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Rethinking satellite-based solar irradiance modelling The SOLIS clear-sky module

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Abstract

Accurate solar irradiance data are not only of particular importance for the assessment of the radiative forcing of the climate system, but also absolutely necessary for efficient planning and operation of solar energy systems. Within the European project Heliosat-3, a new type of solar irradiance scheme is developed. This new type will be based on radiative transfer models (RTM) using atmospheric parameter information retrieved from the Meteosat Second Generation (MSG) satellite (clouds, ozone, water vapour) and the ERS-2/ENVISAT satellites (aerosols, ozone).

This paper focuses on the description of the clear-sky module of the new scheme, especially on the integrated use of a radiative transfer model. The linkage of the clear-sky module with the cloud module is also briefly described in order to point out the benefits of the integrated RTM use for the all-sky situations. The integrated use of an RTM within the new Solar Irradiance Scheme SOLIS is applied by introducing a new fitting function called the modified Lambert–Beer (MLB) relation. Consequently, the modified Lambert–Beer relation and its role for an integrated RTM use are discussed. Comparisons of the calculated clear-sky irradiances with ground-based measurements and the current clear-sky module demonstrate the advantages and benefits of SOLIS. Since SOLIS can provide spectrally resolved irradiance data, it can be used for different applications. Beside improved information for the planning of solar energy systems, the calculation of photosynthetic active radiation, UV index, and illuminance is possible.

Keywords: Solar irradiance modelling; Remote sensing

1. Introduction

Satellite-based remote sensing is a central issue in monitoring and forecasting the state of the Earth's atmosphere. Geostationary satellites such as METEOSAT or GOES provide cloud information in a high spatial and temporal resolution. These satellites are, therefore, not only useful for weather forecasting, but also for the estimation of solar irradiance, since the knowledge of the radiance reflected by clouds is the basis for the calculation of the transmitted irradiance. Additionally, a detailed knowledge about atmospheric parameters involved in scattering and absorption of sunlight is a further necessity. An accurate estimation of the downward solar irradiance is not only of particular importance for assessing the radiative forcing of the climate system, but also absolutely necessary for an efficient planning and operation of solar energy systems and the estimation of the energy load. Solar resource assessment

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from geostationary satellites constitutes a powerful alternative to a meteorological ground network for both climatological and operational data (Perez et al., 1998).

Solar irradiance schemes provide accurate solar irradiance data with a high spatial and temporal resolution using weather satellites such as METEOSAT and Meteosat Second Generation (MSG). Currently, most of the operational calculation schemes for solar irradiance are semiempirical and based on statistical methods. They use cloud information from the current METEOSAT or GOES satellite and climatologies of atmospheric parameters, e.g., turbidity (characterising the combined effect of aerosols and water vapour; see Perez et al., 2001 and references therein). The Heliosat method (Cano et al., 1986; Beyer et al., 2003) is certainly one of the best known. It converts METEOSAT satellite data into irradiance with a better accuracy than interpolated ground measurements could provide (Zelenka et al., 1999; Perez et al., 1998). It is applied routinely in real time at the University of Oldenburg since 1995. It has permitted the establishment of the server Satel-Light, which delivers valuable information on daylight in buildings to architects and other stakeholders (Fontoynont et al., 1997). It has also been used within the SoDa project[1] (Wald et al., 2002) for the calculation of the solar irradiance. Furthermore there exists derivates of Heliosat, e.g., Heliosat-2 (Lefèvre et al., 2002), which is optimised as an operational processing chain for climatological data. With the launch of the Meteosat Second Generation (MSG) satellite, the possibilities for monitoring the Earth's atmosphere have improved enormously. The MSG satellite will not only provide higher spatial (1 km) and temporal (15 min) resolution, but also offers with its 11 channels from 0.6 to 13 μm, the potential for the retrieval of atmospheric parameters such as additional cloud parameters, ozone, water vapour column, and with restrictions aerosols. These capabilities plus the synergy with other sensors, such as those aboard ERS-2 and ENVISAT (GOME/ATSR-2 and SCIAMACHY/AATSR), permit us to attain a refinement in the solar irradiance modelling. These refinements necessitate a rethinking of satellite-based solar irradiance modelling and going ahead with a drastic revision of the current Heliosat processing scheme. The current Heliosat scheme cannot exploit enhanced information about the atmosphere provided by improved satellite capabilities. Thus, it was necessary to develop a new scheme, which will be able to exhaust the enhanced capabilities of MSG (SEVIRI) and ENVISAT (SCIAMACHY). The accuracy of the calculated irradiance is expected to increase significantly with a scheme that can exhaust the capabilities of the new satellites. The new calculation scheme has to be fast, accurate, and should provide—in contrast to Heliosat and Heliosat-2—spectrally resolved solar irradiance data.

[1] Integration and Exploitation of Networked Solar Radiation Databases for Environment Monitoring Project.

As a consequence of the things mentioned above, the new scheme is based on the integrated use of a radiative transfer model (RTM), whereas the information of the atmospheric parameters retrieved from the MSG satellite (clouds, ozone, water vapour) and from the GOME/ATSR-2 instruments aboard the ERS-2 satellites (aerosols, ozone) will be used as input to the RTM-based scheme.[2] The direct integration of an RTM into the calculation schemes—instead of using precalculated look-up tables—is only possible if the necessary computing time can be kept small. For this purpose, a functional treatment of the diurnal solar irradiance variation is applied, allowing an appropriate operational use of an RTM within the calculation scheme. This paper focuses on the description of the new clear-sky module, especially on the integrated use of the radiative transfer model (Section 2). The linkage of the clear-sky module with the cloud module is briefly described in order to point out the benefits of the integrated RTM use for all-sky situations as well.

2. SOLIS—the new scheme

2.1. Overview

The integrated usage of the RTM within the scheme is related to the clear-sky scheme using the well-established $n-k$ relation of the Heliosat method (Cano et al., 1986; Beyer et al., 1996) or the Cloud Optical Depth (COD) option to consider cloud effects. It is important to note that the integrated use of the RTM within the clear-sky module is linked with an enormous improvement for all-sky situations as well. It is not a restriction of the model. This issue will be discussed in more detail in Section 8.1. On the other hand, the benefits and needs of the described clear-sky module can only be understood if it is seen in the context of its main purpose—the operational satellite-based solar irradiance modelling with a large geographical coverage. Keeping this in mind, it is also necessary to describe briefly the treatment of the clouds and the basics of the linkage between the clear-sky module—described in detail in this paper— and the cloud modules, which are partly still under development. The cloud modules will be discussed in more detail in a forthcoming paper after reliable MSG data will be available.

2.1.1. Using $n-k$ relation

The Heliosat method was originally proposed by Cano et al. (1986) and later modified by Beyer et al. (1996) and Hammer (2000). The basic idea of the Heliosat method is a two-step approach. In the first step, a relative normalised cloud reflectivity—the cloud index—is derived from METEOSAT images. The derived cloud index is correlated

[2] In the near future, the information from GOME/ATSR-2 will be replaced by SCIAMACHY/AATSR on ENVISAT.

to the clear-sky index k, which relates the actual ground irradiance G to the irradiance of the cloud-free case $G_{\text{clear sky}}$. Consequently, in addition to the cloud index derived from the satellite signal, a clear-sky model, providing $G_{\text{clear sky}}$, is necessary for the estimation of the actual ground irradiance. The n–k relation is powerful, validated, and leads to small root mean square deviation (RMSD) between measured and calculated solar irradiance for almost homogenous cloud situations (RRMSD of 13–15% for hourly values; Hammer, 2000). With MSG data, it can be expected that the treatment of clouds using the current n–k will be improved only due to the higher spatial and temporal resolution.

2.1.2. Using COD-based code

Within this option, the information of the cloud optical depth (COD) is used to consider the cloud effect. The COD will be retrieved operationally from MSG with software from the German Aerospace Center (DLR), based on the Apollo (Kriebel & Gesell, 1989; Saunders & Kriebel, 1988) or Nakajima (Nakajima & King, 1990) method. The RTM model SBDART (Ricchiazzi et al., 1998) has been used to find a parameterisation in order to relate the all-sky irradiance to the clear-sky irradiance. Within this parameterisation, the effective cloud-particle radii, derivable with the Nakajima and King (1990)-based scheme, can also be used. The derived parametrisation needs some fine-tuning and has to be tested with MSG data. It will be discussed in more detail in a forthcoming paper.

Regardless of the treatment of clouds, the basis for the calculation of the all-sky radiation is the clear-sky module, which is described in detail in the next section.

2.2. Basic considerations

MSG will scan the atmosphere with a very high spatial resolution (see Table 1, e.g., approximately 2.5 million pixels have to be processed every 15 min for Europe). Thus, the computing time necessary to calculate the solar irradiance for each pixel has to be very small to make an operational usage of the solar irradiance scheme possible.

