EUMETSAT Satellite Application Facility on Climate Monitoring

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CM SAF
Climate Monitoring

Algorithm Theoretical Baseline Document

Direct Irradiance at Surface

CM-SAF Product CM-104

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1. Introduction and Definition

The solar surface irradiance consists of a diffuse fraction and a direct fraction. The diffuse fraction of the surface irradiance is defined as the solar radiation that has undergone scattering in the atmosphere. The direct irradiance is the flux reaching a horizontal unit of the earth's surface in the 0.2 - 4 µm wavelength band from the direction of the sun without being scattered. Both quantities are expressed in W/m².

1.1. Motivation and strategy for a direct irradiance product

Accurate information on the direct irradiance is important for

- the prediction of energy yield, the planning, monitoring and system design of solar-thermal power plants (see Figure 1),
- the analysis and understanding of the climate system.

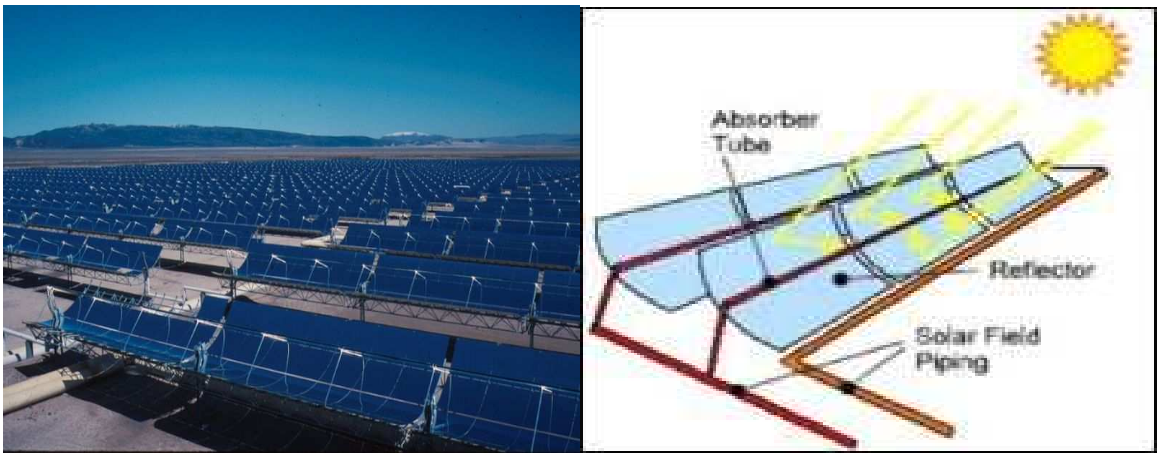

Figure 1: Principle of solar-thermal power plants: The concentration of solar surface irradiance enables the generation of high temperatures, hence the operation of "traditional" cost-efficient steam generators. Various prototypes have already been set up in southern Europe and Morocco.

Only few well-maintained ground measurements of the direct irradiance exist in Europe, while in Africa and over the ocean almost no information on surface radiation is available from surface observations. Geostationary satellites enable the retrieval of area-wide direct irradiance in high spatial and temporal resolution with good accuracy (<15 W/m²).

In the last years, CM-SAF has successfully extended well-established methods used within the Solar Energy community (e.g., Skartveith et al., 1998) to include the extended information on the atmospheric composition nowadays available from the new generation of satellites (e.g., SCIAMACHY, MSG). One important extension of the updated algorithm, which is currently used for the production of the CM-SAF SIS product, is that it employs detailed aerosol information instead of turbidity maps. The clear sky irradiance is completely based on Radiative Transfer Modelling. Finally the possibility to use an improved cloud mask is expected to improve the accuracy. The physical basis of the algorithm is described in Müller et. al (2009) and R. Müller et al. (2003).

1.2. Applicable Documents

Reference	Title	Code
AD 1	CM-SAF Product Requirements Document	SAF/CM/DWD/PRD/1.6

1.3. Reference Documents

Reference	Title	Code
RD.1	CM-SAF Science Plan	SAF/CM/DWD/SCI/3.0
RD.2	Direct Surface Irradiance Validation Report	SAF/CM/DWD/VAL/SID/1.0

2. Algorithm Overview

The calculation of direct irradiance is embedded in the operational chain for the calculation of the solar irradiance, SIS, which is generated operationally since several years.

The retrieval of the clear sky direct irradiance is realised using a look-up table (LUT) approach. For the retrieval of SIS, radiative transfer model (RTM) simulations have been conducted for the direct irradiance and stored in LUTs (Figure 2).

