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Brief Note

A broadband simplified version of the Solis clear sky model

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Abstract

The Solis clear sky model is a new scheme based on radiative transfer calculations and the Lambert–Beer relation. When used on large geographical scale to convert meteorological satellite images into radiation data, the radiative transfer calculations are too computer time consuming. To circumvent this problem, a broadband simplified analytical version of the Solis model is presented in this note. The accuracy for the clear sky beam, global and diffuse irradiance components compared to the original model are, respectively, 1%, 2% and 5% with no bias.

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1. Introduction

The knowledge of the clear sky irradiance reaching the ground is a key parameter in the field of solar radiation modeling and evaluation. Many empirical and physical models can be found in the literature (i.e. Bird and Huldstrom, 1980; Geiger et al., 2002; Gueymard, 1989, 2004; Kasten, 1980; Molineaux et al., 1998; Rigollier et al., 2000), they are well validated and have an accuracy of the order of 30 W m^{-2} for the three components (Ineichen, 2006).

The Solis model (Mueller et al., 2004) was developed within the frame of the European project Heliosat-3 and is used as normalization function in the Meteosat satellite irradiance evaluation process. It is a spectrally resolved physical model, based on radiative transfer model (RTM) calculations, it needs atmospheric water vapor column and aerosol content as main input parameters. These two parameters can be retrieved, for example, from the Aerosol Robotic Network (www.aero-net.org), Soda data bank (www.helioclim.net) or Meteonorm program (www.meteonorm.com).

This technical note presents a broadband simplified version of the model to avoid the time consuming RTM calculations and can therefore be used in real time processes, such as irradiance mapping or solar systems output supervision. The scheme is used to derive the radiation components from the GOES satellites in the US (George et al., 2007).

2. Solis model (Mueller et al., 2004)

The knowledge of the aerosol and water vapor content of the atmosphere makes evaluation of the clear sky irradiance possible with Solis, a model based on radiative transfer calculations. The basis of the model is the Lambert–Beer relation:

$$I_{\mathrm{bn}} = I_{\mathrm{o}} \cdot \exp(-M \cdot \tau) \tag{1}$$

where I_{o} is the extraterrestrial irradiance, I_{bn} the normal beam irradiance reaching the ground, M the optical air mass and τ the total atmospheric optical depth. This expression of the atmospheric transmittance is valid for monochromatic radiation, and the optical depth is then constant over the air mass range. Due to the non-linear nature of the exponential function, the Lambert–Beer relation has to be modified to extend the expression to wavelength bands; it takes then the following form:

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$$I_{\mathrm{bn}} = I_{\mathrm{o}} \cdot \exp\left(\frac{\tau}{\sin^b h}\right) \tag{2}$$

where h is the solar elevation angle and b the fitting parameter obtained from RTM calculations at two different solar elevation angles.

When dealing with global irradiance, the Lambert–Beer relation is no longer applicable because of the back scatter effects, but remains a relatively good approximation, and

$$I_{\mathrm{gh}} = I_{\mathrm{o}} \cdot \exp\left(-\frac{\tau}{\sin^g h}\right) \cdot \sin h \tag{3}$$

is a good fitting function for the horizontal global irradiance (Mueller et al., 2004).

The source of the incoming diffuse irradiance is the attenuation of the beam radiation due to scattering process and it cannot be described in term of attenuation of the incoming radiation. Nevertheless, skipping the $\sin h$ term, the modified Lambert–Beer relation also works well:

$$I_{\mathrm{dh}} = I_{\mathrm{o}} \cdot \exp\left(-\frac{\tau}{\sin^d h}\right) \tag{4}$$

Table 1
Mean bias difference, root mean square difference and correlation coefficient between RTM calculations and actual model for the Solis model parameters