Instead of using look-up tables, a new, more powerful and flexible method, the integrated use of RTM within the scheme based on a modified Lambert–Beer (MLB) relation, will be applied. The integration of an RTM into the calculation schemes, instead of using precalculated look-up tables, is only possible if the necessary computing time can be decreased enormously. For this purpose, a functional treatment of the diurnal solar irradiance variation was applied, making an appropriate explicit operational use of an RTM within the calculation schemes possible.

Starting point of the integrated use is the assumption that daily values of the atmospheric clear-sky parameters in a spatial resolution of 100 × 100 or 50 × 50 km are sufficient. This assumption is reasonable for solar energy applications in consideration of accuracy and operational practicality, because of the following.

- Daily values of water vapour and aerosols are linked with a great improvement compared to the current implicit use of a monthly turbidity climatology or aerosol and water-vapor climatologies.
- Current restrictions in the art of retrieval limit the available input with respect to the temporal and spatial resolution of the atmospheric clear-sky parameters. For example, the retrieval of aerosols from satellites is handicapped by the small aerosol reflectance and the perturbation of the weak signal by clouds and surface reflection. In addition, the retrieval of water vapor is not possible for cloudy pixels. For these reasons, retrieval of daily values in 50 × 50-km resolution with a "global" coverage in an appropriate accuracy would be a great improvement. The effect of ozone is small compared to that of aerosols and water vapour; therefore, daily ozone values are sufficient.
- The temporal daily fluctuations of solar irradiance are generally dominated by cloud fluctuations. The cloud information is used in MSG pixel resolution (see Table 1), hence in a high temporal and spatial resolution.
- The usage of the modified Lambert–Beer function, described in Section 2.5, should enable the correction of derivations from the daily values of the clear-sky irradiance in an easy and fast manner (see Section 2.5).

Using daily values of the atmospheric parameters (O_3, $H_2O_{(g)}$, aerosols) within a region of 100 × 100 km (50 × 50 km) and the modified Lambert–Beer function, only two RTM calculations are necessary to define the complete diurnal variation of the clear-sky irradiance for a given atmospheric state (see Fig. 1). The effect of clouds on the clear-sky irradiance is considered by using the n–k relation or the COD option (Section 2.1). By this way, the cloud effect is considered in MSG pixel resolution, whereby no additional explicit RTM runs are needed. Fig. 1 illustrates the new scheme and the integrated use of the RTM within the clear-sky scheme. The modified Lambert–Beer (MLB) function is discussed in detail in the next section.

2.3. The modified Lambert–Beer function

The Lambert–Beer relation is given by

$$I = I_0 \cdot \exp(-\tau) \tag{1}$$

Table 1
Improvements in METEOSAT resolution

	Spatial resolution	Temporal resolution	Spectral channels
MSG::METEOSAT	1/3 km::2.5/5 km	15 min::30 min	12::3

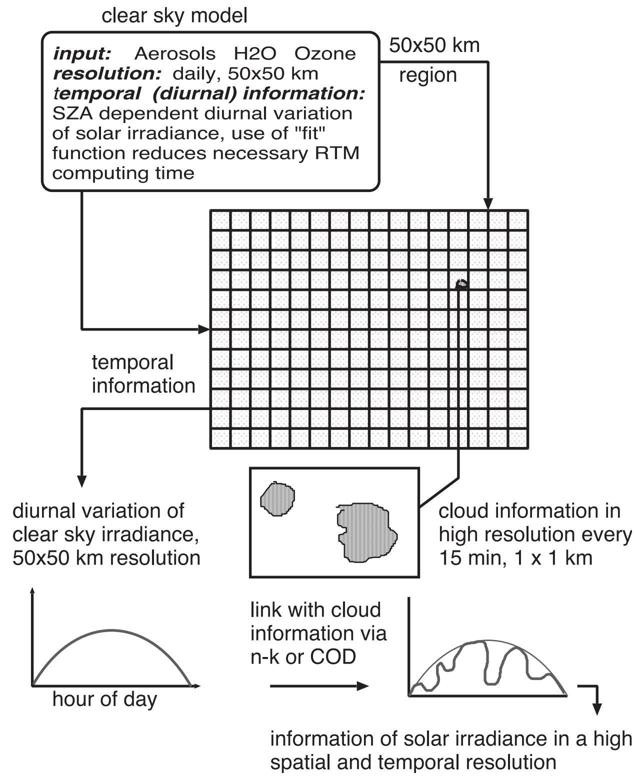

Fig. 1. Diagram of the spatial and temporal linkage between clear-sky and cloud information.

where τ is the optical depth and within the scope of atmospheric radiation, I is the direct radiation at ground with sun in zenith, I_0 is the extraterrestrial irradiance. Consideration of path prolongation and projection to the Earth's surface leads to Eq. (2), where θ_z is the solar zenith angle (SZA) and $I(\theta_z)$ is the irradiance at θ_z.

$$I(\theta_z) = I_0 \cdot \exp\left(\frac{-\tau}{\cos(\theta_z)}\right) \cdot \cos(\theta_z) \quad (2)$$

This formula describes the behaviour of the direct monochromatic radiation in the atmosphere. Transformation of Eq. (2) leads to the optical depth τ

$$\tau = -\ln\left(\frac{I(\theta_z)}{I_0 \cdot \cos(\theta_z)}\right) \cdot \cos(\theta_z) \quad (3)$$

In order to apply the Lambert–Beer relation to wavelength bands of direct irradiance, the above Lambert–Beer relation (Eq. (2)) has to be applied in a modified manner, using a two-step approach.

In a first step, the 'vertical' optical depth τ_0 is calculated at a SZA of zero degree ($\theta_z = 0$), using Eq. (4), which is a special case of Eq. (3).

$$\tau_0 = -\ln\left(\frac{I(\theta_z = 0)}{I_0}\right) \quad (4)$$

In a second step, a correction of τ_0, or the equivalent to this, of the parameter $(\tau_0)/(\cos(\theta_z))$ is performed, leading to the so-called modified Lambert–Beer relation (MLB).

$$I(\theta_z) = I_0 \cdot \exp\left(\frac{-\tau_0}{\cos^a(\theta_z)}\right) \cdot \cos(\theta_z) \quad (5)$$

The correction parameter a is calculated at a SZA of 60°.

The modified Lambert–Beer relation (Eq. (5)) cannot only be applied to wavelength bands for direct irradiance, but also to wavelength bands of global and diffuse irradiance. However, in order to apply the modified Lambert–Beer relation to global and diffuse irradiance, the following things have to be considered. At low visibilities (high optical depth, high aerosol load), I_0 in Eqs. (4) and (5) has to be enhanced for global and diffuse radiation. A general equation has been developed which is applied to I_0 to get $I_{0,\mathrm{enh}}$.

$$I_{0,\mathrm{enh}} = (1 + I_0 \cdot \left(\frac{I_{\mathrm{diffuse}}}{I_{\mathrm{direct}} \cdot I_{\mathrm{global}}}\right) \cdot I_0 \quad (6)$$

In order to avoid switching between I_0 and $I_{0,\mathrm{enh}}$, $I_{0,\mathrm{enh}}$ is always used instead of I_0 in Eqs. (4) and (5) for diffuse and global irradiance.

Additionally, for diffuse irradiance, the multiplication with $\cos(\theta_z)$ in Eq. (3) has to be skipped for diffuse irradiance, since consideration of the projection to the Earth's surface is no longer feasible.

It is important to notice that

- $I(\theta_z)$ in Eqs. (4) and (5) stands either for global, direct, or diffuse irradiance at the given SZA;
- the fitting parameter a has different values for direct, global, and diffuse irradiance;
- τ_0 is always calculated at a SZA of zero and the correction parameter a at a SZA of 60°, independent whether the MLB relation (Eq. (5)) is applied to global, direct, or diffuse irradiance.

Using the Modified Lambert–Beer (MLB) relation, the calculated direct and global radiation can be reproduced very well (see Fig. 2).

2.3.1. General remarks

The usage of the modified Lambert–Beer function is physically motivated, but it is actually a fitting function. This is especially obvious for the case of diffuse radiation. In principle, it is possible to fit the RTM calculations with any appropriate function, for example, a modified polynomial of third or higher degree ($e\cdot\cos^3(x) + f\cdot\cos^2(x) + g$). Hence, the big advantage of the modified Lambert–Beer function is not the feasibility to fit the RTM calculations, but that it is possible to yield a very good match between fitted and calculated values by using only two SZA calculations (e.g., better match than obtained with a polynomial of third degree). This is possible since the change of the irradiance with SZA is related to the Lamber–Beer law; hence, using the modified Lambert–Beer relation, "the degrees of freedom can be reduced." Moreover, the parameter *a* can be calculated without the need for a numerical fit, respectively.

The function was tested for many different atmospheric states, e.g., four different aerosol types, five different visibilities (5, 10, 23, 50, 100), different water-vapour amounts, different standard atmospheres, and surface models. No atmospheric clear-sky state is expected for which the MLB fit will not work. For our purpose, the sense of an appropriate fitting function is to save calculation time without losing "significant" accuracy. The question if a fitting function is usable for that purpose depends on the difference between the fitted values and the RTM calculated values. The differences in the broadband irradiance (306.8–3001.9 nm) are usually less than 8 W/m^2 for high SZA and less than 5 W/m^2 for SZA below 75° (8 and 4 W/m^2 for direct irradiance, respectively). For the wavelength bands, the differences are typically less than 1 W/m^2 below a SZA of 75°.

