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# Comparison of eight clear sky broadband models against 16 independent data banks

Pierre Ineichen

Center of Energy, University of Geneva, Battelle Bât. A, 7 rte de Drize, CH-1227 Carouge, GE, Switzerland

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# Abstract

A selection of eight high performance clear sky solar irradiance models is evaluated against a set of 16 independent data banks covering 20 years/stations, altitudes from sea level to 1600 m and a large range of different climates. Their performance evaluated on very clear condition measurements are within 4% in term of standard deviation.

The conclusions are that the accuracy of the input parameters such as the turbidity is crucial in the validity of the obtained radiation components, and that the choice of a specific model is secondary. The model selection criteria should be based upon either implementation simplicity, input parameter availability (Linke turbidity or aerosol optical depth) or the capacity of the model to produce spectral radiation.

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## 1. Introduction

The meteorological geostationary satellites have a great potential in the field of solar irradiance derivation. Compared to ground measurements interpolation, the advantage are the great spatial and temporal coverage. It has been shown by Zelenka et al. (1999), Perez et al. (1997) for Switzerland and the eastern coast of the United States that hourly satellite estimation of solar irradiance becomes better than interpolation for distances greater than about 25 km.

The derivation of the ground solar irradiance components requires the knowledge of the clear sky atmospheric transmittance and diffusion on the same scales in order to normalize the information retrieved from a satellite image.

A great number of such models can be found in the literature, but they were rarely evaluated and compared against long term highly diversified data banks. Gueymard (1993) conducted such a comparison against a theoretical model, and a restricted data set of measurements (11 models, 7 stations, 480 measurements points). He did the same exercise (2003) over data from five stations (5000 measurement points) and obtained comparable results (root mean square difference (RMSD) in order of 4% for the beam component). Louche et al. (1988) evaluated the Model of Bird on one year hourly data from Carpentras (France) and obtained respectively a RMSD of 4% and 6% for the beam and the global component. In the frame of the European Atlas (Esra), Rigollier et al. (2000) performed a validation of the diffuse Esra

E-mail address: pierre.ineichen@cuepe.unige.ch

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model over seven data banks from Germany and Belgium (2250 points of measurements) and obtained comparable absolute RMSD.

This document presents a validation of eight high performance clear sky broadband models for the beam and the global components against 16 independent ground data banks acquired in various climatic and geographic locations in Europe and the United States. The validation is performed in two steps: on short term time basis (min) to evaluate the dynamic performance of the models, and a hourly basis for the long term accuracy.

# 2. The models

## 2.1. Solis model

In the frame of the European project Heliosat-3 (2000) Mueller et al. (2004) developed a new spectral clear sky transmittance model. The model is based on radiative transfer model (RTM) calculations with LibRadtran (Meyer, 2001) and on a modified Lambert-Beer function; it offers the possibility to obtain a good match between fitted and calculated values using only two zenith angle RTM calculations. The irradiance components are obtained by integration over the solar spectrum. It is fully described in Mueller et al. (2004) and Heliosat-3 (2003).

The input parameters are the ozone content in Dobson units [DU], the water vapour content in  $[kg/m^2$ , precipitable water content of the atmosphere for 1 m<sup>2</sup>] and the aerosol optical depth at 550 nm. The secondary choices are the different atmospheres, the aerosol models, etc.

For the purpose of the comparisons, volcanic aerosols above 2000 m were used.

# 2.2. Bird and Hulstrom model

Bird and Huldstrom (1980) developed a transmittance expression for the different attenuation processes in the atmosphere and based on RTM calculation with SOLTRAN (RTM scheme constructed from LOW-TRAN, McClatchey and Selby (1972)). The description can be found in Bird and Huldstrom (1980).

The model needs three input parameters: water vapour column in [cm], the broadband aerosol optical depth (calculated from the spectral attenuation at two wavelengths commonly used by meteorological networks: 380 and 500 nm, see Appendix A), and the ozone column.