For cloud-contaminated pixel the approach of Skartveit et al. (1998) has been implemented. This semi-empirical approach is derived from a comparison of cloud information and ground-based measurements of global and diffuse irradiance. For fully cloudy pixel the direct irradiance is set to zero.

This strategy requires only minimal modifications of the operational SIS-code. The updated code has already been tested to perform successfully within the operational chain.

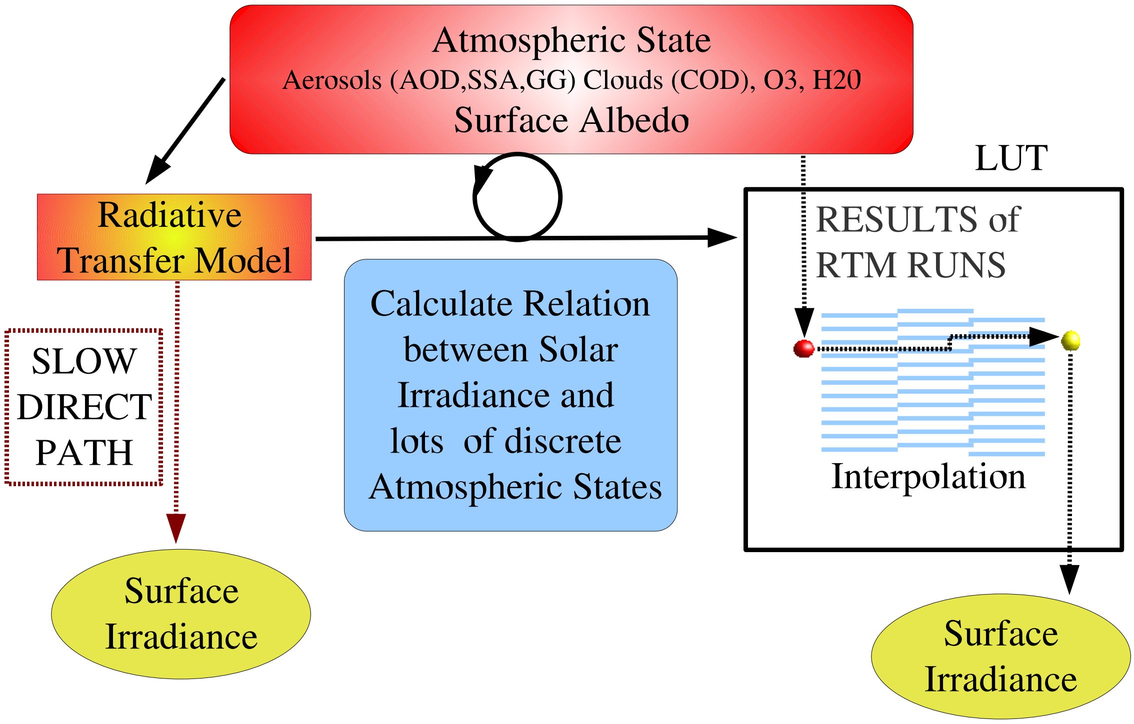

Figure 2: The relation of the transmission to a manifold of atmospheric states is pre-calculated with a radiative transfer model (RTM) and saved in a look-up table (LUT). Once, the LUT has been computed the transmittance for a given atmospheric state can be extracted from the LUT for each satellite pixel and time.

3. Description of the algorithm

In the following, the algorithm used to derive the direct irradiance at the surface is presented in more detail. It comprises of two parts: clear sky and cloudy sky situations. The CM-SAF cloud mask is used to decide whether a pixel is cloudy or cloud free.

3.1. Clear sky situations

Employing a detailed state-of-the-art RTM, the direct irradiance is pre-calculated for a variety of atmospheric states and stored in a LUT. A LUT is a data structure used to replace the time-consuming RTM computation with a simpler and faster interpolation operation within discrete pre-computed RTM results. The LUT contains the relation between the direct irradiance for the selection of clear sky atmospheric conditions. The atmospheric conditions cover different values for water vapour, ozone, aerosol optical depth, aerosol single scattering albedo and asymmetry parameter.

Here, the RTM libRadtran (Mayer and Kylling, 2005) was used for the generation of the LUT. RTM calculations were performed for 24 spectral bands between 250 and 3600 nm) for numerous atmospheric states, covering a wide range of values for water vapour, ozone, aerosol optical thickness and surface albedo (Müller et al., 2009). Several types of aerosols were included (Hess et al., 1998). Increase in the computing performance has been achieved by the use of Modified Lambert Beer (MLB) functions (Müller et al., 2004) and the implementation of hybrid eigenvector LUTs (Müller et al., 2009).

