Solar irradiance in clear atmosphere: study of parameterisations of change with altitude

Armel Oumbe, Philippe Blanc, Benoît Gschwind, Mireille Lefèvre, Zhipeng Qu, Marion Schroedter Homscheidt, Lucien Wald

To cite this version:

Armel Oumbe, Philippe Blanc, Benoît Gschwind, Mireille Lefèvre, Zhipeng Qu, et al.. Solar irradiance in clear atmosphere: study of parameterisations of change with altitude. Advances in Science and Research, Copernicus Publications, 2011, 6, pp.199-203. 10.5194/asr-6-199-2011 . hal-00620372

HAL Id: hal-00620372

https://hal-mines-paristech.archives-ouvertes.fr/hal-00620372

Submitted on 7 Sep 2011

Adv. Sci. Res., 6, 199–203, 2011
www.adv-sci-res.net/6/199/2011/
doi:10.5194/asr-6-199-2011

Advances in Science & Research
Open Access Proceedings

10th EMS Annual Meeting and 8th European Conference on Applied Climatology (ECAC) 2010

Solar irradiance in clear atmosphere: study of parameterisations of change with altitude

A. Oumbe[1], **Ph. Blanc**[2], **B. Gschwind**[2], **M. Lefevre**[2], **Z. Qu**[2], **M. Schroedter-Homscheidt**[1], **and L. Wald**[2]

[1]German Remote Sensing Data Center, German Aerospace Center (DLR), Oberpfaffenhofen, Germany
[2]Centre for Energy and Processes, MINES ParisTech, BP 204, 06905 Sophia Antipolis cedex, France

Received: 22 December 2010 – Revised: 1 June 2011 – Accepted: 27 July 2011 – Published: 3 August 2011

Abstract. Parameterisation of changes of the solar irradiance at ground level with a specific variable (e.g. solar zenith angle, aerosol optical depth, altitude, etc.) is often used in operational processes because it saves computational time. This paper deals with the modelling of the vertical profile of downwelling solar irradiance for the first two kilometres above ground in clear sky conditions. Two analytical parameterisations are evaluated for direct and global irradiance in spectral bands as well as for the total irradiance. These parameterisations reproduce the vertical profile with good accuracy for global spectral irradiance and are less accurate for direct component, especially in turbid atmosphere. A piecewise linear interpolation technique using irradiance values known at surface and 4 altitudes every 500 m performs better in any case.

1 Introduction

Satellite-derived assessments of surface downwelling solar irradiance (SSI) are more and more used by engineering companies in solar energy. Performances are judged satisfactory for the time being. Nevertheless, requests for more accuracy are increasing, in particular in the spectral definition and in the decomposition of the global radiation into its direct and diffuse components. One approach to reach this goal is to improve both the modelling of the radiative transfer and the quality of the inputs describing the optical state of the atmosphere. Within their joint project Heliosat-4, DLR and MINES ParisTech have adopted this approach aiming at creating advanced databases of solar irradiance succeeding to the current ones HelioClim and SolEMi (Oumbe et al., 2009). The Heliosat-4 method will be applied to Meteosat images.

This article contributes to this project and its practical implementation. It deals with clear-sky conditions and focuses on the modelling of the change in the SSI with altitude z for the first two kilometres above ground level at z_0. In operations, the SSI is assessed at the mean elevation of the Meteosat pixel. To answer users' requests, we need to provide the SSI at a different elevation whenever the average pixel elevation is different from that of the considered site. This issue is similar to the modelling of the dependency of irradiance with altitude in the cloud-free atmosphere (Abdel Wahab et al., 2009; Gueymard and Thevenard, 2009). The SSI is then set to the irradiance in the free atmosphere for the corresponding elevation z. It would be possible to run a radiative transfer model (RTM) to obtain such a z-profile. However, running a RTM is very time-consuming and an analytical function or a simple linear interpolation technique would be preferable from an operational point of view (Mueller et al., 2009). Therefore, the problem statement is: can we model the vertical profile up to 2 km with a sufficient accuracy using fast parameterisations or linear interpolators?

