651</td>
<td>34</td>
<td>5.3%</td>
<td>25</td>
<td>3.8%</td>
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</tr>
<tr>
<td>Wien 2004 - 2011</td>
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<td>5.1%</td>
<td>25</td>
<td>4.1%</td>
<td>767</td>
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<tr>
<td>Zlin 2004 - 2009</td>
<td>596</td>
<td>16</td>
<td>2.7%</td>
<td>25</td>
<td>4.1%</td>
<td>834</td>
</tr>
<tr>
<td>All sites</td>
<td>624</td>
<td>18</td>
<td>2.9%</td>
<td>20</td>
<td>3.1%</td>
<td>830</td>
</tr>
<tr>
<td>Lowest bias/σd</td>
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<td>13</td>
<td>2%</td>
<td>-2</td>
<td>-0.2%</td>
</tr>
<tr>
<td>Highest bias/σd</td>
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<td>9.6%</td>
<td>26</td>
<td>4%</td>
<td>-72</td>
<td>-8.8%</td>
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<tr>
<td>Mean absolute bias</td>
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<td>3.0%</td>
<td>13</td>
<td>2%</td>
<td>25</td>
<td>3.0%</td>
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<tr>
<td>Bias standard deviation</td>
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<td>3.4%</td>
<td>34</td>
<td>4.1%</td>
<td>30</td>
<td>33.1%</td>
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9. Acknowledgment

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BSRN. Baseline surface radiation network. Available from: <http://www.bsrn.awi.de/> (last access in August 2015)


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


Shettle E. P. (1989) Models of aerosols, clouds and precipitation for atmospheric propagation studies. AGARD Conference proceedings, Copenhagen, Denmark, 9-13 October