The forward scattering is considered but only from the direction of the sun, assuming the sun as a point source. Any forward scattering from the sun corona is not considered.

In the operational chain the direct irradiance for the actual atmospheric state is derived by linear interpolation between the pre-calculated direct irradiance values associated to different atmospheric states (see Figure 3).

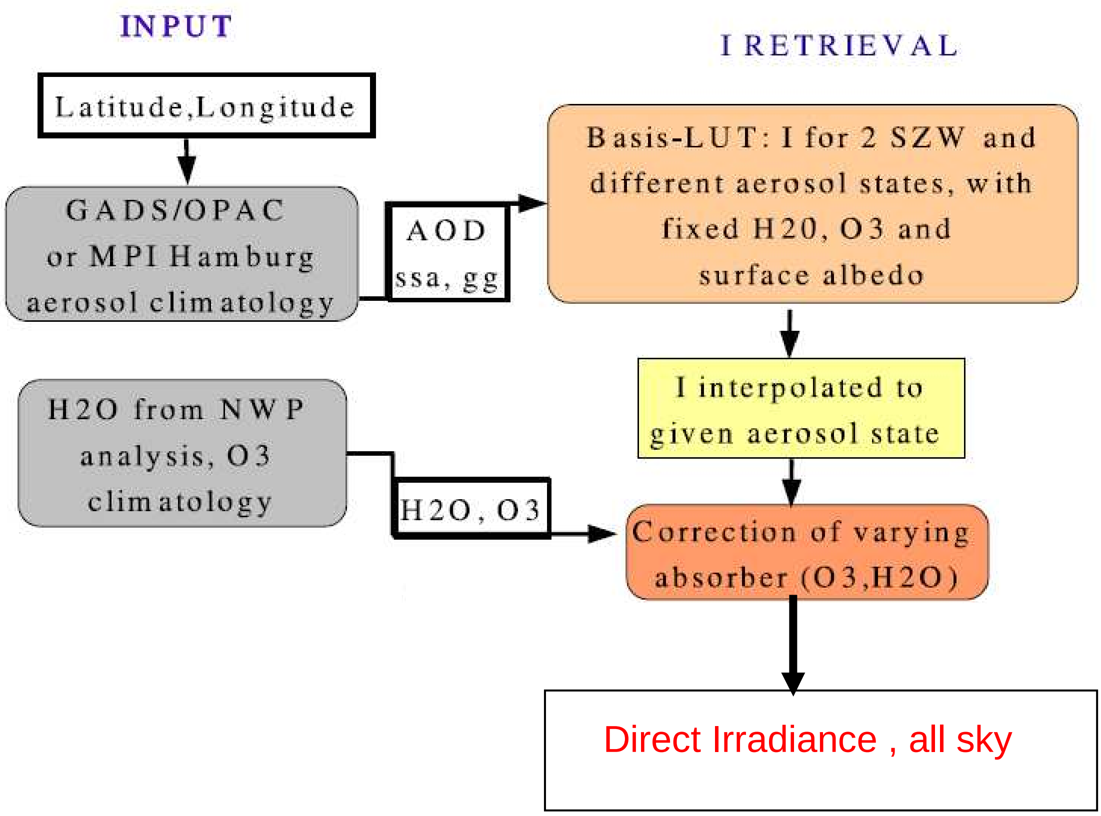

Figure 3: Flow-diagram of the clear sky LUT approach. NWP: Numerical Weather Prediction.

A detailed description of the hybrid-eigenvector LUT approach is given in Müller et al. 2009.

3.2. Cloudy sky situations

For a fully cloudy pixel the direct irradiance is set to zero. For a pixel with fractional cloud cover the formula of Müller et al. (2009) is used, which describes the relation of the direct irradiance (all sky) SID_{allsky} to that of the clear sky direct irradiance SID_{clear} .

$$SID_{allsky} = SID_{clear} * \left(k - 0.38 \cdot (1-k)\right)^{2.5} \quad (1)$$

where k is the clear-sky index. This formula is an adaptation of the Skartveith et al. (1998) diffuse model. The clear sky index k is the ratio between the solar surface irradiance for all sky and for clear sky and is derived from the operational CM-SAF chain.

3.3. Atmospheric input information

Here the atmospheric input information needed to retrieve the direct irradiance is described. The sensitivity of these parameters on the direct irradiance is discussed in section 4.

