

**Determination of
circumsolar radiation
from Meteosat
Second Generation**

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Determination of circumsolar radiation from Meteosat Second Generation

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Abstract

Reliable data on circumsolar radiation, which is caused by scattering of sun light by cloud or aerosol particles, is becoming more and more important for the resource assessment and design of concentrating solar technologies (CSTs). However, measuring circumsolar radiation is demanding and only very limited data sets are available. As a step to bridge this gap, we have developed a method to determine circumsolar radiation from cirrus cloud properties retrieved by the geostationary satellites of the Meteosat Second Generation (MSG) family. The method takes output from the COCS algorithm to generate a cirrus mask from MSG data, then uses the retrieval algorithm APICS to obtain the optical thickness and the effective radius of the detected cirrus, which in turn are used to determine the circumsolar radiation from a pre-calculated lookup table. The lookup table was generated from extensive calculations using a specifically adjusted version of the Monte Carlo radiative transfer model MYSTIC and by developing a fast yet precise parameterization. APICS was also improved such that it determines the surface albedo, which is needed for the cloud property retrieval, in a self-consistent way instead of using external data. Furthermore it was extended to consider new ice particle shapes to allow for an uncertainty analysis concerning this parameter.

We found that the nescience of the ice particle shape leads to an uncertainty of up to 50 %. A validation with ground based measurements of circumsolar radiation show good agreement with the new “Baum v3.5” ice particle shape parameterization. For the circumsolar ratio (CSR) the validation yields a mean absolute deviation (MAD) of 0.10, a bias of 11 % and a Spearman rank correlation $r_{\text{rank, CSR}}$ of 0.54. If measurements with sub-scale cumulus clouds within the relevant satellite pixels are manually excluded, the results improve to MAD = 0.07, bias = -3 % and $r_{\text{rank, CSR}} = 0.71$.

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1 Introduction

Circumsolar radiation with regard to concentrating solar technology (CST) has been investigated mainly for two reasons: first, it can cause an underestimation of optical thickness from ground measurements and thus lead to an overestimation of the direct solar irradiance which is the resource for CST (e.g. Grassl, 1971). Second, for the design and the precise evaluation of high flux solar concentrators the radiance distribution inside and around the sun disk, called sunshape, needs to be known (e.g. Rabl and Bendt, 1982; Schubnell, 1992; Neumann and Witzke, 1999 or Buie and Monger, 2004).

Circumsolar radiation is caused by forward scattering of sun light by cloud or aerosol particles. If these particles are horizontally evenly distributed, the radiance decreases with angular distance from the sun. The steepness and shape of this angular gradient depends on the particles' type, shape and size as well as on the optical thickness. Thus, perception of circumsolar radiation by any optics pointed at the sun is strongly dependent not only on its opening half-angle α but also on the sky conditions. Such optics can be a pyrheliometer with $\alpha = 2.5^\circ$ (World Meteorological Organization standard according to CIMO Guide, 2008, Chap. 7), but, for example, also a concentrating solar thermal power plant with $\alpha < 1^\circ$. Furthermore, the discrepancy in perception caused by different opening angles is not constant, but also varies with sky conditions. Since circumsolar radiation is commonly included in direct normal irradiance (DNI) measurements at higher amounts than perceived by CST plants, this can lead to systematic overestimation of the solar resource when DNI alone is available.

There has been some effort to measure circumsolar radiation from the ground (e.g. Noring et al., 1991; Neumann et al., 2002; DeVore et al., 2009; Wilbert et al., 2011, 2013) and also to simulate it for a range of atmospheric conditions (e.g. Thomalla et al., 1983). So far however, circumsolar radiation has not been determined from satellite measurements which have big advantages considering global coverage, site intra-comparability and financial costs compared to ground measurements. Besides, satellite data are readily available for many regions of the world covering longer time

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spans than most available ground measurement time series of circumsolar radiation. In this study a method is developed to derive the circumsolar radiation utilizing the Spinning Enhanced Visible and Infra-Red Imager (SEVIRI) aboard the geostationary Meteorosol Second Generation (MSG) satellites (Schmetz et al., 2002).

5 The focus of this study lies on circumsolar radiation caused by cirrus clouds. These ice clouds often occur with an optical thickness τ ranging from 0.1 to 2.0, that on one hand still allows the operation of CSTs, and on the other hand makes them detectable by satellites.

10 Our method to derive the circumsolar radiation comprises of two steps. First the particle size and optical thickness of the cirrus clouds are determined using the Algorithm for the Physical Investigation of Clouds with SEVIRI (APICS) (Bugliaro et al., 2011, 2012). A parameterization is then applied to convert these cloud properties into circumsolar radiation. We developed this parameterization based on simulations of the sunshape with an improved version of the radiative transfer solver “Monte Carlo Code for the Physically Correct Tracing of Photons in Cloudy Atmospheres”, MYSTIC (Mayer, 15 2009).