2.3.2. Discussion

For monochromatic radiation, τ is constant and consequently equals τ_0 for all SZA. In the case of wavelength bands, τ is not constant, but changes smoothly with increasing SZA. τ_0 is just the optical depth at $\theta_z = 0$ and no longer equal to τ for all SZA. The reason for that is the nonlinear nature of the exponential function; the monochromatic optical depths are, in contrast to the irradiance, not additive.

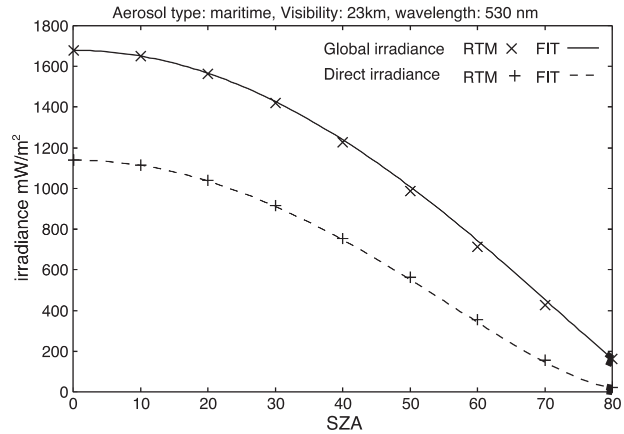

Fig. 3. For monochromatic radiation, the Lambert–Beer relation is still a good approximation if the 'vertical' optical depth τ_0 is used. In order to yield a better match, a correction of formula (2) (MLB relation) is necessary.

$$I = I(\lambda_1) + I(\lambda_2), \text{ but } \tau \neq \tau(\lambda_1) + \tau(\lambda_2) \quad (7)$$

That is the reason why a correction of the optical depth, or an equivalent to this, of the parameter $(\tau)/(\cos(\theta_z))$ is necessary.

With respect to global irradiance, it has to be mentioned that the Lambert–Beer law (Eq. (2)) is still a good approximation for 'monochromatic' global radiation and moderate aerosol load, using τ_0 (see Fig. 3). For high aerosol load, the modified Lambert–Beer relation has to be used in order to get a good match with explicit RTM results. Moreover, for wavelength bands, the use of the modified Lambert–Beer relation is absolutely necessary. The Lambert–Beer relation describes the attenuation of incoming radiation. The incoming diffuse radiation at the top of the atmosphere is negligible. The source of diffuse radiation is the attenuation of the direct radiation due to scattering processes. Hence, the Lambert–Beer law is related to the amount of diffuse radiation, but does not describe the magnitude of the diffuse radiation. However, fitting with the modified Lambert–Beer relation works very well (see Fig. 2).

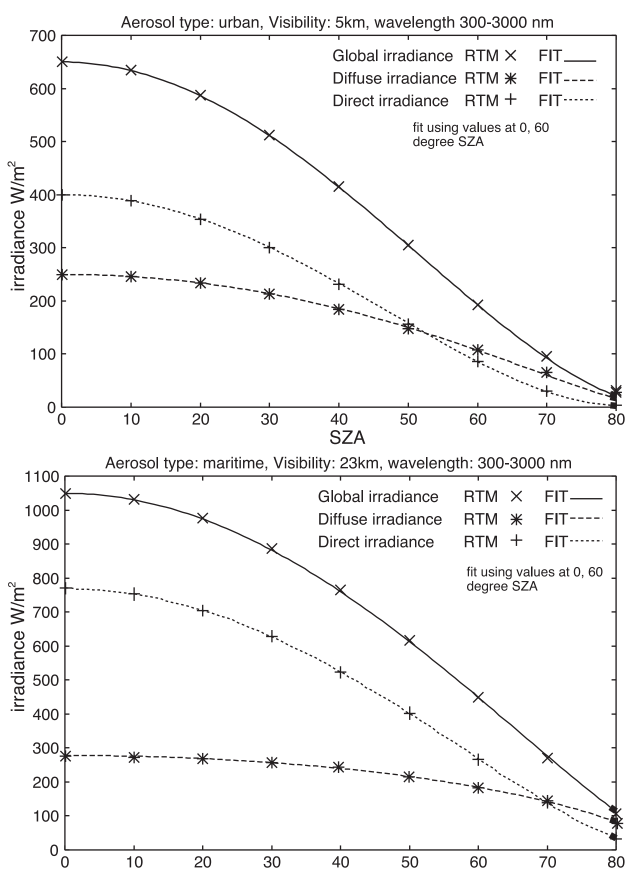

Fig. 2. Comparison between RTM calculations and fit using the modified Lambert–Beer relation for different atmospheric states.

2.4. Radiative transfer model

The radiative transfer model (RTM) used within the clear-sky module, LibRadtran,[3] is a collection of C and Fortran functions and programs for calculation of solar and thermal radiation in the Earth's atmosphere. It has been validated by comparison with other models (Koepke et al., 1998; Van Weele et al., 2000) and radiation measurements (Mayer et al., 1997). It is very flexible with respect to the

[3] available at http://www.libradtran.org.

atmospheric input, e.g., different possibilities for the input of the aerosol information can be chosen by the user.

LibRadtran offers the possibility of using the correlated-k approach of Kato et al. (1999). The correlated-k method is developed to compute the spectral transmittance (hence the spectral fluxes) based on grouping of gaseous absorption coefficients. The main idea is to benefit from the fact that the same value of the absorption coefficient k is encountered many times over a given spectral interval. Thus, the computing time can be decreased by eliminating the redundancy, grouping the values of k, and performing the transmittance calculation only once for a given value of k.

Using the correlated-k option, the spectral resolved data can be calculated operationally in MSG pixel resolution, a new feature, so far not implemented in the Heliosat or Heliosat-2 method. Consequently, solar irradiance scheme (SOLIS) calculates the global, direct, and diffuse irradiance, not only for the broadband wavelength region (300–300 nm), but for each of the Kato correlated-k (Kato et al., 1999) wavelength bands. The spectral output is provided for 27 bands between 306.8 and 3001.9 nm, which is sufficient for solar energy applications. Also, additional wavelength bands below 306.8 or above 3001.9 nm can be used. The MLB relation works very well for the spectrally resolved data (see Fig. 4 as an example).

2.5. Further benefits of the MLB function with respect to the use of water vapour, aerosol and ozone input information

The modified Lambert–Beer relation is defined with the parameters "vertical" optical depth and the correction parameters a_i. These parameters are calculated for a given atmospheric state (O_3, $H_2O_{(g)}$, AOD). A useful feature of the MLB is that different water vapour or ozone content affect the "vertical" optical depth τ_0 and not the correction parameter a (Fig. 5). Since τ_0 is calculated at a SZA of zero degree, the calculation and usage of look-up tables is

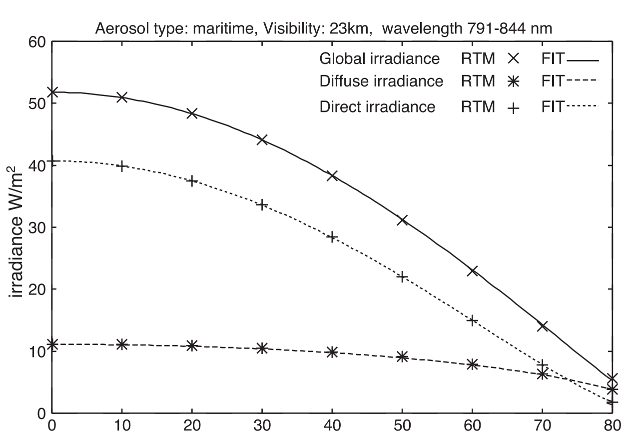

Fig. 4. Comparison between RTM calculations and fit using the modified Lambert–Beer relation. Example for a fit within a small wavelength band.