	I_0	Global		Beam		Diffuse	
	[W/m^2]	τ_{g}	g	τ_{b}	b	τ_{d}	d
Average	1618	0.464	0.402	0.606	0.491	2.698	0.187
mbd	−3	0.001	0.000	0.001	0.000	0.000	0.000
rmsd	10	0.005	0.016	0.007	0.013	0.015	0.004
r^2	0.999	1.000	0.887	1.000	0.946	0.999	0.999

At high aerosol load, I_{o} has to be enhanced for the global and diffuse irradiance calculations, and a common modified I'_{o} irradiance is defined for the three radiation components. The final expression of the model has then the following form:

$$I_{\mathrm{bn}} = I'_{\mathrm{o}} \cdot \exp\left(-\frac{\tau_{\mathrm{b}}}{\sin^b h}\right) \tag{5}$$

$$I_{\mathrm{gh}} = I'_{\mathrm{o}} \cdot \exp\left(-\frac{\tau_{\mathrm{g}}}{\sin^g h}\right) \cdot \sin h \tag{6}$$

$$I_{\mathrm{dh}} = I'_{\mathrm{o}} \cdot \exp\left(-\frac{\tau_{\mathrm{d}}}{\sin^d h}\right) \tag{7}$$

where τ_{b}, τ_{g} andτ_{d} are respectively the beam, global and diffuse total optical depths, and b, g and d the corresponding fitting parameters obtained from RTM calculations.

The Solis clear sky model accuracy evaluated against data from 16 independent measurements stations covering a wide range of latitudes, altitudes and climates is of the order of 15, 20 and 18 W m^{-2} for, respectively, the beam,

Table 2
Mean bias difference, root mean square difference and correlation coefficient between RTM calculations and actual model for the irradiance parameters at optical air mass $M = 2$

	Normal beam		Hor. beam		Global		Diffuse		Global – diffuse	
	[W/m^2]	%	[W/m^2]	%	[W/m^2]	%	[W/m^2]	%	[W/m^2]	%
Average	600	–	220	–	285	–	67	–	65	–
mbd	−2	0%	0	0%	−1	0%	−1	−2%	0	−1%
rmsd	10	2%	3	2%	3	1%	3	5%	3	5%
r^2	0.999		1.000		1.000		0.998		0.996	

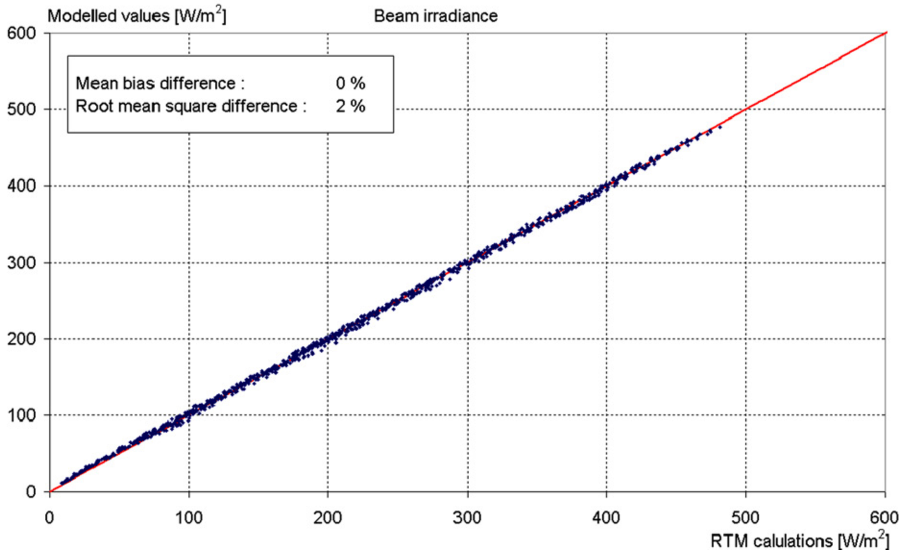

Fig. 1. Modelled beam irradiance versus RTM calculations at $M = 2$.

global and diffuse components. The model is fully described, justified and validated in Mueller et al. (2004) and Ineichen (2006).