Cloud mask:

The information on the cloud mask (cloudy or clear sky) is derived with the now-casting SAF (SAFNWC) software (Derrien and LeGLeau, 2005) operated by CM-SAF. The cloud fraction is only used to decide whether equation 1 is applied or the clear sky LUT without use of equation 1. The cloud mask is available, needed and used in MSG pixel resolution

Aerosol

Aerosols have a significant effect on the solar irradiance. They scatter and absorb the solar irradiance. In order to describe the effect of scattering and absorption, information about the aerosol type and aerosol optical depth is needed. The aerosol type determines the relation between scattering and absorption. These relation can be expressed in terms of singles scattering albedo. The asymmetry parameter depends also on the aerosol type (size and composition) and determines the relation between forward and backscattering. However, for the calculation of direct irradiance only the aerosol optical depth is relevant, as the AOD is defined as the attenuation of direct irradiance. The aerosol type, hence the single scattering albedo and asymmetry factor are only of relevance for the total solar irradiance (diffuse + direct irradiance) and hence the relation between direct and total solar irradiance for a given AOD (please see section4 for details)

Monthly mean aerosol information is taken from the GADS/OPAC climatology (Hess et al., 1998, Köpke et al. 1997) using corresponding climatological NCEP (Kalnay et al., 1996) relative humidity data to consider the effect of relative humidity on aerosol optical depth, single scattering albedo and asymmetry parameter. Alternatively an aerosol climatology by Kinne et al. (2005) can be used. The aerosol climatology consists of long term monthly means either in 2.5 x 2.5 degree resolution (GADS/OPAC) or in 1 x 1 degree resolution. Currently, the GADS/OPAC climatology is used.

Water vapour:

Water vapour is an important absorber, it do not scatter irradiance and it's attenuation effect is pre-dominantly independent on the underlying aerosol state.

Water vapour profiles are taken from the analysis of the global NWP model of the German Weather Service (Majewski et al, 2002).

Ozone:

Ozone is a strong absorber in the UV, but the absorption is quite weak relating to the broadband spectrum, which is relevant for the estimation of the direct irradiance.

For ozone the climatological values of the USS standard atmosphere (~345 DU) are used.

Clear sky index:

The clear sky index is derived from the CM-SAF SIS product. The algorithm to derive SIS is described in detail in Müller et al 2009. The clear sky index is used to consider the effect of clouds on the clear sky irradiance, using equation 1.

4. Averaging

The calculation of the direct surface irradiance (SID) takes place on MSG pixel basis using instantaneous images (at least one per hour). The daily average SID is calculated by arithmetic averaging:

$$SID_{DA} = \frac{\sum_{i=1}^{n} SID_i}{n} \qquad (2)$$

SID_{DA} is the daily average of SID and SID_i *is* the SID for satellite image *i*. n is the number of images available during a day.

The monthly average SID is calculated from the daily means on pixel basis as the arithmetic mean if at least 20 daily means per month are available. After the temporal averaging, a spatial averaging to (15 x 15) km² is performed.

5. Sensitivity and dependence of atmospheric input on direct irradiance

The sensitivity of the direct irradiance on the atmospheric input is discussed. The section provides the uncertainty or sensitivity of the direct irradiance in relation to the input parameter. The error and accuracy of SID is assessed by comparison with in-situ data and provided within the validation report. Beside the effect of the clear sky index, aerosols and water vapour have a significant effect on the attenuation of the direct irradiance.

5.1. Water vapour:

Figure 4 provides the sensitivity of the direct irradiance on water vapour. The deviation of the direct irradiance is plotted against water vapour variations relative to 15 mm (~ value of the USS standard atmosphere). The sensitivity depends on the solar zenith angle and the total amount of water vapour. The sensitivity is much higher for low water vapour amounts and in the order of 20 W/m² for variations of 5 mm water vapour, while it is below 10 W/m² for water vapour contents above 15 mm. The effect on the direct irradiance is only a few W/m² for typical water vapour uncertainties of 1-2 mm.