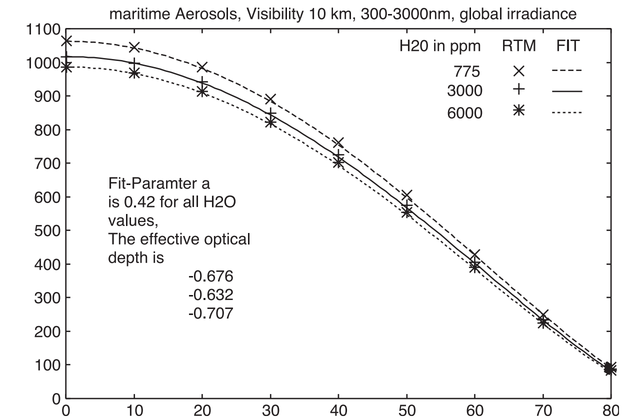

Fig. 5. Correction of H_2O deviations. The values derived with the MLB relation are compared for different $H_2O_{(g)}$ amounts. H_2O is specified in ppm (parts per million). Recalculation of the vertical optical depth leads to a good agreement between MLB values and the explicit RTM runs for the same a_i.

straightforward, because calculations at zero degree SZA deal with vertical columns and not with slant columns. For aerosols, both quantities—τ_0 and a_i—change for different values of the aerosol optical depth (AOD). In contrast to O_3 and $H_2O_{(g)}$, which are pure absorbers, aerosols are strong scattering particles, affecting not only τ_0 but also the correction parameter a_i. If the changes in a_i are neglected and only τ_0 is corrected, deviations occur increasing with increasing SZA. Consequently, another correction has to applied. In the case of aerosols, deviations from the assumed value can be approximately corrected by applying the following equations. To correct for increase of AOD from τ_{A1} to τ_{A2}

$$I_{cor} = 2 \cdot I_{MLB}^{\tau_{A1}} \cdot \frac{I^{0,\tau_{A2}}}{I^{0,\tau_{A1}}} - I^{0,\tau_{A2}} \cdot \cos(\theta_z) \quad (8)$$

To correct for decrease in AOD from τ_{A2} to τ_{A1}

$$I_{cor} = 0.5 \cdot \left(I_{MLB}^{\tau_{A2}} \cdot \frac{I^{0,\tau_{A1}}}{I^{0,\tau_{A2}}} + I^{0,\tau_{A1}} \cdot \cos(\theta_z) \right) \quad (9)$$

Here $I_{MLB}^{\tau_{A1}}$ is the diurnal variation of the irradiance for the AOD A1 or A2, as given by the modified Lambert–Beer fit, $I^{0,\tau_{A2}}$ and $I^{0,\tau_{A2}}$ are the irradiances at a SZA of zero for AOD A1 and A2, respectively. Based on these equations (Eqs. (8) and (9)), the correction and use of look-up tables is

Table 2
Ground stations used for the model–measurements comparison

Station	Latitude (°)	Altitude (m)	Climate	Time base (min)
Albany (NY)	42.7	100	humid continental	1
Burns (OR)	43.6	1265	semiarid	5
Eugene (OR)	44.1	150	temperate	5
FSEC–Cocoa (FL)	28.3	8	subtropical	6
Geneva (CH)	46.2	410	semicontinental	1

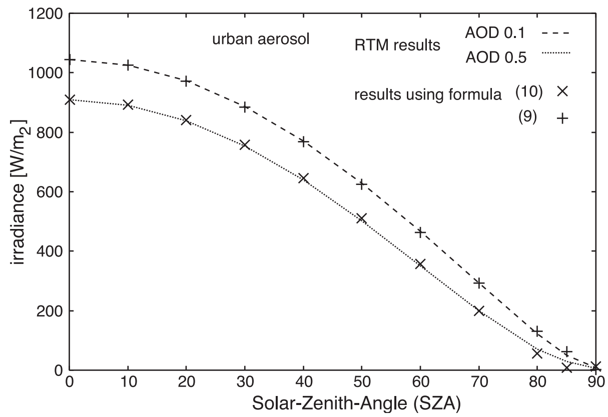

Fig. 6. Correction of Aerosol deviations, here for urban aerosols. The correction leads to an good agreement below SZA of 75°. The correction works also if marine aerosol with a AOD is corrected to urban aerosols with an AOD of 0.5.

straightforward. Look-up tables, providing the irradiance for different AOD, has only to be calculated for a SZA of zero. All other information needed to apply the above correction equations are provided by the MLB fit, using daily values as input. By this way, the effect of deviation from the daily value can be corrected in an easy and fast manner. However, before the correction methods would be included in the operational SOLIS version, further validations and optimisation of the correction procedures have to be performed.

3. Intrinsic precision of the SOLIS irradiance

In this section, the atmospheric data input is retrieved from the ground-based measurements used also for the model–solar irradiance data comparison. The main focus of this comparison is therefore to investigate the intrinsic precision of the direct-beam model.

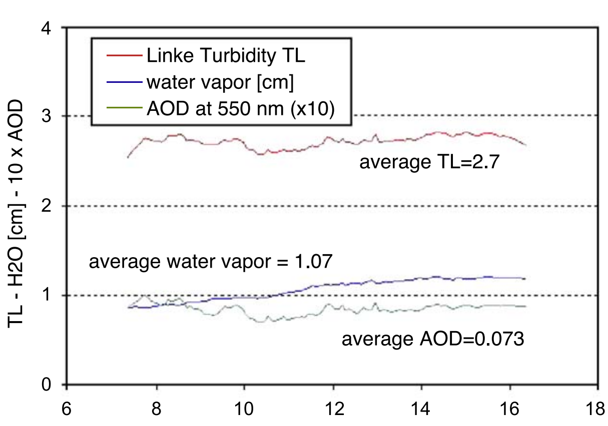

Fig. 7. February 14, 2002, Eugene (OR). The stability of the atmospheric parameters is illustrated vs. solar time.

Table 3
Aerosol load, water-vapor column, and Linke turbidity for the 13 considered days

Station	Day, year	Tau 550	w (cm)	T_L
Albany	June 25,	0.089,	3.0, 1.0	3.2,
	September 16, 2001	0.048		2.5
Burns	January 15,	0.027,	0.4, 2.0,	2.0,
	June 15,	0.093,	1.0	3.1,
	August 12, 2002	0.053		2.5
Eugene	February 14,	0.073,	1.1, 1.5	2.7,
	October 17, 2002	0.032		2.5
FSEC	March 29,	0.142,	2.0, 2.0	3.5,
	November 28, 1999	0.081		3.0
Geneva	July 21,	0.093,	1.5, 1.1	3.0,
	March 31, 1996, 1998	0.384		5.3
Geneva	April 7, July 19,	0.083,	0.6, 1.7	2.6,
	2003, 2002	0.087		3.0

3.1. Comparison of model results against ground measurements

3.1.1. Measurements

The direct-beam and global irradiance produced with the SOLIS scheme is compared with ground measurements taken at five stations with different latitudes, altitudes, and climates as given in Table 2. The comparison is done against measurements for clear and stable meteorological conditions and for different water vapour and aerosol atmospheric loads (Fig. 6). From each of the five databases, 2–4 clear days are extracted for winter and summer season. The stability of the atmospheric conditions is manually verified for each day: 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) are relatively stable as illustrated for February 14, 2002 in Eugene (OR) in Fig. 7.[4] The days used in this comparison are listed in Table 3.

Quality control has been done to eliminate specific measurements for which the direct-beam sensor is obstructed, but not the global sensor.

3.1.2. Retrieval of the atmospheric parameters

For all the data, the Linke turbidity T_L can be calculated from the normal direct-beam radiation. In order to ensure compatibility, even if the turbidity is relatively stable during the considered periods, the coefficient is evaluated at air mass 2. The water vapor column w is evaluated from ground measurements of the ambient temperature and relative humidity. With the knowledge of T_L and w, and with the help of a model developed by Ineichen (2003), the aerosol optical depth can be retrieved. These three parameters are given in Table 3 for the considered data.

An average value of 340 DU for the ozone content is taken for the comparison. It has been shown (Ineichen,

[4] When a complete day is extracted, the morning/afternoon symmetry is respected.

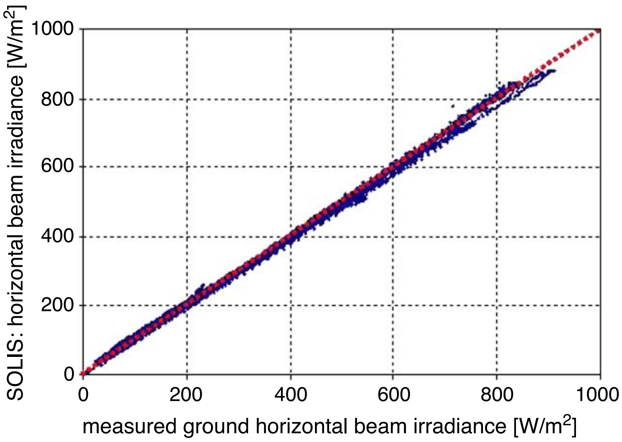

Fig. 8. Horizontal direct-beam irradiance evaluated by SOLIS vs. the correspondent ground measurements.

2003) that the influence of different ozone columns on broadband irradiance estimated by SOLIS is negligible.