3. Simplified model

RTM calculations are computer time consuming and are difficult to implement in a real time process, like in the evaluation of solar irradiance from satellite images on a large geographical scale.

To circumvent this problem, RTM calculations are done for a wide range of altitudes and atmospheric conditions to obtain the Solis model parameters, and a best fit is then conducted on the I'_o, b, g and d with respect to the atmospheric aerosol and water vapor content, and the altitude (the ozone content is taken constant at 340 Dobson units and the aerosol type as urban). This includes more than 900 combinations. The aerosol optical depth used in the fits is taken at 700 nm, this is motivated by its broadband and monochromatic equivalence at this wavelength (Molineaux et al., 1998). The model parameters can then be calculated analytically instead of RTM calculations, and the clear sky irradiances obtained from the above equations.

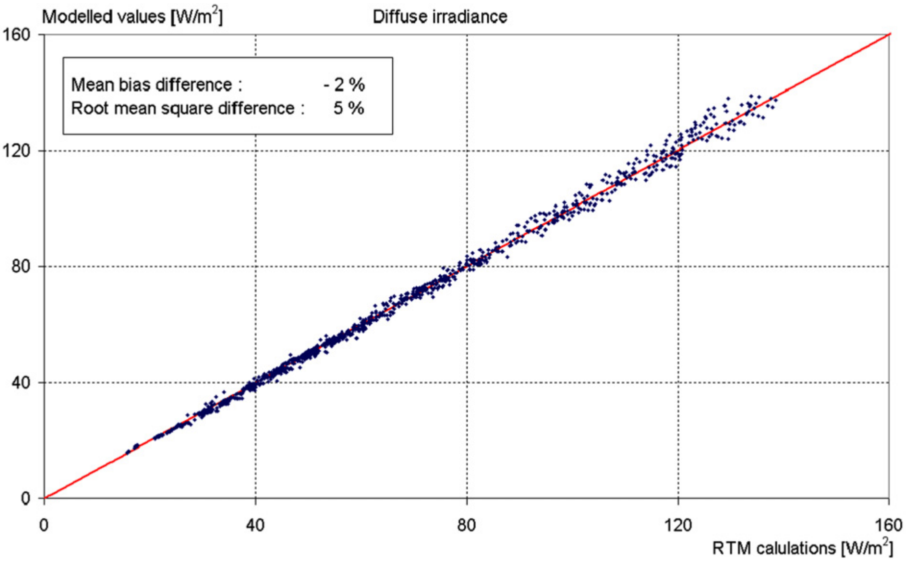

Fig. 2. Modelled diffuse irradiance versus RTM calculations at $M = 2$.