A few parameterisations have been published that may answer this question (Abdel Wahab et al., 2009; Gueymard and Thevenard, 2009; Oumbe and Wald, 2009). However, they have been studied in a limited number of cases. This article establishes the performances of two parameterisations for all clear-sky conditions and for the spectral distribution of the irradiance by comparing their outcomes to those from a RTM considered as delivering reference values. In addition, we compare them to two standard interpolation techniques in order to assess their potential benefits.

Both parameterisations require as inputs solar irradiances at two different altitudes, here 0 km and 2 km. These irradiances are provided by the RTM libRadtran (www.libradtran.org). Aside its use to obtain these two irradiances, libRadtran is a reference against which we assess the performances of each parameterisation in retrieving irradiance for 32 spectral bands and total. The spectral resolution used here is the

---

Correspondence to: A. Oumbe
(armel.oumbe@dlr.de)

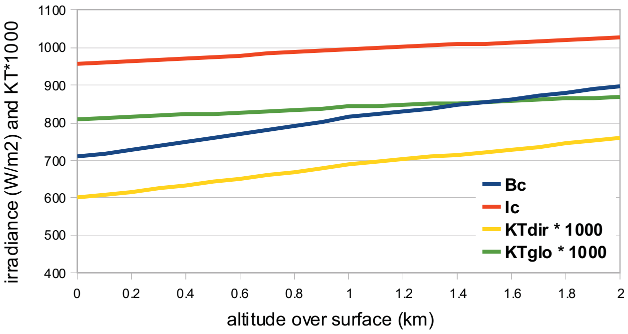

Figure 1. Example of change in irradiance (B_c for direct and I_c for global) and clearness index (KT) with altitude. KTdir and KTglo are direct and global KT.

correlated k-approximation (Kato et al., 1999), for a compromise between accuracy of results and speed of execution. With this method, atmospheric transmittance is computed following the spectral absorption of molecules in the atmosphere. The 32 spectral bands span from 240 nm to 4600 nm. The SSI is null in bands #1 and #2.

2 Parameterisations

Figure 1 illustrates the change in solar downwelling irradiance with altitude z above the surface ranging from 0 km to 2 km. In this example, the irradiances were computed with libRadtran using standard conditions in Europe, a solar zenith angle equal to 30° and an aerosol optical depth at 550 nm equal to 0.3. The shape of the two curves, B_c for direct and I_c for global, is not the same: the direct irradiance increases faster with altitude than the global irradiance, due to the higher AOD sensitivity of direct irradiance.

The clearness index KT is the ratio of the irradiance at ground level to that at the top of atmosphere. Expectedly, the variation of KT (KTdir, KTglo) with altitude is similar to that of SSI (Fig. 1). Actually, in this work, we always compute SSI, with libRadtran and with the chosen parameterisation, and derive KT from it. Using KT is a mean to show how good the method reproduces the effect of atmospheric contents on solar downwelling spectral irradiance, since the errors in SSI are expressed relatively to the irradiance at the top of atmosphere. Using KT instead of SSI is more convenient in several cases and both should be used. For example, the magnitude of the SSI changes from one Kato band to another and it is difficult to compare the deviation in SSI for different Kato bands. On the other side, errors in KT are commensurate and one can analyse and compare the errors for all cases more efficiently. Moreover, the parameterisations are explicitly products of extraterrestrial irradiance (I_0) and other parameter, corresponding to KT. They are based on the assumption that the vertical profile of irradiance follows an exponential form. This assumption is supported by the law of Beer-Bouguer-Lambert for the direct component.