3.1.3. Comparison

The result of the comparison is given in Fig. 8. The graph illustrates the modelled horizontal direct-beam irradiance vs. the ground measurements. The mean bias difference between model and measurements (MBD) and the root mean square difference (RMSD) for the 4320 values are the following:

- horizontal direct-beam irradiance: MBD = – 1 W/m^2 or – 0.2% and the RMSD = 11 W/m^2, or 2.3%
- horizontal global irradiance: MBD = 0 W/m^2 and the RMSD = 22 W/m^2, or 4.0%

The result for the global irradiance is remarkably good, taking into account that the same aerosol type was used for all the simulations. It is important to note that for the purpose of this comparison, the atmospheric clear-sky parameters are retrieved from the direct-beam measurements against which the model is compared. Within this scope, the result of the direct-beam comparison can be considered as the intrinsic precision of the SOLIS model, if accurate daily values of the atmospheric clear-sky parameter are used as input.[5]

4. Application of the model: comparison with measurements using autonomous atmospheric input

The purpose of the comparison is to discuss the advantages and benefits of the SOLIS clear-sky module especially with respect to the use of aerosol and water-vapor information instead of turbidity. The benefits and limitations of the currently available atmospheric input date is discussed briefly as well. Therefore, calculation using the described SOLIS scheme are compared with measurements from the IDMP station in Freiburg (47°59′ N, 7°50′ E) and with measurements of the meteorological station in Bergen, Norway (60.4°N, 5.3°E). Additionally, SOLIS calculations are compared with the clear-sky model used in the Heliosat method (Cano et al., 1986; Beyer et al., 2003).

4.1. Atmospheric data input

The present study deals with the clear-sky case, relevant input parameter are ozone, water vapor, and aerosols. Standard climatology profitless are used in order to take the effect of Rayleigh scattering and the effect of other gas absorber into account.

4.1.1. Ozone

To derive actual distributions of total column ozone, backscatter measurements from the Global Ozone Monitoring Experiment (GOME) onboard the ERS-2 satellite are used (Burrows et al., 1998). The core element of the retrieval is a DOAS (Differential Optical Absorption Spectroscopy) fitting technique. Due to the scanning geometry, the level-2 total column ozone data are distributed heterogeneously in time and space. To gain synoptic distributions of total column ozone and to consider atmospheric variability the data assimilation technique Kalman-Filtering is used (Daley, 1991). It is applied in conjunction with a spectral statistical planetary wave approach (Bittner et al., 1997; Bittner & Erbertseder, 2000) For this study, GOME GDP level 2 data version 3.0 from ESA/DLR are used, this data are also available at http://wdc.dlr.de. The data assimilation approach delivers global ozone column maps for a certain point in time with a horizontal resolution of 0.36°.

4.1.2. Water vapour

Total water-vapour column data (TWC) were prepared using the TOVS (TIROS Operational Vertical Sounder) instrument on the NOAA-14 satellite. TOVS raw data are analysed with the International TOVS Processing Package (ITPP; Jun et al., 1994; Jun, 1994), a physical retrieval scheme to derive atmospheric temperature and water vapour profitless for both cloudy and cloud-free situations. The average distance between retrievals is approximately 80 km, but the data are distributed irregularly in space (polar orbiting satellite). Therefore, a distance-weighting interpolation scheme is applied which delivers twice daily an European TWC data set with a spatial resolution of 0.5° (Schroedter et al., 2003). This data product is available at the World Data Center for Remote Sensing of the Atmosphere http://wdc.dlr.de). The quality of TWC in comparison with the ECMWF (European Center of Middle Range Weather Forecasting) model has been monitored for the whole year 2000. The comparison delivers differences from 0.19 ± 4.41 mm[6] for December 2000 to 4.56 ± 5.75 mm for August

[5] Daily values are not daily means.

[6] Bias ± standard deviation.

2000. This fits the required data accuracy of less than 10 mm very well.

In the future, it is planned to use water vapour column information derived from MSG itself. This will provide an improved spatial resolution and a better coverage for both Europe and Africa. It can be expected that the accuracy of the retrieved $H_2O_{(g)}$ amounts will be in the same range.

4.1.3. Aerosols

The new surface irradiance scheme allows the use of further aerosol data sets with aerosol optical depth (AOD) and aerosol type as parameters. It has recently been shown that aerosol parameters can be retrieved over land from the MISR and MODIS instruments onboard the EOS-TERRA1 (launched December 1999) and EOS-AQUA (launched May 2002) satellites (Tanre et al., 2001; Kahn et al., 1997) and from a synergetic retrieval (Holzer-Popp et al., in press a,b) of SCIAMACHY and AATSR onboard the ENVISAT satellite (launched March 2002). Therefore, the proposed new scheme holds the potential to use this upcoming operational satellite data sets in order to include up-to-date aerosol information.

In order to get the information about the aerosols for the comparison presented in this paper, Linke turbidity values based on Kasten (1996) together with the GADS/OPAC aerosol climatology are used. The GADS/OPAC climatology (Hess et al., 1998; Koepke et al., 1997) provides information of the AOD and the aerosol type, whereby the AOD is dependent on the relative humidity. However, the spatial and temporal resolution of the GADS/OPAC climatology is coarse, as only summer and winter season and a 5° spatial resolution is available. The Linke turbidity climatology provides Linke turbidities in a monthly and 5 min of arc angle resolution worldwide (available at http://www.helioclim.net/-linke/index.html). It has to be noted that this small spatial resolution is just possible, using improved interpolation routines such as data fusion. The underlying measurement data have a much higher spatial resolution.

4.2. Comparison of measurements and model, Freiburg, August 2000

Cloud-free situations were selected according to the cloud index derived with the Heliosat method from METEOSAT images. A situation was assumed to be cloud-free if the cloud index n of the respective pixel was within the interval from -0.03 to 0.03 and the spatial variation of the cloud index was less than 0.02. It is likely that some situations with partial cloud cover are still included, which especially affects the direct irradiance, leading to an increasing statistical uncertainty.

The ground measurements have originally a temporal resolution of 10 s. They are averaged to 30-min means in accordance with the temporal resolution of the satellite. The point in time when the pixel above the measurement station is scanned from the satellite lies in the middle of the 30-min averaging window. The input values for ozone and water vapor were 275 DU and 15 mm, respectively. Note that ozone has no big effect on the broadband irradiance, but does on the UV.

The turbidity map provides a turbidity of 4 for the respective months. That corresponds to a visibility of 34 km and an aerosol optical depth (AOD) of 0.23, respectively. The conversion of turbidity to visibility has been performed with the radiative transfer model MODTRAN (Abreu & Anderson, 1996). GADS/OPAC provides an AOD of 0.18–0.25 for relative humidities between 50% and 80% and urban as an aerosol type. The range of the AOD is in consistency with the visibility derived from the Linke turbidity climatology. The average relative humidity for the clear-sky days was approximately 50%, leading to an AOD of 0.18.

In Figs. 9 and 10, the comparison between SOLIS calculated and measured direct and global irradiance is diagrammed. It has to be noted that whether urban or rural aerosols are used, no significant differences in the calculated direct solar irradiance occur. Hence, just the results for the urban aerosols are diagrammed. In the case of global irradiance, the chosen aerosol type has a significant effect on the global irradiance. In both figures, the results of the Heliosat clear-sky model, described in Beyer et al. (2003), are also diagrammed.

Using the aerosol information provided by the OPAC/GADS climatology (AOD of 0.18, urban aerosol type) as input, the calculated global and direct irradiance matches the measurements very well, as shown in Figs. 9 and 10. The relative root mean square error is 1.9% for global and 4.2% for direct irradiance with a relative bias of 0.6%and 0.5%, respectively. In addition, the SZA dependency is reproduced very well by the SOLIS model.

In contrast to the results of the SOLIS calculations, the Heliosat model results in a good match for the global irradiance, but with a significant underestimation of the direct

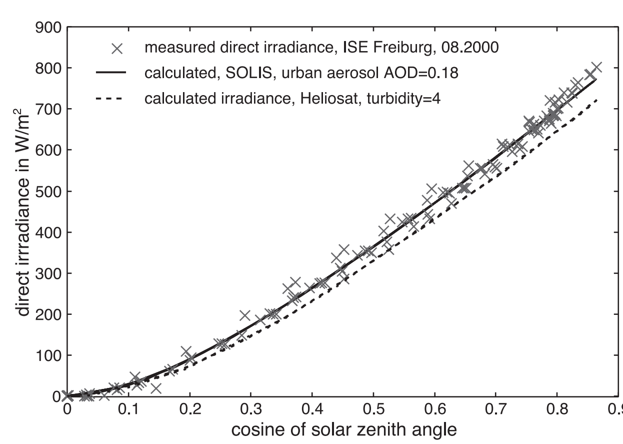

Fig. 9. Comparison between SOLIS and measurements using the GADS/OPAC information for the aerosols. The calculated Heliosat clear-sky irradiance is also diagrammed. The differences between the models are mainly due to the different atmospheric input information.