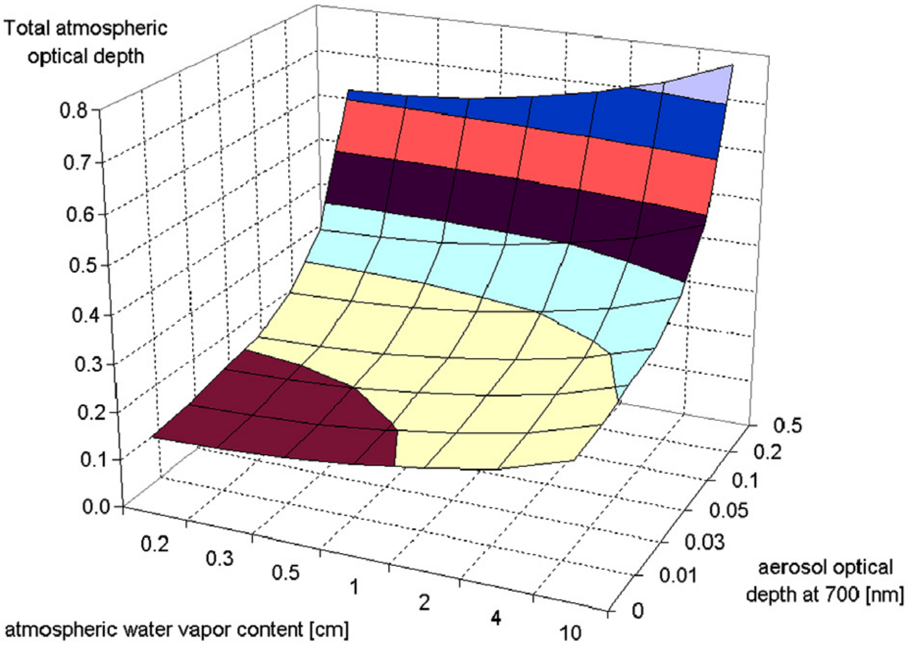

Fig. 3. Broadband total optical depth versus the water vapor column and the atmospheric aerosol load obtained with the simplified model.

The range of altitude and atmospheric parameters used to conduct the best fit are the following:

sea level $<$ altitude < 7000 m
$0 < \mathrm{aod}_{700} < 0.45$
0.2 cm $< \mathrm{w} < 10$ cm

where w is the water vapor column in cm and aod_{700} is the aerosol optical depth at 700 nm.

The formulation of the different model parameters are given in Appendix, and the fitting statistics in Table 1. It has to be noted here that these statistics concern the transition from RTM calculations to the simplified version, and not from measurements to model. The latter statistics are given in Ineichen (2006).

The final products of the simplified model are the clear sky irradiance components, and these have to be evaluated and compared to the original RTM Solis model. This is done for the normal and horizontal beam components, the horizontal global and diffuse components, and the diffuse obtained by subtraction of the horizontal global and beam irradiances. The statistics of the validation are given in Table 2 and illustrated in Figs. 1 and 2 for, respectively, the normal beam and the diffuse irradiance for the typical value of optical air mass $M = 2$. The fitted coefficients are independent from air mass and a validation on other air mass values gives the same results.

For all of the irradiance components, the bias is negligible (less than $2\ \mathrm{W\,m^{-2}}$), the standard deviation is $10\ \mathrm{W\,m^{-2}}$ for the normal beam irradiance, and $3\ \mathrm{W\,m^{-2}}$ for all the other components.

The 3-dimensional graph in Fig. 3 shows the broadband atmospheric optical depth τ (Eq. (1)) obtained with the present simplified model versus the atmospheric water vapor content and the aerosol optical depth at 700 nm.

4. Conclusion

In order to minimize the clear sky irradiances evaluation time when needed on a large geographical scale, a simplified version of the RTM based Solis model is developed. The driving coefficients of the model are calculated from analytical expressions instead of being retrieved from RTM calculations.

The input parameters are the atmospheric aerosol optical depth and water vapor column, while the ozone content is taken constant at 340 Dobson units and the aerosol type as urban. Evaluated on a large range of input parameters, the irradiances obtained with the simplified version are within 1% for the global component, 2% for the beam component and 5% for the diffuse component, with a negligible bias ($<2\ \mathrm{W\,m^{-2}}$), all this compared to the original RTM Solis model.

Appendix

Parametrization of the different coefficients.

Enhanced extraterrestrial irradiance I'_{o}:

$$I'_{\mathrm{o}} = I_{\mathrm{o}} * \{I_{\mathrm{o2}} * \mathrm{aod}_{700}^2 + I_{\mathrm{o1}} * \mathrm{aod}_{700} + I_{\mathrm{o0}} + 0.071 * \ln(p/p_{\mathrm{o}})\}$$

$$\text{with } I_{\mathrm{o0}} = 1.08 * w^{0.0051}$$
$$I_{\mathrm{o1}} = 0.97 * w^{0.032}$$
$$I_{\mathrm{o2}} = 0.12 * w^{0.56}$$

where p_{o} is the atmospheric pressure at sea level, p the atmospheric pressure at considered altitude, w the water vapor column in [cm] and aod_{700} the aerosol optical depth at 700 nm.