20 The manuscript is structured as follows. In Sect. 2 basic definitions are made. The problems and solutions with respect to the exact simulation of the sunshape with MYSTIC are described. Furthermore the difficulties of retrieving properties of thin cirrus clouds with APICS and respective improvements are outlined. Finally, the parameterization of the circumsolar radiation is developed. In Sect. 3 we apply the method to one year of SEVIRI data processed through APICS and study the impact of the ice particle shape that so far cannot be determined from MSG. The results are also compared to ground measurements of the circumsolar ratio (CSR) performed at the Plataforma Solar de Almería (PSA) with the measurement system presented in (Wilbert et al., 2013). 25 A conclusion is given in Sect. 4.

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2 Material and methods

2.1 Sunshape and circumsolar ratio

The one-dimensional radiance distribution along a radial cut outwards from the sun center is called sunshape. The circumsolar ratio (CSR) is a common scalar quantity that can be used to characterize the sunshape (Buie et al., 2003). It is defined as the normal irradiance coming from an annular region around the sun divided by the normal irradiance from this circumsolar region and the sun disk. For the remainder of the document the term irradiance always refers to normal irradiance, i.e. irradiance on a surface perpendicular to the direction pointing at the sun.

The disk angle α_{sun} gives the extent of the sun disk measured from its center to the edge. The circumsolar region reaches from the sun's edge to the angle α_{cir} ($> \alpha_{\text{sun}}$) which is subject to arbitrary definition and measured from the sun's center as well. With this we can write

$$\text{CSR}(\alpha_{\text{cir}}) = \frac{\int_0^{2\pi} \int_{\alpha_{\text{sun}}}^{\alpha_{\text{cir}}} L(\alpha) \cos(\alpha) \sin(\alpha) d\alpha d\phi}{\int_0^{2\pi} \int_0^{\alpha_{\text{cir}}} L(\alpha) \cos(\alpha) \sin(\alpha) d\alpha d\phi} \quad (1)$$

where L is the sunshape – i.e. the radiance depending on the angular distance α from the sun center. The cosine term is safely neglected in our calculations, as even for the maximum α_{cir} of 5° considered in this study, the errors due to this are smaller than 0.2%.

2.2 Radiative transfer modelling

The parameterization for the circumsolar radiation that is developed in the following is based on extensive simulations of the sunshape under different atmospheric conditions. Let us therefore briefly consider the radiative transfer code MYSTIC and how we have improved it to allow for an exact simulation of the sunshape.

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MYSTIC (Mayer, 2009) is a 3-D Monte Carlo radiative transfer solver which is part of the libRadtran radiative transfer package (Mayer and Kylling, 2005). It traces individual photon paths through the atmosphere, either forward or backward. All events in which the photon interacts with the atmosphere, like scattering and absorption, are treated statistically according to their physical probability density functions.

The scattering phase function of ice crystals exhibits a strong forward peak. This may cause rare but result-dominating events – so called “spikes”. Leveling the spikes increases computing time excessively. A solution for this problem was given recently by Buras and Mayer (2011). The variance reduction methods described in this publication are implemented in MYSTIC. It is therefore well suited to simulate the radiance distribution in the circumsolar region.

To simplify the radiative transfer the sun is commonly assumed to be a point source at infinite distance. All sun rays are therefore parallel and enter the atmosphere under the same angle. However this approximation is not appropriate when simulating radiance in the vicinity of the sun disk since the sun has a finite angular extent. Furthermore the center of the sun disk is brighter than the limb. This so called limb darkening is caused by absorption in the sun’s atmosphere and is therefore wavelength dependent. To take account of these effects a sun disk source was implemented in MYSTIC which uses the wavelength dependent limb darkening model as given in Scheffler and Elsässer (1990) and Köpke et al. (2001). This disk source is used in the simulation of the diffuse, as in the simulation of the direct radiation.

All simulations in the following neglect the temporal course of the angular sun radius α_{sun} and refer to a mean angular sun radius of 0.266° . From reference simulations we estimate that the absolute error in CSR that arises from this is less than ± 0.004 as long as $\alpha_{\text{cir}} > 0.375^\circ$. However, as Neumann et al. (2002) have demonstrated, it is important that the integration limit α_{sun} in Eq. (1) is consistent with the sun radius, or else larger errors will arise. Therefore, the actual sun radius according to the sun-earth distance should be taken into account in Eq. (1) when calculating CSR from real ground based sunshape measurements.