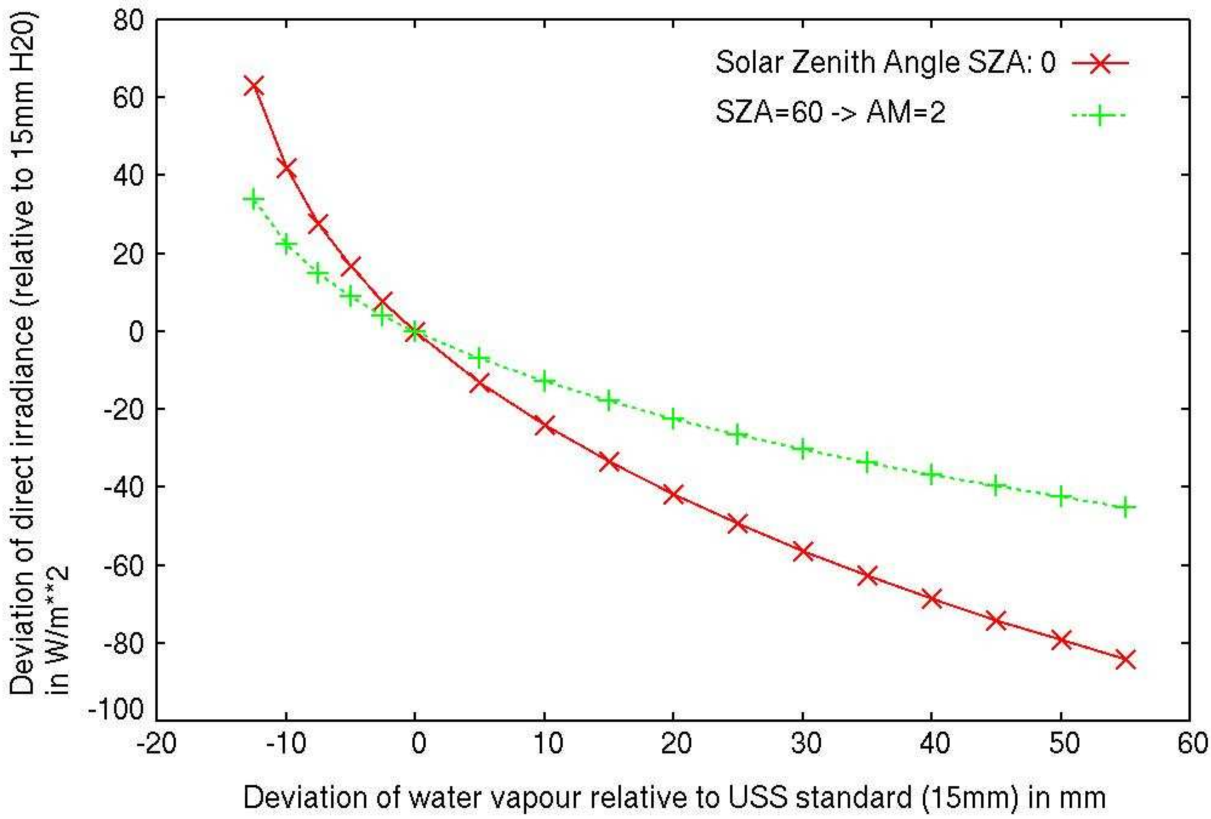

Figure 4: The sensitivity of direct irradiance on water vapour for a SZA of zero and 60 degree.

5.2. Ozone

Figure 5 provides the sensitivity of the direct irradiance on ozone. The deviation of the direct irradiance is given in dependency of ozone variations relative to 345 DU (~ value of the USS standard atmosphere). The sensitivity depends on the solar zenith angle and is quite small throughout the ozone range. The deviation of direct irradiance is about 1W/m² for typical ozone variation (+/-100 DU) within the SEVIRI disk.