#### 2.3. Molineaux model

The Molineaux model is based on the equivalence of pyrheliometric and monochromatic aerosol optical

depths at a single key wavelength. It is based on MOD-TRAN (Berk et al., 1989) and Smarts2 (Gueymard, 1995) calculations with SRA (Standard Radiation Atmosphere, 1982) atmospheres (dust-like, water soluble, soot, oceanic, continental and urban/industrial) and Shettle and Fenn atmospheres (large rural, small rural, large urban, small urban, oceanic, rural mix, urban mix and maritime mix). The panchromatic optical depths for the clear and dry atmosphere and the water vapour column are fitted on MODTRAN and Smarts2 calculations. The theoretical background is given in Molineaux et al. (1998). The global irradiance component cannot be evaluated with this model.

The input parameters are: the water vapour column in [cm] and the broadband aerosol optical depth (or aerosol optical depth at 700 nm).

## 2.4. Esra model

The model was developed in the frame of the European Solar Radiation Atlas (Esra) and used in heliosat-2 (Rigollier et al., 2000; Geiger et al., 2002). It is based on Kasten's (1996) Rayleigh optical depth parameterization and the Linke turbidity at air mass 2.

The input parameter is the Linke turbidity coefficient at air mass 2.

## 2.5. Ineichen model

This model was developed to define a modified air mass independent Linke turbidity coefficient parameterization (Ineichen and Perez, 2002); it is an evolution of a model defined for Geneva in 1983.

The model needs the Linke turbidity as input.

# 2.6. CPCR2 model

A two band radiation modeling technique is used and a transmittance of each extinction layer is parameterized. The beam and diffuse irradiance components are obtained as functions of these layer transmittances. It is fully described in Gueymard (1989).

The aerosol input to the model is the Angstrom size coefficient  $\alpha$  (1.3 was used in the two bands) and the turbidity coefficient  $\beta$ . They are related to the aerosol optical depth by the Angstrom relation.

# 2.7. REST2 model

REST2 model is a new two band model developed by Gueymard (2004) that uses the general features of CPCR2 along with updates of the transmittances functions and using the latest extraterrestrial spectral distribution and solar constant value.

As for CPCR2, the main input parameters to the model are the water vapour content of the atmosphere

and the Angstrom turbidity coefficient  $\beta$ . The model offers the possibility of choosing the rural–urban environment within a scale from 1 (clear) to 5 (very polluted). An intermediate value of 3 (moderately clear) was used for all the stations.

The model needs also the reduced  $NO_2$  (default value 0.0002 atm cm) and  $O_3$  vertical path lengths.

# 2.8. Kasten model

The basis of the Kasten model is the pyrheliometric formula developed by Kasten (1980). The irradiances are calculated by taking into account the absorption and diffusion at two different altitudes: 2500 m and 8000 m (Kasten, 1984). The model needs the Linke turbidity at air mass 2 as input.

## 3. Ground measurements

Data from 16 high quality ground stations were collected to validate the models. The stations cover latitudes from 28°N to 45°N, altitudes from sea level to 1600 m and a great variety of climates. Except for Lisboa, where the beam irradiance is retrieved from diffuse measurements, the normal beam irradiance is available for all stations. High precision instruments (K + Z cm10, Eppley PSP and NIP, WMO (1996)) are used to acquire the data. 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), BSRN (2002) network, ARM (2002), Pacific Northwest Network), the coherence of the data was verified by the author. The list of the stations, their climate, latitude, longitude, altitude and time step is given in Table 1.

### 4. Dynamic validation

The aim of a dynamic validation is to assess the capability of a model to predict the solar irradiance for any altitude and air mass, and for correctly known inputs parameters (aerosols and water vapour content of the atmosphere).

A selection of clear days from five stations with various altitudes and climates was manually carried out (see Table 2). To conduct the comparison, the aerosol and water vapour parameters are retrieved from ground measurements and can be considered as a good representation of the reality. The model-measurements discrepancies will then be representative of the capability of the model to reproduce the dynamic shape of the ground radiation diurnal evolution. The results of the dynamic validation can be considered as the intrinsic precision of the models.