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The model extensions are illustrated in Fig. 1. The differences between a simulation of the diffuse radiance with a point source (blue) and a sun disk source (green) are pronounced for angles smaller than $\approx 1^\circ$ from the sun center, which is in line with findings by Grassl (1971). The red curve shows the total sunshape consisting of direct and diffuse radiation.

2.3 Optical properties of cirrus clouds

Passive satellite instruments with only one viewing direction do not provide information about the ice particle shape composition within a cloud, which therefore has to be assumed a priori. The particle shape influences the optical properties of the cloud, like the scattering phase function and the single scattering albedo. This in turn influences the modelling of the circumsolar radiation as well as the cloud property retrieval, which in the end is also based on radiative transfer modelling. To assess the uncertainty that is caused by the assumption of the ice particle shape, we use a range of cloud bulk optical properties for modelling the circumsolar radiation, as well as for the cloud property retrieval with APICS.

Optical properties for clouds featuring a particle shape mixture are considered as well as for clouds composed of particles of only one single shape. We use the latter to represent the extremes in the natural variability of the cloud's composition.

The particle mixtures and associated optical properties are described in Baum et al. (2005a,b) and Baum et al. (2011). We call the older version “Baum v2” and the newer version “Baum v3.5”. The latter incorporates more particle shapes and the particle surface is “severely roughened” while “Baum v2” is composed of particles with flat surfaces. The five different single particle shapes that are considered here comprise solid- and hollow-columns, aggregates composed of eight hexagonal columns, planar bullet rosettes, and droxtals. They all have flat surfaces like in “Baum v2”. The bulk optical properties for the single particle shapes have been generated by Hong Gang and Claudia Emde, using single-scattering properties derived from the models of Yang et al. (2000, 2005) (Claudia Emde, personal communication, 2012). Correspondent to

the contributors Hong, Emde, Yang, they are referred to under the acronym HEY. All optical property datasets cover an effective radius range of 5–90 μm , except for “Baum v3.5” which only extends from 5 μm to 60 μm .

The effective radius r_{eff} is a parameter that is commonly used to characterize the scattering and absorption properties of disperse particle size distributions by means of a single scalar (Hansen and Travis, 1974; McFarquhar and Heymsfield, 1998). For spherical particles like water droplets it is defined as the ratio of the third to the second moment of the size distribution. There is however an ambiguity in the definition of r_{eff} for non-spherical particles. We stick to the definition that was used in the generation of the bulk optical properties (e.g. Baum et al., 2005a):

$$r_{\text{eff}} = \frac{3 \int V(D)n(D)dD}{4 \int A(D)n(D)dD} \quad (2)$$

where n is the number concentration, D the maximum dimension, V the volume and A the projected area of the particles.

2.4 Remote sensing of ice clouds with APICS and its optimization for optically thin clouds

This study relies on the “Algorithm for the Physical Investigation of Clouds with SEVIRI” (APICS) framework to derive effective radius and optical thickness of the cirrus clouds. APICS (Bugliaro et al., 2011, 2012, 2013) implements a cloud property retrieval based on Nakajima and King (1990) for the SEVIRI channels 1 and 3 in the solar spectrum (centered at 0.6 μm and 1.6 μm). While APICS was originally developed as a multi-purpose cloud property retrieval, it is especially important in the context of this study that optically thin cirrus clouds are retrieved as well as possible. To account for that we modified APICS as described in the following.

The retrieval is only performed for pixels classified as cirrus. While APICS originally relied on a cirrus cloud mask generated by the Meteosat Second Generation Cirrus

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Detection Algorithm v2 (MeCiDa) (Krebs et al., 2007; Ewald et al., 2013), we produced cloud masks based on the algorithm “Cloud Optical properties derived from CALIOP and SEVIRI” (COCS) (Kox et al., 2011; Kox, 2012) since it detects more of the optically thin cirrus. Ostler (2011) and Bugliaro et al. (2012) compared the detection efficiency of COCS and MeCiDa utilizing airborne LIDAR observations. They found that both algorithms detect virtually all of the cirrus clouds with $\tau > 0.5$, but COCS has advantages at smaller optical thickness: while MeCiDa detects about 50 % of the cirrus clouds with $\tau \approx 0.2$, COCS shows a higher detection efficiency of over 80 %. COCS uses a neural network approach to convert the brightness temperature information from the infrared channels of SEVIRI into the parameters ice optical thickness and cloud top pressure. The neural network was trained with a collocated dataset of SEVIRI observations and retrieval results for the CALIOP LIDAR, which is flying aboard the polar orbiting satellite CALIPSO (Winker et al., 2009). As mentioned, the output of COCS is not a cloud flag per se, but an optical thickness value. To generate a cloud mask, all pixels that are assigned an optical thickness larger than 0.1 by COCS are assumed to be cloudy. This cut-off criterion of $\tau > 0.1$ is necessary to keep the false alarm rate at an acceptable level (Stephan Kox, personal communication, 2012).