2.1 Parameterisation 1

The parameterisation 1 (p1) describes the global and direct irradiances with the following functions (Oumbe and Wald, 2009):

$$\begin{aligned} I_c(z) &= I_0(1-A(z_0)\exp[-\alpha(z-z_0)]) \\ B_c(z) &= I_0(1-A_B(z_0)\exp[-\alpha_B(z-z_0)]) \end{aligned} \tag{1}$$

Knowing clear-sky irradiances at two different altitudes, $I_c(z_H)$ at z_H and $I_c(z_0)$ at z_0, $A(z_0)$ and α are determined:

$$\begin{aligned} A(z_0) &= 1-(I_c(z_0)/I_0) \\ \alpha &= -\ln[(I_0-I_c(z_H))/(I_0-I_c(z_0))]/(z_H-z_0) \end{aligned} \tag{2}$$

The same equations hold for $A_B(z_0)$ and α_B, where $B_c(z_H)$ and $B_c(z_0)$ are the direct clear-sky irradiances at z_H and $z_{0.}$

2.2 Parameterisation 2

The second parameterisation (p2) is an extension of that proposed by Abdel Wahab et al. (2009) and inspired from Gueymard and Thevenard (2009). Here, global and direct irradiances are defined as:

$$\begin{aligned} I_c(z) &= I_0\exp[-\tau(z_0)\beta^{(z0-z)}] \\ B_c(z) &= I_0\exp[-\tau_B(z_0)\beta_B^{(z0-z)}] \end{aligned} \tag{3}$$

Knowing clear-sky irradiances at two different altitudes, $I_c(z_H)$ at z_H and $I_c(z_0)$ at z_0, $\tau(z_0)$ and β are given by:

$$\begin{aligned} \tau(z_0) &= -\ln(I_c(z_0)/I_0) \\ \beta &= \exp[\ln(\tau(z_0)/\tau(z_H))/(z_0-z_H)] \end{aligned} \tag{4}$$

The same equations hold for $\tau_B(z_0)$ and β_B, where $B_c(z_H)$and $B_c(z_0)$ are the direct clear-sky irradiances at z_H and z_0.

2.3 Linear interpolations

The interpolator p3 is a simple linear interpolation between the irradiances known at 0 km and 2 km and extrapolation for other altitudes. The interpolator p4 is a piecewise linear interpolation. Four intervals are defined, from 0 km to 2 km, every 500 m. The irradiance is known at each of the five limits. Within each interval, the irradiance is computed by a linear interpolation; extrapolation is performed for other altitudes.

3 Comparison with libRadtran

A Monte-Carlo technique is applied to randomly select 5000 sets within the 9D-space defined by discrete values taken by the 9 most prominent inputs to libRadtran with respect SSI: solar zenith angle, aerosol optical depth, type and Angstrom