## 4.1. Input parameters retrieval

## 4.1.1. Ozone

The influence of ozone absorption on broadband radiation is very low: the variation of the atmospheric broadband transmittance is less than 0.5% for a variation of the ozone amount in a vertical column from 300 to 400 DU. An average constant value of 340 DU is used in the present study.

Nevertheless, ozone content of the atmosphere can be retrieved from satellite remote sensing, ground photom-

Table 1

Latitude, longitude, altitude, time step and climate of the 16 ground measurements data banks

Station	Climate	Latitude	Longitude	Altitude	Time step	Notes
Albany NY (2001)	Humid continental	42.7	-73.9	100	15′/1′	BSRN (2002)
Albuquerque, NM (1999)	Arid	35.1	-106.7	1532	60'	Sandia Natl. Labs,
						ARM Protocol
Austin, TX (2002)	Dry continental/subtropical	30.3	-97.8	180	60'	University of Texas
Burlington, KS (1999)	Dry continental	38.2	-95.6	358	60'	ARM-SGP Extended Facility
Burns, OR (2002)	Semi-arid	43.6	-119.0	1265	20'/5'	Pacific Northwest Network
Desert Rock (2002)	Desert	36.6	-116.0	1000	60'	SURFRAD Network
Eugene, OR (2002)	Temperate maritime	44.1	-123.1	150	15′/5′	Pacific Northwest Network
FSEC Cocoa, FL (1999)	Subtropical	28.3	-80.7	8	12'/6'	Florida Solar Energy Center
Freiburg, D (1993–1994)	Temperate-humid	48.0	7.8	300	30'	Fraunhofer Institute
Geneva, CH (1994–2003)	Semi-continental	42.6	6.1	420	60′/1′	CUEPE
Gladstone, OR (2000)	Temperate humid	45.4	-122.6	98	60'	Pacific Northwest Network
Golden, CO (2000–2001)	Semi-arid	39.8	-105.2	1600	60'	NREL
Hermiston, OR (1999–2000)	Temperate semi-arid	45.8	-119.4	180	60'	Pacific Northwest Network
Klamath Falls, OR (2000)	Temperate semi-arid	42.2	-121.7	1220	60′	Pacific Northwest Network
Kramer Junction, CA (1999)	Desert	35.0	-117.5	824	60'	SEGS Power Plant Monitoring
Lisboa, P (1994)	Temperate humid	38.8	-9.1	106	60′	General Class IDMP Station

Table 2						
Input parameters retrieved from measurements	s and used in	the dynamic	validation for	the	11 clear	days

Station	Day	Time step [min]	Altitude [m]	$\tau_{550}$	<i>w</i> [cm]	$T_{\rm L}$	
Albany	June 25, 2001	1	100	0.089	3.0	3.2	
Albany	September 16, 2001	1	100	0.051	1.0	2.5	
Burns	June 25, 2002	5	1265	0.082	2.0	3.1	
Burns	August 12, 2002	5	1265	0.056	1.0	2.5	
Eugene	February 14, 2002	5	150	0.079	1.1	2.7	
Eugene	October 17, 2002	5	150	0.035	1.5	2.5	
FSEC	March 29,1999	6	8	0.157	2.0	3.5	
FSEC	November 28, 1999	6	8	0.084	2.0	3.0	
Geneva	April 7, 2003	1	420	0.097	0.6	2.6	
Geneva	December 16, 2003	1	420	0.039	0.7	2.3	
Geneva	December 24, 2004	1	420	0.034	0.6	2.2	

eter measurements or climatological data bases (Swiss Meteorological Institute, 2003). It becomes non negligible for specific spectral region.

# 4.1.2. Water vapour

With a 0.2% variation in the modeled normal beam irradiance for a 10% variation of the water vapour column w (Gueymard, 2003), the precipitable water has no major influence on the atmospheric transmittance. The total precipitable water content can be retrieved from ground measurements of the ambient temperature and the relative humidity with a sufficient precision in regard to its influence in the models (Atwater and Ball, 1976; Cole, 1976; Leckner, 1978; Won, 1977); the Atwater relation was used in the present study.