It is assumed that channels 1 and 3 of the SEVIRI instrument aboard the “Meteosat 9”-MSG satellite exhibit an underestimation of about 6 % (Ham and Sohn, 2010) and an overestimation of 2 % respectively (Philip Watts, EUMETSAT, personal communication, 2009). A preprocessing step takes care of the corresponding recalibration of reflectance values.

The APICS retrieval uses lookup tables (LUTs) in which pre-simulated reflectivity values for the two SEVIRI channels are stored as a function of the most relevant parameters, namely as a function of the sun and satellite zenith angles, the relative azimuth between sun and satellite, the albedo in both channels, the particle size in terms of the effective radius and the optical thickness. Simplifications and assumptions about the state of the atmosphere are required because the two independent pieces of informa-

tion (the two satellite channels) allow only the retrieval of two quantities, in our case optical thickness and effective radius.

The most important sources of uncertainty considering thin ice clouds are the assumptions about the ground reflectivity, aerosol beneath the clouds and the ice particle shape. While we have no solution for the latter, we adapted APICS such that errors in the cloud property retrieval due to wrong assumptions of the ground reflectivity and long term aerosol variability are reduced. This is outlined in the following.

APICS relies on an albedo value to describe the ground reflectivity. It must be determined a priori for both SEVIRI channels at every pixel. The original version of APICS used albedo products based on measurements of the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard polar orbiting satellites – either the “blacksky” or “whitesky” albedo from the Ambrals processing scheme (Strahler et al., 1999). Now we modified APICS so that it generates its own self-consistent albedo product. This product is based on the SEVIRI “Clear Sky Reflectance Map”, which is the average of the reflectance for a given time of day over the seven preceding days under clear sky conditions (EUM OPS DOC 09 5165, 2011). The clear sky reflectance contains contributions from the ground as well as from the atmosphere. From this combined signal the ground albedo needs to be extracted. The albedo values in both SEVIRI channels are therefore retrieved using the APICS LUTs. To this end it is evaluated for which albedo the pre-simulated reflectivity values match the clear sky reflectance best, where $\tau = 0$. This procedure has the advantage of being consistent with the cloud property retrieval concerning atmospheric gas composition, radiative transfer modelling and instrument calibration. Furthermore it is assumed that the thus retrieved albedo also corrects for some of the long term variability in the aerosol properties which may deviate from the constant aerosol properties assumed in the simulations for the APICS LUTs.

The “Clear Sky Reflectance Map” is routinely only available for 12:00 UTC. Therefore the albedo is only retrieved at this time and assumed to be constant during the day. The success rates (defined in the following) reached by APICS with this method are superior when compared to using the MODIS albedo datasets.

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The cloud property retrieval results can be erroneous, because of the uncertainties in the assumptions described above, and because of other shortcomings (e.g. 1-D radiative transfer calculations). Often the measured reflectivity pair cannot even be reproduced by any parameter combination in the LUT. In these cases the retrieval will return the maximal or minimal values of τ or r_{eff} from the LUT such that the difference between the measured and pre-simulated reflectivity combination is minimized. We call these occurrences “outliers”. Please note that our definition of “outlier” is very strict. In principle one could add all those data points to the “hits”, which lie within the uncertainty range of the retrieval due to errors in the measurements and in the assumptions. These errors are, however, difficult to quantify. Since we use the number of outliers only as a relative quality criterion, the exact definition is not relevant. The success rate S of the cloud property retrieval is defined as one minus the ratio of the number of outliers to the total number of considered pixels in a domain

$$S = 1 - \frac{\text{number of outliers}}{\text{number of considered pixels}}. \quad (3)$$

The success rate was calculated within a test sector (location shown in Fig. 5) for four months meant to represent the four different seasons (June 2011, September 2011, December 2011 and March 2012). The averages over these four months for the MODIS “blacksky”, the MODIS “whitesky” and the APICS-generated albedo are 62 %, 62 % and 81 % respectively, when using the “Baum v2” optical properties. Considering the better results with the APICS-generated albedo, APICS was operated with this new albedo product for the retrieval of circumsolar radiation. Note that success means the retrieval got values covered by the LUT, which still need not be correct, though. In the following, all retrieval results are considered, successful or not, because both have an inherent uncertainty and even the “outliers” are the best possible result for the given set of measurements.

One can conclude from the imperfect success rate of 81 % that this approach of generating a self-consistent surface albedo alleviates the problems with wrong a priori

assumptions, but does not solve them completely. The APICS-generated albedo product can adapt to changes of the real surface albedo only on the scale of a few days, while real changes can be on the scale of hours. Further reading on the influence of an inhomogeneous surface albedo on Nakajima and King-like cloud property retrievals can be found in Fricke et al. (2012).