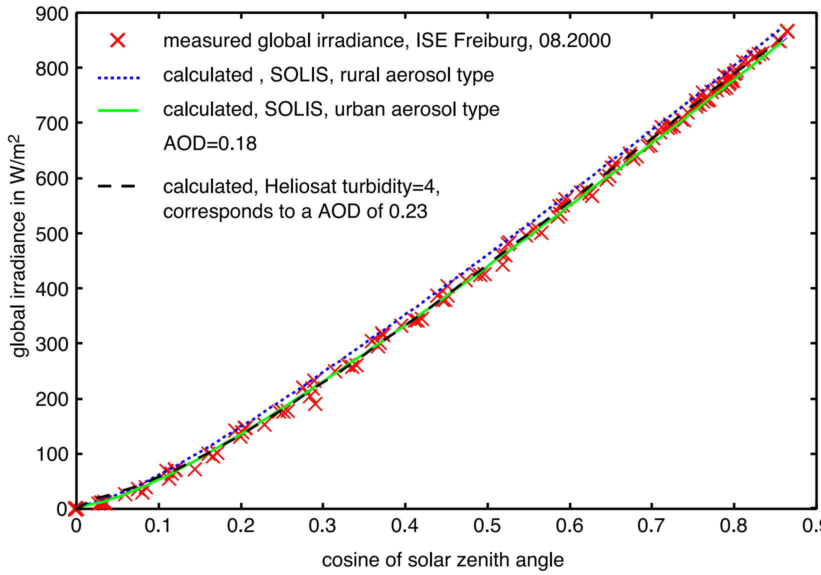

Fig. 10. Comparison between SOLIS and measurements using the GADS/OPAC information for the aerosols. The calculated Heliosat clear-sky irradiance is also diagrammed.

irradiance for the given turbidity of 4. Since the turbidity defines the attenuation of the direct irradiance, this indicates that the chosen turbidity is too low. However, decreasing the turbidity to values around 3 leads to a better match between the measurements and the Heliosat modelled direct irradiance, on the one hand, but it leads to an overestimation of the global irradiance on the other. The reason is the redundant information of the turbidity in comparison with a separated treatment of aerosol type, aerosol optical depth, and water vapour. The effect of the aerosol type on the global irradiance cannot be considered by using turbidity.

Consequently, a consistent match between measurements and calculated direct and global irradiance is only possible using information about the aerosol optical depth, the aerosol type and the water content "separately." Using the Heliosat clear-sky model or any other model that is just based on turbidity, the effect of different aerosol types on the global irradiance cannot be considered, because the information about the atmospheric state is redundant. This effect is even significant for the measurement site, but is higher for sites with higher aerosol load, or for sites characterised by special types of aerosols events, like desert storms or biomass burning. That is a drawback of Heliosat-1 and -2, but demonstrates the advantages of the SOLIS model. Moreover, reliable information of the spectral distribution of the irradiance cannot be derived by using only turbidity, without any additional information about the atmospheric state. Additionally, changes in stratospheric aerosols, e.g., an increase of the load after a volcanic eruption, cannot be treated with the current Heliosat method without a refitting of the empirical equation. Using SOLIS, just the enhanced aerosol load has to be changed in the input file and the effect is considered.

In a comparison with measurements at Mannheim (Germany), it was possible to verify that urban aerosols with a AOD of 0.18 is a reliable input for Freiburg. The station Mannheim is nearby the station Freiburg and is characterised by a similar micro-climate—cities within the Rhine valley climate. The bias between SOLIS results and measurements was below 1 ‰.

4.2.1. Spectral resolved irradiance data

Using the same atmospheric input (urban aerosol, AOD = 0.18), the measured and calculated illuminance has been compared for August 2000, Freiburg. The illuminance is a measurement of a quantity of light as perceived by the human eye. In order to calculate the illuminance, the spectrally resolved irradiance output of SOLIS is weighted with the light sensitivity of the human eye. The derived value is then multiplied with 0.683 in order to convert W/m^2 to klux. The measurements and the calculation matches very well, demonstrating that the spectral output of the model is reliable (see Fig. 11). In addition, the model results for rural aerosols are also diagrammed.

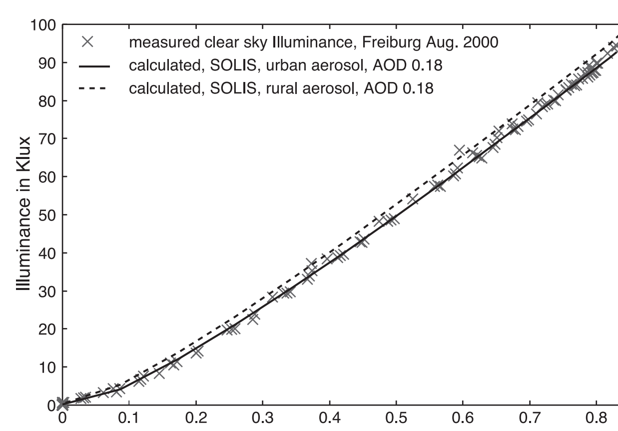

Fig. 11. Measured and modelled illuminance, clear-sky situations, Freiburg, August 2000.

Table 4
The clear days (all in May) used in this comparison

Station	Day	Year	Water column (mm)	Ozone (DU)
Bergen	7, 19	1999	7.5, 10.6	368, 316
(60.4N, 5.3E)	6, 8	2000	8.1, 11.6	347, 342
	12, 13, 14	2000	13.6, 11.0, 8.1	309, 306, 319

4.2.2. General remarks

It has to be mentioned that a good match between measured and calculated irradiances cannot be expected for every month within one season. Similar comparisons for September 2000 and 1999 lead to an acceptable but inferior match between measurements and SOLIS calculated irradiance. This is most probably due to the fact that a seasonal aerosol climatology is to coarse, see also Section 4.3. Changes in the aerosol content within a season due to transport processes are not considered, but they affect the measurements. Using climatological atmospheric data instead of daily values as input to SOLIS increases the RMSE significantly. This effect has been investigated within a study for Geneva (P. Ineichen, personal communication).

4.3. Comparison in Scandinavia

SOLIS calculations are compared against ground-measured hourly global and direct irradiance of the Nordic site: Bergen, Norway (60.4°N 5.3°E). Cloud-free days were selected according to the following criteria: (1) The ground-observed cloud cover should not exceed 1 octa during the day; (2) the curve of direct-beam normal radiation should be smooth and symmetric around noon solar time. To allow the comparison with the clear-sky model of Heliosat, which uses monthly Linke turbidity coefficients as input, days were selected from the same month (here May). The selected days are shown in Table 4. The value of the Linke turbidity for May is 3.6 for Bergen. Daily values of total water column (TWC) and ozone were used as input to SOLIS, see 4.1. The GADS/OPAC aerosol climatology suggests 'maritime tropical' and 'summer maritime tropical' as aerosol types for Bergen. In SOLIS, 'maritime' aerosols were used, in addition to 'rural' and 'urban' ones. For Bergen, the aerosol optical depth at 0.55 μm is given as 0.06 and 0.15 for a relative humidity of 10% and 90%, respectively. The actual relative humidity varies between 10% and 90% for the clear days, with the lowest humidities around and after noon.

4.3.1. Results

4.3.1.1. Direct irradiance. Fig. 12 shows the observed direct irradiance for the clear days in Bergen plotted against the SOLIS and Heliosat modelled values. Most observations fit well the SOLIS data for low and high aerosol optical depth (0.06 and 0.15). However, for 1 day in Bergen, the measured values are clearly lower and fit well with a higher aerosol optical depth of 0.28. This value is not unreasonable; Olseth and Skartveit (1989) found the range of aerosol optical depth in Bergen to be 0.07 to 0.28 with a mean value of 0.13. The effect of water vapour is seen to be smaller than the effect of aerosols. The effect of ozone is negligible (for broadband irradiance as here). However, for spectral output, also accurate values of water vapour and ozone are of great importance.

It is clear that the Heliosat model with monthly input cannot be expected to be very accurate on day to day variations, but may give good mean values. It appears, however, that SOLIS is capable of reproducing hourly radiation, given that the daily input (in particular aerosols) is accurate.

4.3.1.2. Global irradiance. Observed global irradiances for Bergen are plotted against SOLIS and Heliosat modelled values in Fig. 13 (top). Here, the SOLIS values are too high, while the Heliosat clear-sky model is closer to the observed values. However, if the aerosol type is changed from 'maritime' to 'urban', SOLIS match the observed values much better (Fig. 13, bottom). For the calculated direct irradiance, the aerosol type was of little or no importance, but for global irradiance, the aerosol type (single scattering albedo) largely

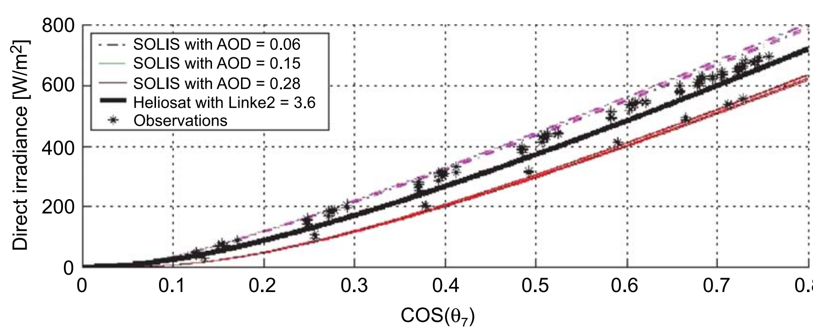

Fig. 12. Observed direct irradiances vs. modelled values by SOLIS and Heliosat. The aerosol optical depths are shown in the legend. Aerosol type is "maritime."