## 4.1.3. Turbidity

The turbidity has the highest influence on the atmospheric transmittance, but is also the most difficult to retrieve. The input parameters to the models are either the Linke turbidity at air mass 2 (Kasten, Esra, and Ineichen) the aerosol optical depth (Solis, Bird and Molineaux) or the Angstrom turbidity (CPCR2, REST2). These three different quantifications of the aerosol atmospheric content are related and can be converted from one to the other (see Appendix A). As no spectral measurements are available for the considered stations, and even if it is not the best aerosol quantification parameter, the Linke turbidity  $T_L$  at air mass M = 2 will be used to conduct the comparison. It can be retrieved from the normal beam measurements  $G_b$ , for  $1.8 \le M \le 2.2$  by the use of Kasten's pyrheliometric formula (1980):

$$T_{\rm L} = {\rm Ln}(I_0/G_{\rm b}) * (9.4 + 0.9 * M)/M \tag{1}$$

If the stability between the morning and the afternoon measurements is acceptable, an average value (morning/afternoon) is used for the considered day.

The majority of the measuring stations are situated in suburbs or city centers. As the use of urban type aerosols in the models' application gives better results than rural type, only urban aerosols are considered in the present study.

Table 2 gives the list of the days, the time step of measurement and the quantities used as input to the models.

# 4.2. Validation

The stability of the atmospheric conditions is manually verified for each day used in the validation: during the considered period of time, the water vapour content, the aerosol optical depth and the Linke turbidity coefficient as defined by Ineichen and Perez (2002) should be relatively stable as illustrated in Fig. 1 for February 14, 2002 in Eugene (OR). The morning/afternoon symmetry is also respected.

A quality control is then applied to eliminate specific measurements for which one of the sensors is obstructed from the sun, but not the other (this can be the case when the 2 sensors are not exactly alongside).

The result of the comparison is illustrated in Fig. 2, where the modeled direct normal and global horizontal component are plotted versus the ground measurements for the Solis model and the 11 considered days.

The models producing the irradiance components reaching the ground during a clear day are often used in a relative manner to normalize the measurements. The fluctuation of the model-measurements deviation can be illustrated in the form of a clear sky index ( $K_b$  = measurements/model), its variation with the cosine of the zenith angle is given in Fig. 3 for the Bird and Hulstrom model, where it can be seen that the majority of the points are near unity. The differences that occur at high zenith angles can be attributed to measurements uncertainties, models deficiencies and to slight aerosol and/or water vapour column variation near sunrise or sunset time.

All the validation results are given in Table 3 for the horizontal beam and global radiation, in absolute and



Fig. 1. February 14, 2002, Eugene (OR). On the left graph, the stability of the atmospheric parameters is illustrated versus solar time. On the right graph, the normal beam, global and diffuse irradiance, measurements and model.



Fig. 2. Comparison of normal beam (left) and global horizontal (right) irradiance produced with the Solis model versus ground measurements for the 11 considered clear days.



Fig. 3. Clear sky index ( $K_b$  = meas./mod.) versus the cosine of the zenith angle for the Bird and Hulstrom model.

relative values, and in term of a model-measurements mean bias difference (MBD), root mean square difference (RMSD) and standard deviation (SD) around the bias. Fig. 4 illustrates these results for the normal beam, and global radiation components.

#### 5. Seasonal validation

The seasonal evaluation of the clear sky broadband models provides the capability of a given model to reproduce the maximum available solar irradiance when the local water vapour and aerosol atmospheric contents are known.

The seasonal validation is performed over 20 years/stations hourly data banks (the data of five stations are integrated over smaller time interval (12–30 min)). The considered values are integrated over time period.