2.5 Parametrization of circumsolar radiation

In this section a way of efficiently parameterizing the CSR is developed. We thereby build on the concept of an apparent optical thickness. We also evaluate the uncertainty of the parameterization under the fact that the ice particle shape cannot be retrieved from MSG.

As mentioned previously, the circumsolar radiation relevant for CST-applications is mainly caused by scattering by aerosol or thin cirrus layers. When modelling circumsolar radiation it is sufficient to focus on the properties of the atmospheric layers containing scattering particulates. Therefore, varying Rayleigh scattering due to changing sun zenith angle or different elevations as well as surface albedo changes are neglected in the following. The effects of this simplifications were analysed by several simulations for the largest, and therefore most sensitive field of view (FOV) considered in this study of $\alpha_{\text{cir}} = 5^\circ$. The control simulations show that Rayleigh scattering causes a circumsolar irradiance of less than 1 W m^{-2} and a CSR of less than 0.0015, even for the extreme assumption of the surface albedo being 1. This was tested for varying sun zenith angles θ_{sun} between 0° and 88° . The effect of changing the surface albedo was assessed by varying it between 0 and 1, while different cloud types were incorporated. Resulting changes in diffuse irradiance were always below 2 W m^{-2} or 0.0025 in CSR respectively. Therefore, all simulations used for the development of the circumsolar radiation parameterization were performed with $\theta_{\text{sun}} = 0^\circ$, albedo 0 and elevation 0 m.

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2.5.1 Concept of the apparent optical thickness

Shiobara and Asano (1994) and Kinne et al. (1997) corrected sun photometer measurements in the case of cirrus clouds with the concept of an apparent optical thickness. Recently Segal-Rosenheimer et al. (2013) developed this approach further into a cloud property retrieval for sun photometer data. We will use the apparent optical thickness in the following to parameterize the circumsolar radiation.

The direct transmission T through the atmosphere can be decomposed into a particulate and molecular transmission

$$T = T_p T_m. \quad (4)$$

The particulate transmission T_p is expressed as

$$T_p = \exp(-\tau_s), \quad (5)$$

where τ_s is the particulate slant path optical thickness along the line of sight from the observer to the sun. The molecular transmission T_m is determined by Rayleigh scattering and absorption on air molecules.

Diffuse radiation – that is radiation having been scattered in the atmosphere – will enter any optics with a finite FOV pointed towards the sun in addition to the direct radiation. The direct radiation has not been scattered and therefore stems only from the sun while diffuse radiation can come from both – the sun disk region and the circumsolar region.

Considering the total radiation entering the FOV one may consider an apparent transmission T' which describes both the diffuse, and the direct contribution. T' can as well be decomposed into a particulate and molecular part:

$$T' = T'_p T'_m. \quad (6)$$

Since Rayleigh scattering on molecules contributes only a negligible part to the radiation in the circumsolar region, one can approximate $T'_m = T_m$. The molecular transmissi-

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sion T_m will not be further discussed here, since it will cancel out later in the relevant formulas.

The apparent particulate transmission T'_p can be parameterized as

$$T'_p = \exp(-k\tau_s), \quad (7)$$

with k taking values between 0 and 1. This means that the difference between the direct particulate transmission – following Beer’s law – and the apparent particulate transmission can be accounted for with the factor k . Defining the apparent optical thickness $\tau_{app} = k\tau_s$ one obtains

$$T'_p = \exp(-\tau_{app}). \quad (8)$$

It is notable that the corrective factor k depends mainly on r_{eff} , FOV and particle type or shape but is almost independent of τ_s itself. This holds true as long as the optical thickness does not get too large: for this study extensive Monte Carlo simulations showed that, as long as $0 < \tau_s < 3$, k varies by less than 3% if all other parameters except the optical thickness are kept constant. These simulations were performed with different ice particle types, but also with different aerosol species.

Shiobara and Asano (1994) showed that k can be approximated by evaluating the single scattering phase function P :

$$k \approx 1 - \omega_0 \frac{\int_0^{\alpha_{cir}} P(\theta) \sin(\theta) d\theta}{\int_0^\pi P(\theta) \sin(\theta) d\theta} \quad (9)$$

with ω_0 being the single scattering albedo. We verified this with the cirrus optical properties considered in this study at one wavelength (550 nm) by performing MYSTIC simulations. We found that the approximation leads to deviations of less than 5% in $k(550\text{ nm})$ as long as $\tau_s < 3$ and $\alpha_{cir} > 0.5^\circ$. For smaller angles the extent of the sun which is not captured by the approximation causes larger deviations from the values

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obtained from MYSTIC simulations. Therefore we used the more exact results from MYSTIC to compute k .