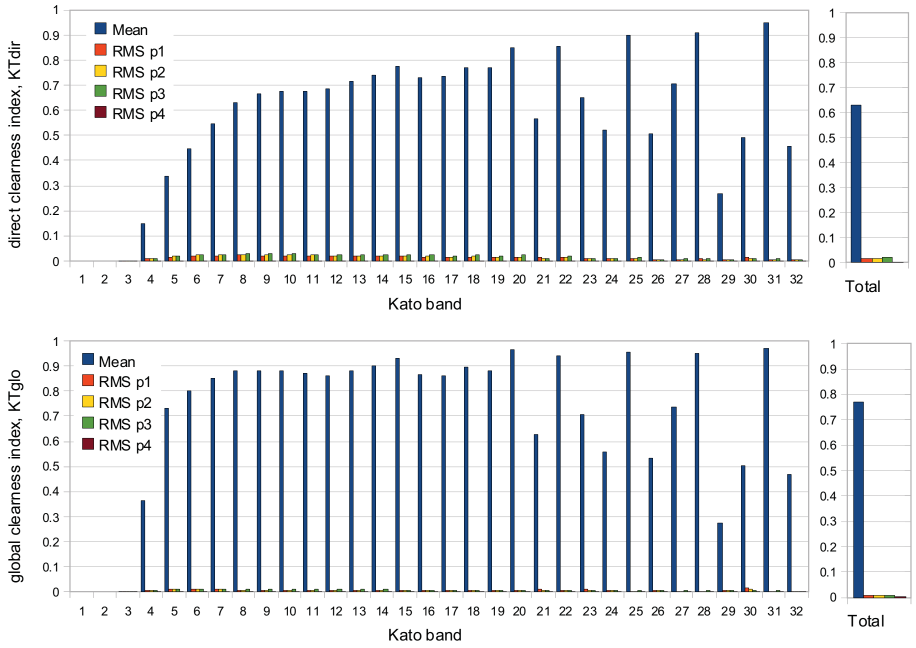

Figure 2. Mean KT and RMS for each parameterisation.

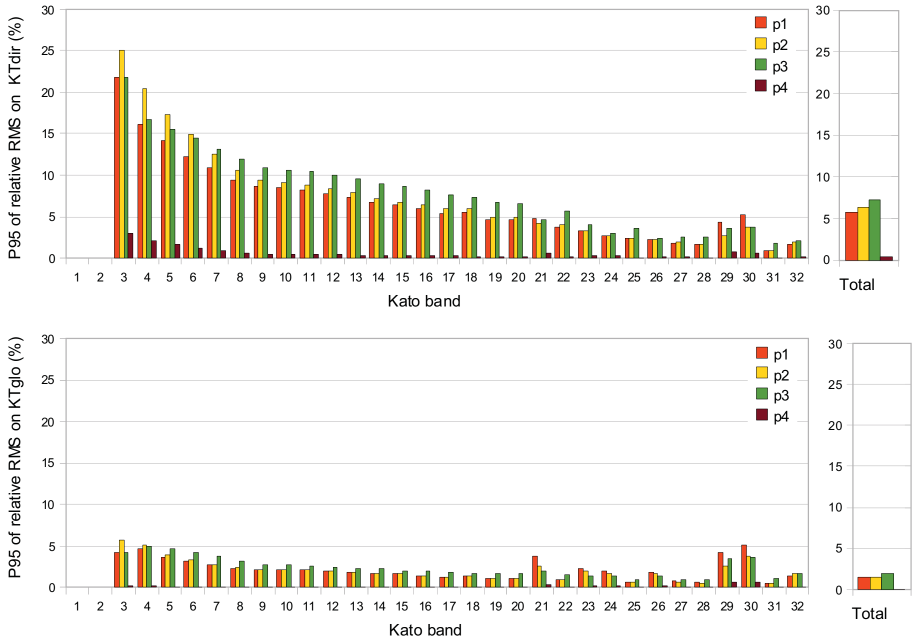

Figure 3. P95 of relative RMS for each parameterisation.

exponent, total column water, total column ozone, altitude of the ground, ground albedo and atmospheric profile. We have selected these optical properties considering their observed marginal distribution. More precisely, we have chosen the uniform distribution as a model for marginal probability for all parameters except for the parameters related to aerosol, albedo and ozone. We have selected the normal law for the Angstrom coefficient, the gamma law for the aerosol optical depth and the beta law for total column ozone and ground albedo. The parameters of the laws are empirically determined from the analyses of the observations made in the AERONET network for aerosol properties and from meteorological satellite-based ozone products. The aerosol type "continental average" is used half the time. By weighting