Coefficients for Eq. (5):

$$\tau_{\mathrm{b}} = t_{\mathrm{b1}} * \mathrm{aod}_{700} + t_{\mathrm{b0}} + t_{\mathrm{bp}} * \ln(p/p_{\mathrm{o}})$$

$$\text{with } t_{\mathrm{b1}} = 1.82 + 0.056 * \ln(w) + 0.0071 * \ln^2(w)$$
$$t_{\mathrm{b0}} = 0.33 + 0.045 * \ln(w) + 0.0096 * \ln^2(w)$$
$$t_{\mathrm{bp}} = 0.0089 * w + 0.13$$

$$b = b_1 * \ln(w) + b_0$$

$$\text{with } b_1 = 0.00925 * \mathrm{aod}_{700}^2 + 0.0148 * \mathrm{aod}_{700} - 0.0172$$
$$b_0 = -0.7565 * \mathrm{aod}_{700}^2 + 0.5057 * \mathrm{aod}_{700} + 0.4557$$

Coefficients for Eq. (6):

$$\tau_{\mathrm{g}} = t_{\mathrm{g1}} * \mathrm{aod}_{700} + t_{\mathrm{g0}} + t_{\mathrm{gp}} * \ln(p/p_{\mathrm{o}})$$

$$\text{with } t_{\mathrm{g1}} = 1.24 + 0.047 * \ln(w) + 0.0061 * \ln^2(w)$$
$$t_{\mathrm{g0}} = 0.27 + 0.043 * \ln(w) + 0.0090 * \ln^2(w)$$
$$t_{\mathrm{gp}} = 0.0079 * w + 0.1$$

$$g = -0.0147 * \ln(w) - 0.3079 * \mathrm{aod}_{700}^2 + 0.2846 * \mathrm{aod}_{700} + 0.3798$$

Coefficients for Eq. (7):

$$\tau_{\mathrm{d}} = t_{\mathrm{d4}} * \mathrm{aod}_{700}^4 + t_{\mathrm{d3}} * \mathrm{aod}_{700}^3 + t_{\mathrm{d2}} * \mathrm{aod}_{700}^2 + t_{\mathrm{d1}} * \mathrm{aod}_{700} + t_{\mathrm{d0}} + t_{\mathrm{dp}} * \ln(p/p_{\mathrm{o}})$$

with for $\mathrm{aod}_{700} < .05$

$$t_{\mathrm{d4}} = 86 * w - 13800$$
$$t_{\mathrm{d3}} = -3.11 * w + 79.4$$
$$t_{\mathrm{d2}} = -0.23 * w + 74.8$$
$$t_{\mathrm{d1}} = 0.092 * w - 8.86$$
$$t_{\mathrm{d0}} = 0.0042 * w + 3.12$$
$$t_{\mathrm{dp}} = -0.83 * (1 + \mathrm{aod}_{700})^{-17.2}$$

and for $\mathrm{aod}_{700} >= .05$

$$t_{\mathrm{d4}} = -0.21 * w + 11.6$$
$$t_{\mathrm{d3}} = 0.27 * w - 20.7$$
$$t_{\mathrm{d2}} = -0.134 * w + 15.5$$
$$t_{\mathrm{d1}} = 0.0554 * w - 5.71$$
$$t_{\mathrm{d0}} = 0.0057 * w + 2.94$$
$$t_{\mathrm{dp}} = -0.71 * (1 + \mathrm{aod}_{700})^{-15.0}$$

$$d = -0.337 * \text{aod}_{700}^2 + 0.63 * \text{aod}_{700} + 0.116 + d_p * \ln(p/p_o)$$

with $d_p = 1/(18 + 152 * \text{aod}_{700})$

If not known, aod_{700} can be evaluated from aod_{500} or aod_{550} with the help of Angström relation with the hypothesis of normal size aerosols, or by the use of Bird and Hulstrom formulation (1980):

$$\text{aod}_{700} = 0.27583 * \text{aod}_{380} + 0.35 * \text{aod}_{500}$$

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