## 5.1. Input parameters retrieval

The clear sky models are usually normalization functions in the process of retrieving radiation parameters. They depend on the input parameters, and can be representative of the clearest conditions or average clear conditions. This has to be kept in mind when applying them into all-weather models. In the present paper and in order to outline the difference, the two sets of input parameters were used.

difference (M	lifference (MBD), root mean square difference (RMSD), and standard deviation (SD) over the 11 considered days											
Model	Horizon	irradiance		Horizontal global irradiance								
	MBD		RMSD		SD		MBD		RMSD		SD	
	$W/m^2$	%	$W/m^2$	%	$W/m^2$	%	W/m <sup>2</sup>	%	$W/m^2$	%	W/m <sup>2</sup>	%
Solis	2	0	7	1	7	1	9	2	19	4	16	3
CPCR2	-4	-1	10	1	9	1	11	2	21	4	17	3
REST2	-4	0	9	1	8	1	10	2	19	4	15	3
Kasten	3	0	14	2	13	2	9	2	21	4	17	3
Esra	2	0	8	1	8	1	13	3	23	5	18	4
Ineichen	-6	-1	12	2	9	1	-6	-1	19	4	18	4
Molineaux	0	0	6	1	6	1						
Bird	-2	0	9	1	8	1	10	2	21	4	17	3

Comparison results for the horizontal beam and the global components in absolute and relative values and in terms of mean bias difference (MBD), root mean square difference (RMSD), and standard deviation (SD) over the 11 considered days

The number of points is 3491, the average beam irradiance is 435 W/m<sup>2</sup> and the average global radiation 496 W/m<sup>2</sup>.



Fig. 4. Comparison results for the normal beam and the global components in absolute values and in terms of mean bias difference (MBD), root mean square difference (RMSD), and standard deviation (SD) over the 11 considered days. The total number of points is 3491, the average beam irradiance is 789 W/m<sup>2</sup> and the average global radiation 496 W/m<sup>2</sup>.

The *clearest* conditions occur only for a few days in the year for the majority of the considered stations, and can be derived from measurements by using for example the lower limit of the Linke turbidity coefficient at air mass 2. These turbidity values will be representative of very clear conditions with very low water vapour content. Applying these values as input parameters to the models will generate the upper limit of the considered irradiances.

Several climatic data banks for water vapour content and turbidity over large geographic area can be found (SODA, 2002; Satel-Light, 2002, etc.). They are representative of average clear sky conditions and are mainly the results of interpolation between ground stations, with the help of satellite data. They will be labelled as *climatic* or *average clear sky conditions* in the present paper.

# 5.1.1. Ozone

Table 3

As for the dynamic validation, a constant value of the atmospheric ozone content of 340 DU has been used.

#### 5.1.2. Water vapour

The reduced water vapour content of the atmosphere can be retrieved from radio soundings, sunphotometer measurements, satellite remote sensing, GPS positioning delay informations, ground measurements, climatological databases, etc. Relative humidity measurements converted to a water vapour content of the atmosphere were used in the present study.

For the south-west United State region, the climatological data are retrieved from Randel et al. (1996), and for the other stations either from ground measurements or from Meteonorm (2003).

The climatic seasonal variation is the result of 12 monthly averaged values smoothed over the year (to avoid discontinuities); a minimum value is also retrieved and attributed to the clearest sky conditions. Fig. 5 is the illustration of the method for the station of Gladstone.

# 5.1.3. Aerosol content

In the present validation, the climatic turbidity is derived from SODA (2002) data bank. This data bank gives monthly value of the Linke turbidity. To avoid



Fig. 5. Variation of the water vapour column over the year for the station of Gladstone as generated with Meteonorm. The upper curve is the climatic fit used in the comparison, and the lower curve is the fit corresponding to the clearest conditions.

discontinuities, a fit on the monthly values is used in the comparison as illustrated for the station of Hermiston in Fig. 6.

The clearest conditions are derived from measurements through the beam radiation component giving the Linke turbidity at air mass 2 and the lower limit is manually fitted. The curve in Fig. 7 represents this limit for the Geneva's data as a function of the solar declination.

## 5.2. Selection of clear sky conditions

When using all-weather conditions data banks and considering only the beam irradiance, the clear sky conditions can easily be selected by choosing the highest irradiance values (Fig. 8, left graph). It is not the case when the global irradiance is considered. A high radiation level can occur when clouds are situated around the sun direction and reflect the beam radiation. There-



Fig. 6. Monthly values of the Linke turbidity as retrieved from a climatic data bank for the station of Hermiston. The curve is the corresponding fit used in the validation.