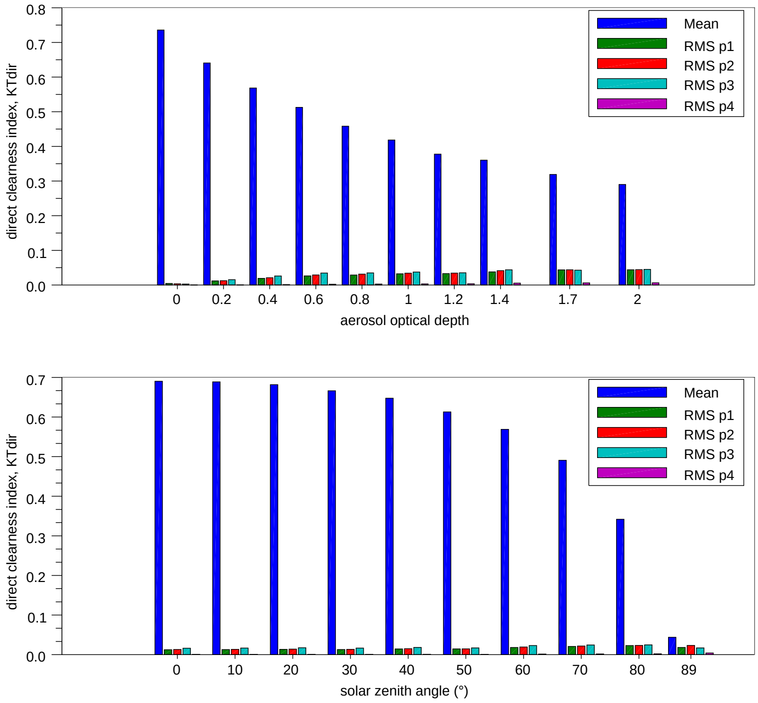

Figure 4. Variation of KTdir and of corresponding RMS with aerosol optical depth and solar zenith angle. Spectral and total KT are mixed up.

these selections, we reduce the amount of rare atmospheric states where very few SSI and large relative errors are obtained. For each 9-tuple, libRadtran outputs are total global and direct irradiances, and their spectral values for the 32 Kato spectral bands, for 21 altitudes from 0 to 2 km every 100 m above the surface.

The parameterisations p1, p2 and p3 are adjusted on the irradiances at 0 km and 2 km. Three more altitudes are used with p4. Irradiances at altitudes not used are computed with each parameterisation p1 to p4 and compared to those from libRadtran. The comparison is made on the clearness index KT defined as the ratio between the spectral surface irradiance and the corresponding spectral top-of-atmosphere. KTdir and KTglo are computed. The differences are synthesized by the RMS (Root Mean Square deviation) and the percentile 95 % (P95) of the frequency distribution of the RMS within the 21 altitudes. They are compared to the mean KT (Fig. 2).

Errors in KTglo are very small for each band and total: each parameterisation reproduces well the vertical profile. As for the total, the errors in KTdir are greater in absolute value than those in KTglo for each band. Their relative values are also greater: they may amount to 3–5 % at short wavelength and 1–2 % at long wavelength. The parameterisation p3 performs the worst of the four tested functions. The parameterisation p1 and p2 are close, their accuracies are similar on KTglo, p1 performs better than p2 at wavelengths shorter than 800 nm, and p2 performs better at longer wavelengths. The parameterisation p4 performs the best.

Figure 3 shows the P95 and stresses the inaccuracies that can occur in very turbid atmospheres.

P95 for KTglo is less than 5 % for all parameterisations and for most wavelengths. P95 is less than 10 % for KTdir for all parameterisations for wavelengths greater than 600 nm, and reaches a maximum of 25 % at 300 nm for p2. This demonstrates that these parameterisations are accurate for the global and direct irradiances. Note that P95 in KTdir and KTglo for p4 is very low for all bands. Relative performances of parameterisations are the same as in Fig. 2. p3 remains the worst and p4 the best. p1 is better than p2 at short wavelengths and p1 is better at longer wavelengths. If one selects the best parameterisation between p1 and p2 at each Kato band, P95 will be less than 5 % for KTglo for all wavelengths and for KTdir for all wavelengths greater than 800 nm. P95 greater than 10 % will be obtained only for wavelengths less than 450 nm. These regions are not the main contributors to the total extraterrestrial irradiance: they represent only 15 %, and the conclusion should take this into account of total irradiance. Accuracy of p4 remains good; the error is the greatest in the less-energetic bands and is less than 10 % for all bands. Actually, these large relative errors in KT are small in SSI: the corresponding RMS is less than 6 W m^{-2} and 8 W m^{-2} on direct and global total irradiance.