Interestingly the concept of apparent optical thickness, which was born out of shortcomings in *measuring direct* radiation, shows parallels to a concept developed due to shortcomings in *simulating diffuse* radiation – the well known δ -scaling approach (e.g. Joseph et al., 1976). The basic concept of δ -scaling is that the forward peak of the phase function is truncated which is accounted for by a reduction of the optical thickness. I.e. forward scattered radiation is treated as direct radiation.

Please note that APICS returns the optical thickness at 550 nm, however for this study we are interested in integrated solar broad band (bb) circumsolar radiation. Therefore we also incorporate the conversion from optical thickness at 550 nm to the integrated solar value into k . Hence the tabulated values of k will translate a slant path optical thickness at 550 nm into a broad band *apparent* optical thickness. We tabulated k from MYSTIC simulations for cirrus clouds as a function of three parameters: the FOV which is characterized by the instrument's opening half angle α , the particle shape and the effective radius of the particles r_{eff} . An exemplary excerpt of the table is given in Table 1. A NetCDF file with the full table is available as an electronic supplement to this paper.

A lookup table approach allows the fast computation of $\text{CSR}(\alpha)$ from the cloud parameters τ and r_{eff} using a parameterization instead of solving the radiative transfer equation. Thereby k is interpolated linearly between the tabulated values.

If we denote the circumsolar irradiance within a given FOV with an opening angle α as I_{cir} , the total irradiance from within the same FOV as $I_{\text{tot},\alpha}$ and the total irradiance coming from within the sun disk as $I_{\text{tot},\text{sun}}$, then we can write

$$\begin{aligned} \text{CSR} &= \frac{I_{\text{cir}}}{I_{\text{tot},\text{sun}} + I_{\text{cir}}} = \frac{I_{\text{tot},\text{sun}} + I_{\text{cir}} - I_{\text{tot},\text{sun}}}{I_{\text{tot},\text{sun}} + I_{\text{cir}}} \\ &= 1 - \frac{I_{\text{tot},\text{sun}}}{I_{\text{cir}} + I_{\text{tot},\text{sun}}} = 1 - \frac{I_{\text{tot},\text{sun}}}{I_{\text{tot},\alpha}}. \end{aligned} \quad (10)$$

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In general we can express the total irradiance $I_{\text{tot, sun}}$ and $I_{\text{tot, } \alpha}$ for a given atmosphere by

$$I_{\text{tot, sun}} = I_0 T'_{\text{p, sun}} = I_0 \exp(-k_{\text{sun}} \tau_s) \quad (11)$$

$$I_{\text{tot, } \alpha} = I_0 T'_{\text{p, } \alpha} = I_0 \exp(-k_{\alpha} \tau_s) \quad (12)$$

with k_{sun} being the corrective factor for a FOV correspondent to the sun's angular radius and k_{α} for a FOV correspondent to the limiting angle for which the CSR shall be calculated. I_0 denotes the solar constant I_s corrected for molecular transmission:

$$I_0 = I_s T_m. \quad (13)$$

Applying Eqs. (11) and (12) to Eq. (10) yields

$$\text{CSR} = 1 - \frac{\exp(-k_{\text{sun}} \tau_s)}{\exp(-k_{\alpha} \tau_s)} = 1 - \exp[-(k_{\text{sun}} - k_{\alpha}) \tau_s]. \quad (14)$$

k_{sun} and k_{α} are subtracted which can lead to an adding of the individual errors. Therefore the error in CSR due to tabulating them independently of the optical thickness can reach up to 20 %, but most times it is well below 10 %. Since the angular radius of the sun is assumed constant, we can re-write Eq. (14) as

$$\text{CSR} = 1 - \exp(-\Delta k_{\alpha} \tau_s) \quad (15)$$

with $\Delta k_{\alpha} = k_{\text{sun}} - k_{\alpha}$. One can even simplify further: $\text{CSR} \approx \Delta k_{\alpha} \tau_s$ as long as $\Delta k_{\alpha} \tau_s$ is much smaller than 1.

It should be noted that this approach can be used in the derivation of other circumsolar radiation parameters besides CSR as well. The diffuse irradiance in the circumsolar region $I_{\text{cir}} = I_{\text{tot, } \alpha} - I_{\text{tot, sun}}$, for example, is the relevant parameter when considering solar resource overestimation by pyrheliometers. Since $I_{\text{tot, } \alpha}$ is basically the integral of

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the sunshape L (comp. denominator in Eq. 1) over the solid angle, one can also obtain the mean value of the sunshape \bar{L} between the limiting angles α_1 and α_2 by numerical differentiation of $I_{\text{tot},\alpha}$ with respect to the solid angle Ω enclosed by the corresponding FOV as

$$\bar{L}(\alpha_1 < \alpha < \alpha_2) = \frac{I_{\text{tot},\alpha_2} - I_{\text{tot},\alpha_1}}{\Omega(\alpha_2) - \Omega(\alpha_1)} \quad (16)$$

This way the sunshape can be coarsely reproduced from the k -LUT, although this may not be the most straightforward way of use.