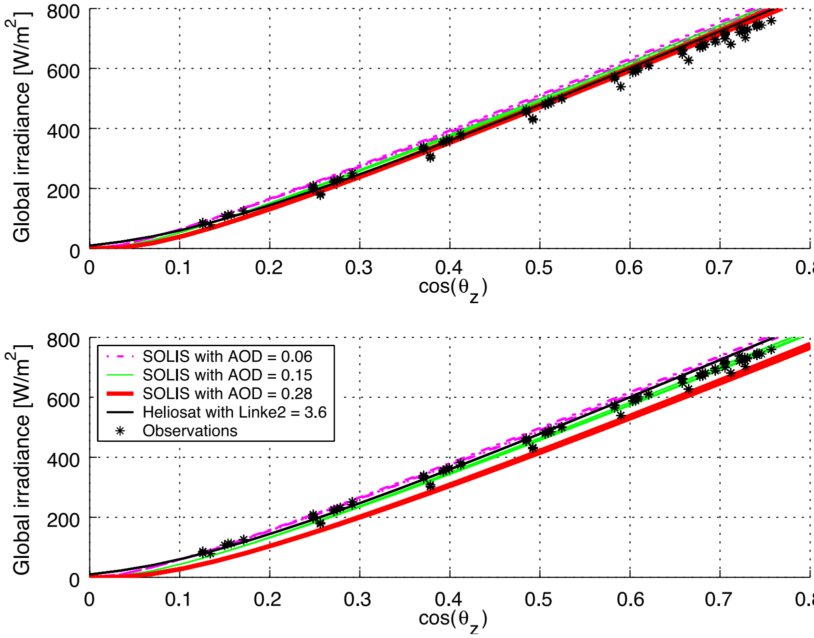

Fig. 13. Same as Fig. 12, but for global irradiance. Aerosol type is "maritime" on upper figure, and "urban" on lower figure.

affects the diffuse part. Since Bergen is a city with 235,000 citizens, urban aerosols are not unreasonable. The GADS/OPAC climatology has quite coarse resolution (5°), so it cannot account for microclimatic conditions represented by cities, especially if they are surrounded by a rural region.

5. Discussion

5.1. Treatment of clouds

The integrated use of the RTM is performed within the clear-sky module. For the treatment of clouds the $n-k$ relation or the COD option is used. With respect to the COD option, an RTM is used to find the parameterisation, but not directly integrated. The question arises why an integrated use of an RTM within the cloud module is not needed on the one hand or not possible on the other. The $n-k$ or COD option works well for almost homogenous cloud situations. Consequently, the difficulties or limitations of both options arises from heterogenous cloud effects.

With respect to 3-D cloud effects, an operational usage of an RTM for the treatment of heterogenous clouds (whether directly or using precalculated look-up tables) is not feasible today. The limitations of 3-D cloud modelling do not enable realistic RTM calculations of 3-D cloud problems in an operational manner. Just case studies are feasible. With respect to the operational use of an RTM, the problem is the nonavailability of realistic specification of heterogenous clouds from measurements. MSG will not provide sufficient information about 3-D cloud characteristics. No other satellite or measurement setup provides this information for the needed temporal resolution and spatial coverage nowadays. Besides, an explicit or integrated use of RTM is not practicable since the needed calculation time of 3-D RTM models is too large for an operational adaptation.

5.2. Spectral resolved irradiance for cloudy situations

Within previous studies, it has been shown that the cloud index is independent on the wavelength in the range of the MSG visible channels. However, the shape of the spectral clear-sky irradiance changes due to the scattering effects in consequence of the cloud particles. In order to correct the change in the spectral shape, the RTM model LibRadtran has been used to calculate look-up tables. First comparisons between measured and simulated illuminance indicate that the spectrally resolved output is now serviceable for "all-sky" situations as well. However, further validations should be done.

Using the COD option for the treatment of clouds, the effect of clouds on the spectral distribution of clear-sky irradiance is already considered. Consequently, the integrated use of the RTM is the basis for spectral resolved solar irradiance data for all-sky situations as well.

6. Summary and conclusion

Within this paper, the power and advantages of the new SOLIS model have been discussed. The main scope has been the SOLIS clear-sky module, but also the treatment of the clouds, even though this is still under development,[7] has been briefly discussed in order to explain the expected

[7] However, a SOLIS all-sky working version is available on request.

benefits of the integrated RTM use for the all-sky situations as well.

The integration of the RTM into the calculation schemes is associated with a high flexibility with respect to changes of the atmospheric state and the different user requirements on the solar irradiance data. SOLIS provides the possibility to use enhanced information of the atmospheric state and, hence, the potential to improve the accuracy of the calculated direct, global, and diffuse irradiance. Additionally, spectrally resolved data can be calculated operationally in MSG pixel resolution.

The Modified Lambert–Beer relation enables the integrated use of RTM within the clear-sky scheme. The integrated use of RTM is linked with high flexibility relating to the input of the atmospheric state, changes in theory (e.g., new aerosol models), and the desirable output parameters.

The integrated use of the RTM is linked with the following benefits:

- Spectral information is automatically provided using the correlated-*k* option included in the RTM LibRadtran package (http://www.libradtran.org/).
- Consistent calculations of global, direct, and diffuse radiation for clear-sky cases within one single scheme considering different aerosol types and not only turbidity. Hence, an improved estimation of the relation between global and direct radiation is possible, especially for clear-sky situations. The separated use of H_2O and aerosol information is a requirement for accurate information of the spectral distribution of irradiance.
- Deviations of the atmospheric state from the average (O_3, $H_2O_{(g)}$, aerosols) can be easily corrected using the results of the modified Lambert–Beer fit.
- Clear and easy linkage with cloudy sky scheme, whereby the treatment of heterogenous cloud effects is not restricted.

The usage of the modified Lambert–Beer law enables not only the direct integration of an RTM into the irradiance scheme, but also the potential for the calculation and use of easy handling look-up tables. The advantages of the modified Lambert–Beer relation, and hence, the integrated RTM use, can be adapted to other solar irradiance models as well and is therefore a new milestone in solar irradiance modelling.

The SOLIS model has been validated in three steps.

- In Section 2.3, it has been demonstrated that the MLB function matches the RTM results very well. The differences in the broadband irradiance (306.8–3001.9 nm) are usually less than 8 W/m^2 for high SZA and less than 5 W/m^2 for SZA below 75° (8 and 4 W/m^2 for direct irradiance, respectively).
- In Section 3, it has been demonstrated that SOLIS is able to reproduce very accurately (hourly) values of direct and global broadband irradiance if accurate daily atmospheric input parameters are used. The estimated RMSD is 2.3% for direct irradiance and 4% for global irradiance.
- In Section 4, SOLIS has been compared with measurements and with the Heliosat method, whereby $H_2O_{(g)}$ and O_3 retrieved from satellite data and the GADS/OPAC aerosol climatology (Hess et al., 1998; Koepke et al., 1997) have been used as input to SOLIS. It has been demonstrated that SOLIS is able to reproduce the measurements very well within the scope of the uncertainties introduced by the rough spatial and temporal resolution of the aerosol climatology. For broadband clear-sky irradiance aerosols are by far the most important parameter. Since a model depends on accurate atmospheric input data, there is an urgent need to improve the information about aerosols. Additionally, it has been shown that the aerosol type has a significant effect on the global irradiance. A consistent match between model and measurements for both global and direct irradiance was only possible by consideration of the aerosol type. In contrast to the Heliosat method (Beyer et al., 2003), which is dedicated to use turbidity information, the full information about the clear sky atmosphere, including aerosol type, can be used by SOLIS.

The improvements in the art of retrieval during the last years are impressive and still going on. Together with new remote sensing instruments such as SCIAMACHY or SEVIRI (aboard ENVISAT, MSG), it can be expected that the information about the atmospheric state, especially with respect to clouds and aerosols, will be further improved. In order to benefit from the enhanced information about the atmospheric state, a model such as SOLIS is necessary.

Keeping this in mind, the final conclusion can be drawn that the enhanced capabilities of the new MSG and ENVISAT satellites, together with the new type of solar irradiance scheme, SOLIS, will provide solar irradiance data with high accuracy, high spatial and temporal resolution, and large geographical coverage, all within the European Heliosat-3 project.

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References

Abreu, L., & Anderson, G. (1996). *The MODTRAN 2/3 report and LOWTRAN model*. Technical report, Philips Laboratory, Hanscom.

Beyer, H., Costanzo, C., Heinemann, D. (1996). Modifications of the heliosat procedure for irradiance estimates from satellite images. *Solar Energy*, *56*, 207–212.

Bittner, M., & Erbertseder, T. (2000). The STREAMER project: An overview. *Air pollution VIII*. Southhampton, Boston: WIT Press.

Bittner, M., Dech, S., Meisner, R., & Ruppert, T. (1997). *Generating GOME level 3 data products at DFD*. Technical report, DLR-DFD.