The errors for each parameterisation are not related to precipitable water and ground albedo but depend on solar zenith angle and aerosol optical depth (Fig. 4). The RMS increases with the solar zenith angle or aerosol optical depth, and therefore as KTdir decreases. This does not lead to an important absolute RMS, but its relative value can be greater than 50 %, especially when both solar zenith angle and aerosol optical depth are large. In such extreme cases, only the parameterisation p4 performs well. The RMS increases also with Angstrom alpha coefficient, especially for large wavelengths. Similar observations are made for the bias.

4 Conclusions

This study demonstrates that it is possible to reproduce the vertical profile of the spectral global and direct irradiances under clear-sky with sufficient accuracy using an analytical parameterisation. Such parameterisations can be used in the case of extrapolating irradiance assessed for a pixel to a site of different altitude within this pixel, or extrapolating irradiance measured at a station to a close site of different altitude, or for designing a fast method for processing satellite data based on RTM.

In low atmospheric turbidity, all four assessed parameterisations are accurate. The accuracy decreases as the radiation path length in the atmosphere (turbidity and solar zenith angle) increases, especially for direct irradiance. For standard atmospheric compositions, p1 performs well for wavelengths shorter than 800 nm and p2 performs well for longer wavelengths. They could be good candidates for the regions in the field-of-view of Meteosat where the aerosol optical depth is rarely greater than 1, with a mean close to 0.3–0.4. Other cases are rare and correspond to very small irradiances. In such extreme cases, high relative deviations are obtained with p1, p2 and p3. If one looks for a robust modelling, one should select the piecewise linear interpolation.

Acknowledgements. The research leading to these results has received funding from the European Union's Seventh Framework Programme (FP7/2007-2013) under Grant Agreement no. 218793 (MACC project). The authors would also like to thank the developers of libRadtran (http://www.libradtran.org).

Edited by: S.-E. Gryning
Reviewed by: two anonymous referees

The publication of this article is sponsored by the Swiss Academy of Sciences.

References

Abdel Wahab, M., El-Metwally, M., Hassan, R., Lefèvre, M., Oumbe, A., and Wald, L.: Assessing surface solar irradiance in Northern Africa desert climate and its long-term variations from Meteosat images, Int. J. Remote Sens., 31, 261–280, 2009.

Gueymard, C. A. and Thevenard, D.: Monthly average clear-sky broadband irradiance database for worldwide solar heat gain and building cooling load calculations, Sol. Energy, 83, 1998–2018, 2009.

Kato, S., Ackerman, T., Mather, J., and Clothiaux, E.: The k-distribution method and correlated-k approximation for shortwave radiative transfer model, J. Quant. Spectrosc. Ra., 62, 109–121, 1999.

Mueller, R. W., Matsoukas, C., Gratzki, A., Behr, H. D., and Hollmann, R.: The CM-SAF operational scheme for the satellite based retrieval of solar surface irradiance – A LUT based eigenvector hybrid approach, Remote Sens. Environ., 113, 1012–1024, 2009.

Oumbe, A. and Wald, L.: A parameterisation of vertical profile of solar irradiance for correcting solar fluxes for changes in terrain elevation, in: Earth Observation and Water Cycle Science Towards a Water Cycle Multi-mission Observation Strategy, 18–20 November at ESRIN, Frascati, Italy, 2009.

Oumbe, A., Blanc, Ph., Ranchin, T., Schroedter-Homscheidt, M., and Wald, L.: A new method for estimating solar energy resource, in: Proceedings of the ISRSE 33, Stresa, Italy, 4–9 May 2009, published by Joint Research Center, Ispra, Italy, USBKey, paper 773, 2009.