2.5.2 Uncertainty due to unknown ice particle shape

Of the three parameters determining the k -LUT values – FOV, effective radius and ice particle shape – the FOV is the only one which is easy to determine. The effective radius can be retrieved from MSG with APICS, but is subject to uncertainties, particularly for optically very thin clouds. The ice particle shape cannot be retrieved with passive remote sensing methods like APICS at all. In Fig. 2 possible CSR-values are depicted as a function of the FOV for a variety of cirrus clouds, each composed of a random mixture of particle shapes. The left panel shows values for clouds with $\tau_s = 0.4$, the right one for $\tau_s = 2.0$. From the scatter of the data points one can deduce which uncertainties arise in the determination of CSR if either the information about one parameter – particle shape – or about both parameters – particle shape and effective radius – are absent. The possible CSR values for the whole range of particle shapes and effective radii contained in the k -LUT (see Sect. 2.3) are displayed: if the optical thickness is the only information available, the whole band composed of the different symbols must be considered. In this case the determined values have a large uncertainty. If the effective radius is known, the range of possible values narrows to the band filled by the corresponding symbol type. The remaining uncertainty originates from differences in the optical properties of the ice particle shapes. This is the uncertainty that is inherent to the method even for an otherwise perfect retrieval of the cloud properties τ_s and r_{eff} .

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were excluded using a land/water mask from the EUMETSAT Land Surface Analysis Satellite Applications Facility.

3.1 Consideration of different ice particle shapes in the whole retrieval chain

In Sects. 2.5 and 2.4 it was outlined that uncertainties exist in the cloud property retrieval as well as in the conversion of these properties to CSR values due to the unknown ice particle shape (mixture). It is not obvious how these uncertainties interact, in particular, whether they cancel at least partially. Therefore the overall variability was investigated by applying the complete retrieval chain yielding circumsolar radiation from SEVIRI measurements several times using different setups.

To this end CSR values for a limiting angle $\alpha = 2.5^\circ$ have been retrieved from one year within the SEVIRI test sector. This was done for the five ice particle shapes and the two shape mixtures described in Sect. 2.3. I.e. seven distinct APICS runs were performed with different cloud optical properties. In the following conversion from the retrieved cloud properties to CSR values, optical properties for the same particle shape were used as in the correspondent APICS run. Therefore seven different CSR datasets were obtained in total.

A histogram of the occurrence of CSR values relative to all time steps with $\theta_{\text{sun}} < 80^\circ$ was computed for every ice particle shape, considering the whole domain. These histograms are shown in Fig. 6 which gives a first illustration of the uncertainty induced by not knowing the particle shape. The “Baum” optical properties are based on a realistic mixture of particle shapes, so that an operational retrieval would rely on them rather than on individual particle shapes. Therefore the corresponding lines are highlighted. Figure 7 shows basically the same histogram, but this time only values contribute that go along with total irradiance values $I_{\text{tot},\alpha=2.5^\circ} > 200 \text{ W m}^{-2}$. We considered this to be the lower operation limit of a hypothetical CST plant. Here the occurrence is shown relative to all time steps that fulfil $I_{\text{tot},\alpha=2.5^\circ} > 200 \text{ W m}^{-2}$, i.e. inclusive corresponding clear sky time steps. For the calculation of $I_{\text{tot},\alpha=2.5^\circ}$ the clear sky direct irradiance I_0 is required (Eq. 12). It was obtained from libRadtran calculations assuming an elevation

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of 0 ma.s.l. everywhere. In the presence of water clouds, $I_{\text{tot},\alpha=2.5^\circ}$ was assumed to be below the 200W m^{-2} threshold because water clouds are at most times optically too thick to allow higher values. These cases were identified with a general cloud mask from EUMETSAT (EUM OPS DOC 09 5164; EUM MET REP 07 0132). Pixels marked cloudy in this mask but not in the COCS cirrus cloud mask were assumed to contain water clouds. While on average 22% of the SEVIRI measurements in the test data set produce a cirrus cloud detection, only 8–10% additionally satisfy the 200W m^{-2} criterion (depending on the assumed ice particle shape).

To gain insight into how much the retrieval results scatter, Fig. 8 shows, as an example, the distribution of CSR from the retrieval with “Baum v2.0” applied to a subset of SEVIRI measurements – namely to the subset for which the retrieval with “Baum v3.5” yielded CSR values between 0.17 and 0.18. Ideally, if the ice particle shape had no influence, all “Baum v2.0” results would also fall into the same interval. However in reality the distribution is clearly wider.