Burrows, J., Weber, M., Buchwitz, M., Rozanov, V., Ladstätter-Weißenmayer, A., Richter, A., de Beek, R., Hoogen, R., Bramstedt, K., Eichmann, K.-U., Eisinger, M., & Perner, D. (1998). The Global Ozone Monitoring Experiment (GOME): Mission concept and first scientific results. *Journal of Atmospheric Sciences*, *56*, 151–175.

Cano, D., Monget, J., Albuisson, M., Guillard, H., Regas, N., & Wald, L. (1986). A method for the determination of the global solar radiation from meteorological satellite data. *Solar Energy*, *37*, 31–39.

Daley, R. (1991). *Atmospheric data analysis*. Cambridge, UK: Cambridge University Press.

Fontoynont, M., Dumortier, D., Heinemann, D., Hammer, A., Olseth, J., Skartveit, A., Ineichen, P., Reise, C., Page, J., Roche, L., Beyer, H., & Wald, L. (1997). Satellight: A european programme dedicated to serving daylight data computed from meteosat images. *Proceedings Lux Europa 1997. Vol. The 8th European Lighting Conference, Amsterdam*. Available at: http://www.satellight.com/indexgT.htm.

Hammer, A. (2000). *Anwendungsspezifische Solarstrahlungsinformationen aus Meteosat-Daten*. PhD, School of Mathematics and Natural Sciences. University of Oldenburg.

Hammer, A., Heinemman, D., Hoyer, C., Kuhlemann, R., Lorenz, E., Müller, R., & Beyer, H. G. (2003). Solar energy assessment using remote sensing technologies. *Remote Sensing of the Environment*, *86*(3), 423–432.

Hess, M., Koepke, P., & Schult, I. (1998). Optical properties of aerosols and clouds: The software package opac. *Bulletin of the American Meteorological Society*, *79*, 831–844.

Holzer-Popp, T., Schroedter, M., & Gesell, G. (2002a). Retrieving aerosol optical depth and type in the boundary layer over land and ocean from simultaneous GOME spectrometer and ATSR-2 radiometer measurements: 1. Method description. *Journal of Geophysical Research*, *107*(D21), 4578.

Holzer-Popp, T., Schroedter, M., & Gesell, G. (2002b). Retrieving aerosol optical depth and type in the boundary layer over land and ocean from simultaneous GOME spectrometer and ATSR-2 radiometer measurements: 2. Case study application and validation. *Journal of Geophysical Research*, *107*(D24), 4770.

Ineichen, P. (2003). *Broadband comparison of SOLIS clear sky scheme against other clear sky models and 5 data banks*. Working paper Heliosat-3 project.

Ineichen, P., & Perez, R. (2002). A new airmass independent formulation for the Linke turbidity coefficient. *Solar Energy*, *73*, 151–157.

Jun, L. (1994). Temperature and water vapour weighting functions from radiative transfer equation with surface emissivity and solar reflectivity. *Advances in Atmospheric Sciences*, *11*(4), 421–426.

Jun, L., Fengxian, Z., & Qingcun, Z. (1994). Simultaneous non-linear retrieval os atmospheric temperature and absorbing constituent profiles from satellite infrared sounder radiances. *Advances in Atmospheric Sciences*, *11*(2), 128–138.

Kahn, R., West, R., McDonald, D., Rheingans, B., & Mishchenko, M. (1997). Sensitivity of multiangle remote sensing observations to aerosol sphericity. *Journal of Geophysical Research*, *102*, 16861–16870.

Kasten, F. (1996). The Linke turbidity factor based on improved values of the integral Rayleigh optical thickness. *Solar Energy*, *56*, 239–244.

Kato, S., Ackerman, T., Mather, J., & Clothiaux, E. (1999). The k-distribution method and correlated-*k* approximation for a short-wave radiative transfer. *Journal of Quantitative Spectroscopy and Radiation Transfer*, 62.

Koepke, P., Bais, A., Balis, D., Buchwitz, M., de Backer, H., de Cabo, X., Eckert, P., Eriksen, P., Gillotay, D., Koskela, T., Lapeta, V., Litynska, Z., Lorente, J., Mayer, B., Renauld, A., Ruggaber, A., Schauberger, G., Seckmeyer, G., Seifert, P., Schmalwieser, A., Schwander, H., Vanicek, K., Weber, M. (1998). Comparison of models used for UV index calculations. *Photochemistry and Photobiology*, *67*, 657–662.

Koepke, P., Hess, M., Schult, I., & Shettle, E. (1997). *Global aerosol data set*. Technical report, MPI Meteorologie Hamburg Report.

Kriebel, K. T., Saunders, R., & Gesell, G. (1989). Optical properties of clouds derived from fully cloudy AVHRR pixels. *Beiträge zur Physik der Atmosphäre*, *62*, 165–171.

Lefèvre, M., Albuisson, M., & Wald, L. (2002). *Joint report on interpolation scheme 'meteosat' and database 'climatology' i (meteosat)*. Technical report, Report for the European Commission. Available at http://www.soda-iscom/publications.

Mayer, B., Seckmeyer, G., & Kylling, A. (1997). Systematic long-term comparison of spectral UV measurements and UVSPEC modeling results. *Journal of Geophysical Research*, *102*, 8755–8767.

Nakajima, T., King, M. (1990). Determination of the optical thickness and effective particle radius of clouds from reflected solar radiation measurements: Part I. Theory. *Journal of the Atmospheric Sciences*, *47*(15).

Olseth, J., & Skartveit, A. (1989). Observed and modelled hourly luminous efficacies under arbitrary cloudiness. *Solar Energy*, *42*, 221–233.

Perez, R., Aguiar, R., Collares-Pereira, M., Dumortier, D., Estrada-Cajigal, V., Gueymard, C., Ineichen, P., Littlefair, P., Lund, H., Michalsky, J., Olseth, J., Renne, D., Rymes, M., Skartveit, A., Vignola, F., Zelenka, A. (2001). Solar resource assessment: A review. *Solar energy—the state of the art. No. ISBN 1 902916239 in ISES position papers*. (pp. 497–562). London: James and James Science Publishers.

Perez, R., Renne, D., Seals, R., & Zelenka, A. (1998a). *The strength of satellite-based solar resource assessment. Production of site/time-specific irradiances from satellite and ground data*. Report 98-3. New York State Energy Research and Development Authority, Corporate Plaza West, 286 Washington Evenue Extension, Albany, NY 12203-6399.

Perez, R., Seals, R., & Zelenka, A. (1998b). *Production of site/time-specific hourly irradiances—Satellite remote sensing vs. network interpolation. Production of site/time-specific irradiances from satellite and ground data*. Report 98-3. New York State Energy Research and Development Authority, Corporate Plaza West, 286 Washington Evenue Extension, Albany, NY 12203-6399.

Ricchiazzi, P., Yang, S., Gautier, C., & Sowle, D. (1998). Sbdart: A research and teaching software tool for plane-parallel radiative transfer in the earth's atmosphere. *Bulletin of the American Meteorological Society*, *79*(10).

Saunders, R., & Kriebel, K. (1988). An improved method for detecting clear sky and cloudy radiances from AVHRR data. *International Journal of Remote Sensing*, *9*, 123–150.

Schroedter, M., Olesen, F., & Fischer, H. (2003). Determination of land surface temperature distributions from single channel IR measurements: an effective spatial interpolation method for the use of TOVS, ECMWF and radiosonde profiles in the atmospheric correction scheme. *International Journal of Remote Sensing*, *24*(6), 1189–1196.

Tanre, D., Kaufman, Y., Holben, B., Chatenet, B., Karnieli, A., Lavenu, F., Blarel, L., Dubovik, O., Remer, L., & Smirnov, A. (2001). Climatology of dust aerosol size distribution and optical properties derived from remotely sensed data in the solar spectrum. *Journal of Geophysical Research*, *106*(18).

Van Weele, M., Martin, T., Blumthaler, M., Brogniez, C., den Outer, P., Engelsen, O., Lenoble, J., Pfister, G., Ruggaber, A., Walravens, B., Weihs, P., Dieter, H., Gardiner, B., Gillotay, D., Kylling, A., Mayer, B., Seckmeyer, G., & Wauben, G. (2000). From model intercomparisons towards benchmark UV spectra for six real atmospheric cases. *Journal of Geophysical Research*, *105*, 4915–4925.

Wald, L., Albuisson, M., Best, C., Delamare, C., Dumortier, D., Gaboardi, E., Hammer, A., Heinemann, D., Kift, R., Kunz, S., Lefèvre, M., Leroy, S., Martinoli, M., Ménard, L., Page, J., Prager, T., Ratto, C., Reise, C., Remund, J., Rimoczi-Paal, A., Van der Goot, E., Vanroy, F., & Webb, A. (2002). Soda: A project for the integration and exploitation of networked solar radiation databases. In W. Pillmann, & K. Tochtermann (Eds.), *Environmental communication in the information society: No. Part 2* (pp. 713–720). Vienna, Austria: International Society for Environmental Protection.

Zelenka, A., Perez, R., Seals, R., & Renne, D. (1999). Effective accuracy of satellite derived hourly irradiances. *Theoretical and Applied Climatology*, *62*, 199–207.