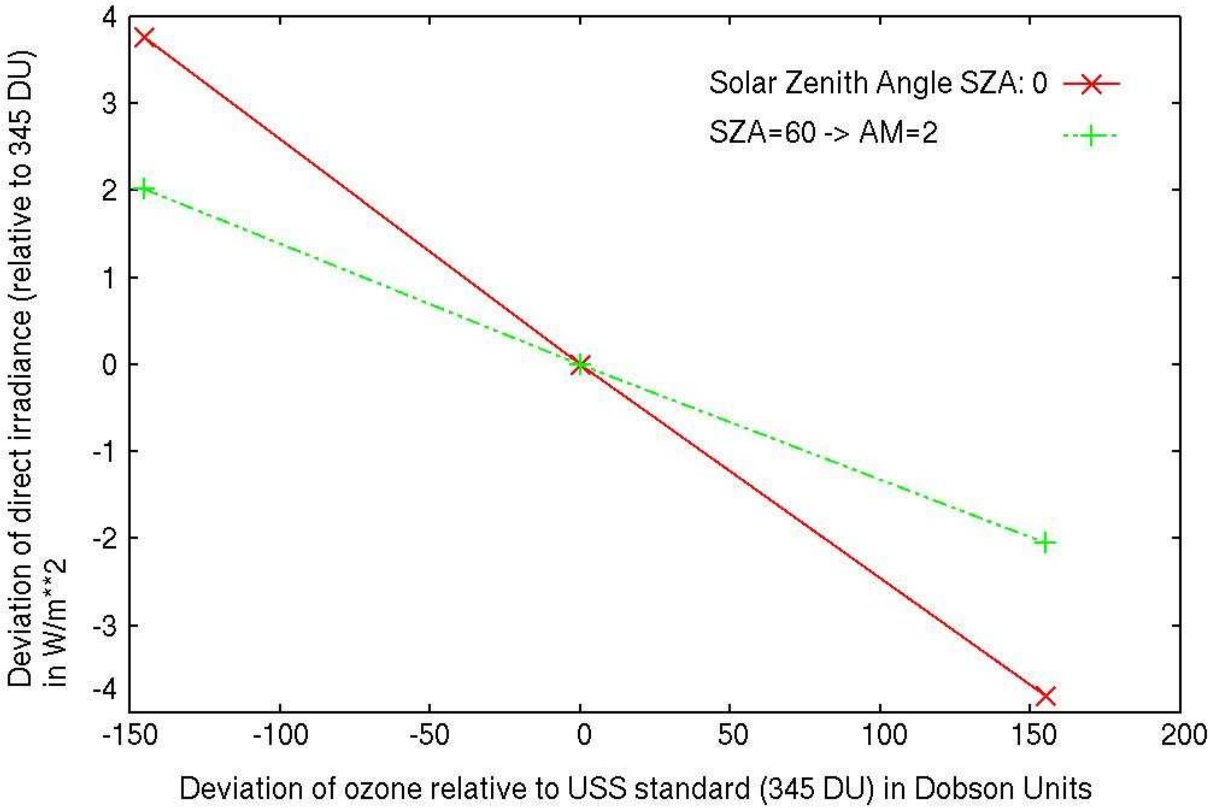

Figure 5: The sensitivity of direct irradiance to ozone for a SZA of zero and 60 degree.

5.3. Aerosols

Aerosol type. expressed as single scattering albedo and asymmetry parameter has a significant effect on the solar irradiance and determines the relation between solar irradiance and direct irradiance. Single scattering albedo describes the relation between scattering and absorption while asymmetry parameter describes the relation between forward and backscattering However the attenuation of the direct irradiance by aerosols is completely defined by the AOD, which by definition, describes the attenuation of the direct irradiance. Hence, for direct irradiance it is only of relevance to investigate the sensitivity on the aerosol optical depth AOD. This is depicted in Figure 6 and Figure 7. The global (total solar irradiance) and direct irradiance is plotted for the USS standard atmosphere over the aerosol optical depth for two different values of single scattering albedo for a solar zenith angle of 60 degrees and a solar zenith angle of 0 degree (Figure 6 and Figure 7). The single scattering albedo has a significant effect on the global irradiance, but not on the direct irradiance, the respective RTM runs lead identical values, see Figure 6 and Figure 7. The effect of the AOD is much larger for the direct irradiance than for the global irradiance, hence, the sensitivity of the direct irradiance on AOD is much higher. Typical uncertainties in the monthly mean aerosol optical depth of 0.1 relative to a background of AOD=0.2 leads to uncertainties of about 10 W/m² for AM2 and about 20 W/m² for solar zenith angle of 0 degree.