Fig. 7. Determination of the lowest limit of the Linke turbidity coefficient at air mass 2 for the station of Geneva. The curve is the corresponding fit used in the comparison.

fore, the highest global irradiance values are not representative of the clearest sky conditions.

To evaluate the precision of the models, the clear sky conditions have to be identified. The corresponding measurements were empirically selected by applying the following conditions on the measured beam irradiance  $G_{\text{bn}}$ :

$G_{\rm bn} > 0.9 * G_{\rm bnc}$	where $G_{\text{bnc}} = G_{\text{sc}} * \exp(-2 * \alpha_k)$	(2)
and $\alpha_k = M * (9.4)$	$4 + 0.9 * M)^{-1}$	(3)

where  $G_{sc}$  is the eccentricity corrected extraterrestrial solar constant and on its variability:

$$\Delta G_{\rm bn} = (G_{\rm bn}(n-1) + G_{\rm bn}(n+1))/G_{\rm bn}$$
(4)

The absolute difference of the above variability  $|\Delta G_{\rm bn} - \Delta G_{\rm bnc}|$  should be within 10%.

The application of the above criteria is illustrated in Fig. 8 where the selected clear sky conditions are plotted in gray. On the left graph, the modeled beam clear sky radiation is represented versus the all conditions beam irradiance measurements, and on the right graph, the same representation for the global irradiance. Such a selection is not exhaustive and its choice has an influence on the validation results. Nevertheless, it permits to evaluate and to compare the models.

# 5.3. Validation for the clearest conditions

The input parameters for the clearest conditions are the atmospheric lowest turbidity, aerosol load and water vapour content. These parameters are retrieved from ground measurements of the beam radiation, the ambient temperature and the relative humidity.

#### 5.3.1. Beam component

The above selection for the clear sky conditions was applied on all the data. The resulting validation values



Fig. 8. Measured irradiances plotted versus modeled clear sky irradiances for the station of Burns. The selected clear sky conditions are plotted in gray.

are given in terms of MBD, RMSD and SD. The results are illustrated in Fig. 9 for the Solis model and for input parameters based on measurements. The biases are better than 1% and the RMSD range from 2% to 4%. It is interesting to note that there is no relation between the station specific results and their altitude or climate (Albuquerque, Burns, Desert Rock, Golden and Klamath are above 1000 m).

Fig. 10 illustrates the comparison for the eight models over all the data banks, and the overall performance. It can be seen on this graph that the standard deviation are very similar for all the models.

#### 5.3.2. Global component

Seven of the eight described models offer the possibility to derive the global component. We applied the validation procedure and obtained the results illustrated in Fig. 11 (for the CPCR2 model). Here again, no typical correlation can be outlined between the results and the altitude or climate. As for the beam component, there is no significant difference between the models, the standard deviations are around  $20 \text{ W/m}^2$ .

All the validation results are given in Table 4.

## 5.4. Validation based on climatic inputs

Generally, the turbidity, the water vapour and/or the aerosol atmospheric contents are not known for a given site. Therefore they have to be retrieved from large climatic data banks that are inter- and extrapolated from a restricted dataset of local measurements or satellite derived. A similar validation based on the same selection criteria was made with such climatic databases as input to the models.

## 5.4.1. Beam component

For all the stations, the mean bias becomes negative, up to 6% (Geneva) and the standard deviations are



Fig. 9. Solis scheme validation against ground measurements acquired at the 16 stations. The mean bias difference, the root mean square difference and the standard deviation are given for input parameters based on measurements.



Fig. 10. Validation of the eight horizontal beam component models over the 16 data banks. The mean bias difference, the root mean square difference and the standard deviation are given for input parameters based on measurements.



Fig. 11. CPCR2 model validation against ground measurements acquired at the 16 stations for the global irradiance component. The mean bias difference, the root mean square difference and the standard deviation are given for input parameters based on measurements.