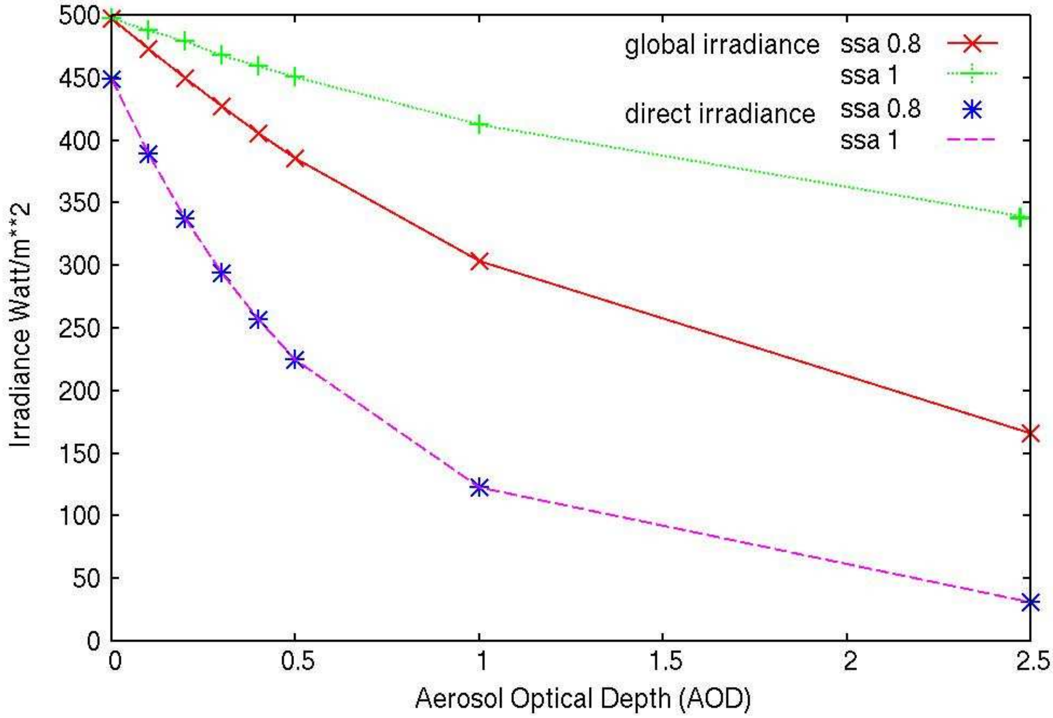

Figure 6: Sensitivity of Aerosol optical depth and single scattering albedo on direct irradiance in comparison to total solar irradiance for a solar zenith angle of 60 degree (air mass of 2)

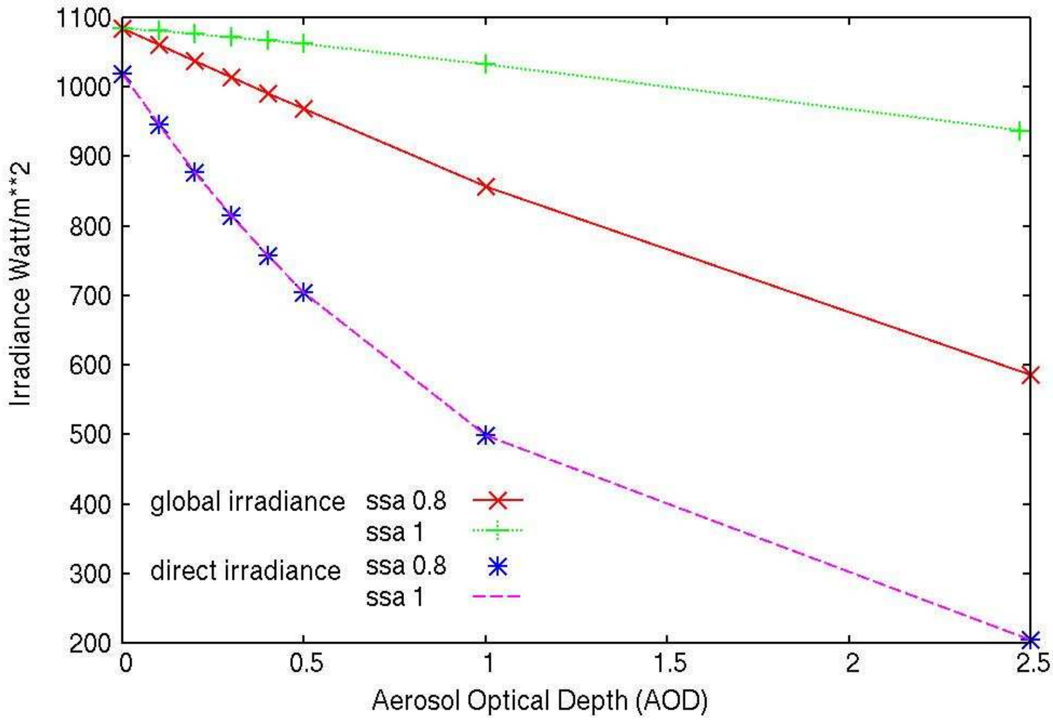

Figure 7: Sensitivity of Aerosol optical depth and single scattering albedo on direct irradiance in comparison to total solar irradiance for a solar zenith angle of 0 degree.

5.4. Clear sky index

The clear sky index is derived from the CM-SAF SIS product and is used to consider the effect of clouds on the clear sky irradiance, using equation 1. The dependence of the direct irradiance on the clear sky index is shown in Figure 8, together with the deviation of the direct irradiance resulting from the uncertainty of the clear sky index.

It is evident that the dependency / sensitivity of the direct irradiance on the clear sky index is quite large. An uncertainty of 2% has been evaluated for the clear sky index based on the accuracy of SIS CM-SAF product. This uncertainty leads to deviations of about 10 % in the direct irradiance, demonstrating the importance of an accurate clear sky index (hence SIS) on the direct irradiance.

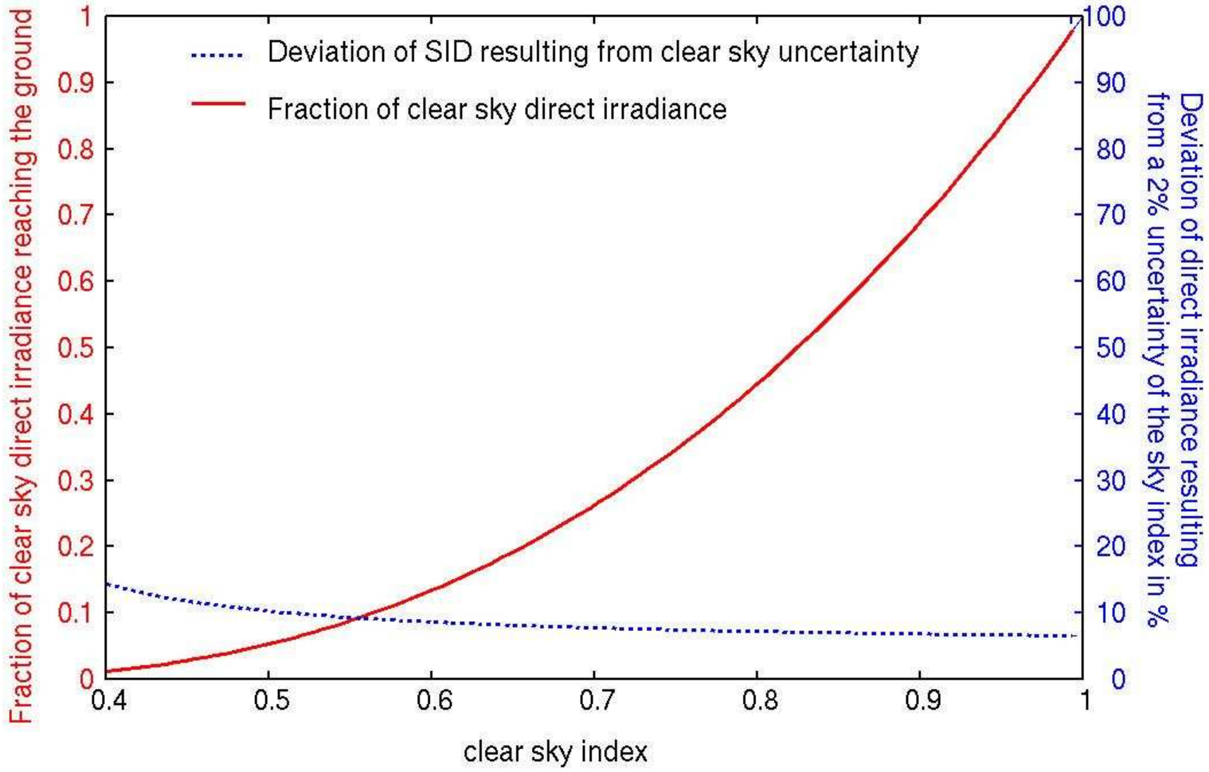

Figure 8: Sensitivity of direct irradiance on the clear sky index.

6. Assumption, limitations and future improvements

The quality of the direct irradiance strongly depends on the quality of the information about the atmospheric state, especially the aerosol information, the integrated water vapour and the clear sky index.

Accounting for the spatial variability of clouds in equation 1 might improve the accuracy of the product. This could be achieved by empirically adjusting equation 1. For totally cloudy pixel the implementation of a threshold for the cloud optical depth (COT) ought to be discussed.

The use of the clear sky index derived from SIS couples the accuracy of SID to that of SIS. An approach using the cloud index for the calculation of the clear sky index would resolve the coupling. This approach will be performed for the Heliosat based data sets. The weakness and strength of the approach discussed in this ATBD can be further analysed once the Heliosat based data sets have been generated.

The performed validation indicates that the accuracy of the SID monthly mean product is better than 15 W/m^2, which is a very promising result .Details of the validation results are given in the respective validation report [RD.2]

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Appendix A Glossary

COT	Cloud optical depth
GADS/OPAC:	Global Aerosol Data Set / Optical Properties of Aerosols and Clouds
k:	Clear sky index.
LUT:	Look-up table
NCEP:	National Centers for Environmental Prediction
RTM:	Radiative Transfer Model
SID:	Surface Direct Irradiance (beam).