Table 4

Validation results for the three radiation components and the eight models on the 16 data banks and based on the clearest input conditions

Fotal number of measurements: 138,602 points; selected points: 9384 points												
All stations Model	Normal beam average: 909 W/m <sup>2</sup>			Horizontal beam average: 497 W/m <sup>2</sup>			Horizontal global average: 547 W/m <sup>2</sup>			Horizontal diffuse average: 51 W/m <sup>2</sup>		
	Bias	SD	RMSD	Bias	RMSD	SD	Bias	RMSD	SD	Bias	RMSD	SD
Solis	2	29	29	-1	14	14	10	27	21	11	25	18
CPCR2	-14	33	28	-9	18	15	12	28	21	21	30	18
REST2	-25	37	27	-12	18	14	2	24	20	14	26	18
Kasten	6	38	34	8	20	17	14	32	24	6	36	32
Esra	5	29	27	4	15	14	22	33	21	17	30	19
Ineichen	-16	35	30	-10	19	16	-1	25	20	-10	26	19
Molineaux	1	28	27	0	14	13						
Bird	8	33	29	4	18	16	17	33	21	13	26	18

higher up to a factor two. From these results, it can be pointed out that not only the absolute climatic value of the turbidity retrieved from large data banks is too high for the majority of the stations (negative biases), but also the seasonal variation is not always in accordance with the climate during the considered period.

#### 5.4.2. Global component

When applying the same procedure to the global component, the biases are also negative for the majority of the stations and the standard deviations around  $25 \text{ W/m}^2$ . Here again, no specific correlation can be drawn between the altitude/climate and the results.

## 6. Conclusions

Eight actual clear sky models have been validated over 16 data banks with various latitudes, altitudes and climates. The comparison with measurements was performed on a dynamic basis to evaluate their capacity to follow the diurnal shape of the incoming radiation, and over yearly data banks to cover all seasons.

The first conclusion is that the input parameters (namely turbidity) have the highest influence on model accuracy. The use of climatic data banks instead of locally measured parameters leads to systematic underestimation of both beam and global radiation components.

The second conclusion is that accuracy is not highly dependent on the model. Hence, the model selection criteria should be based upon either implementation simplicity (Esra, Molineaux), input parameter availability (Linke turbidity or aerosol optical depth) or the capacity of the model to produce spectral radiation (Solis).

If the complexity and the calculating time is not an issue, the Solis model should be the first choice, it gives the overall best results and spectrally resolved outputs.

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# Appendix A. The conversion function between $T_{\rm L}$ and the aerosol optical depth

From numerically integrated spectral simulations done with Modtran (Berk et al., 1989), Molineaux et al. (1998) obtained for the panchromatic optical depth of a clean and dry atmosphere (fictitious atmosphere that comprises only the effects of Rayleigh scattering and absorption by the atmosphere gases other than the water vapour) the following expression:

$$\Delta_{\rm cda} = -0.101 + 0.235 * M^{-0.16}$$

and the panchromatic water vapour optical depth:

$$\Delta_w = 0.112 * M^{-0.55} * w^{0.34}$$

where w is the precipitable water vapour content of the atmosphere in [cm]. The precision of these fits is better than 1% when compared with Modtran simulations in the range  $1 \le M \le 6$  and  $0 \le w \le 5$  cm. Using the Kasten pyrheliometric formula (1980), the Linke turbidity at M = 2 can then be written:

$$T_{L2}(\varDelta_a, w) = -(9.4 + 0.9 * M)$$
$$* \operatorname{Ln}(\exp((-M * (\varDelta_{cda} + \varDelta_w + \varDelta_a)))/M$$

with  $\Delta_a = \delta_{a700}$  (Molineaux etal., 1998)

or  $\Delta_a = 0.27583 * \delta_{a380} + 0.35 * \delta_{a500}$ 

(Bird and Huldstrom, 1980)

The inverse function can be used to convert the Linke turbidity  $T_{\rm L}$  to the aerosol optical depth. The inverse function can be used to convert the Linke turbidity  $T_{\rm L}$  to the aerosol optical depth  $\Delta_a$ .

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## Further reading

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