Figure 9 gives a more complete comparison of the scatter between the different optical properties: for this purpose, the SEVIRI measurements were binned into CSR (retrieved using “Baum v3.5”) intervals of width 0.01. Each subset is then processed again assuming other cloud optical properties (specified in the y-axis label of each panel). The resulting new CSR distribution is then color-coded along the y-axis. Figure 8 shows the “Baum v2”-CSR-distribution within one of these subsets and is simply a vertical cross section through the upper left panel. From Fig. 9 one can see that droxtals yield quite different CSR results than “Baum v3.5”: the results within the individual CSR subsets scatter widely and most times droxtals yield smaller CSR values than “Baum v3.5” (distribution is curved to lower values). Hollow columns and rough aggregates have rather narrow distributions but also show some curvature – implying a bias compared to “Baum v3.5”. Rosettes produce a relatively narrow distribution close to the 1 : 1 line. The distributions for “Baum v2.0” and solid columns are quite similar, being rather broad with no clear bias visible.

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3.2 Circumsolar irradiance

The average circumsolar irradiance during CST plant operation is strongly dependent on the lower DNI limit the plant can work at. As an example, we calculated the mean circumsolar irradiance in W m^{-2} for a FOV of $\alpha = 2.5^\circ$. Again we considered only values for this for which the total irradiance $I_{\text{tot},\alpha=2.5^\circ}$ was computed as being above 200 W m^{-2} . Figure 10 shows two maps of the circumsolar irradiance averaged over all time steps with $I_{\text{tot},\alpha=2.5^\circ} > 200 \text{ W m}^{-2}$ – one for the “Baum v3.5” optical properties and one for “Baum v2.0”. The values for “Baum v2.0” are on average about 50 % higher than for “Baum v3.5” but the regional distribution patterns are similar. Therefore intra-site comparisons are possible with our method with considerably less dependence on the assumed ice particle shape. In this example the “Baum” parameterizations also mark the extremes of the temporally and spatially averaged values and the HEY parameterizations lie in between (not shown here). There are few red pixels visible in the figure standing out from their environment. These are caused by unusually frequent cloud detections by COCS at these locations.

3.3 Validation with ground measurements

In this section we compare our results with ground measurements of the CSR performed at the Plataforma Solar de Almería (location marked in Fig. 5) with the system presented in (Wilbert et al., 2013). This system consists of the Sun and Aureole Measurement System (SAM) (DeVore et al., 2009), a Cimel sun photometer that is part of the AERONET (Holben et al., 1998) and a dedicated post processing software. The software determines the broadband sunshape and the broadband circumsolar ratio based on the spectral radiance measurements from the SAM and the AERONET data. This involves also the use of a slightly modified version of the SMARTS2.9.5 code (Gueymard, 2001). Approximately five weeks of CSR measurements were available (1 June 2011–4 July 2011). The SAM based measurements show varying frequency but

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were generally done at least once per minute, except for a few days which had to be discarded due to technical failures of the instrument.

The comparison of satellite data with ground measurements is not trivial due to the different spatial scales of the instrument footprints. To get a best possible match we applied methods discussed by Greuell and Roebeling (2009): we implemented a correction of the parallax displacement that results from the two instruments (SAM and SEVIRI) looking at an elevated cloud layer under different geometries. In our case the parallax correction must consider not only the satellite viewing geometry but also the sun geometry since the SAM instrument looks into the sun. For these corrections the cirrus was assumed to lie between heights of 10 and 11 km.

The retrieval results from three consecutive SEVIRI measurements at times $t_0 - 15$ min, t_0 and $t_0 + 15$ min were averaged to reduce short term variability which can deteriorate the validation results if the SEVIRI and SAM measurements are not perfectly collocated.

SAM measures CSR only at one place while our method delivers an average CSR for several square kilometers. To alleviate this scale discrepancy we brought the ground measurements to the same time grid as the SEVIRI measurements by averaging them within a symmetrical time span Δt around t_0 . The averaging of the CSR from SAM was done applying a Gaussian weighting function w to the measurements

$$w = \exp \left[\frac{-2(t - t_0)^2}{\Delta t^2} \right] \quad (17)$$

with t being the time of the SAM measurement and t_0 being the time of the central SEVIRI measurement. Underlying this is the assumption that a *temporal* average of the advected cloud properties is more representative of the *spatial* average of cloud properties that we retrieve at distinct times from SEVIRI. We found the averaging time of $\Delta t = 35$ min to deliver good agreement between satellite and ground measurements, and did not see much better agreement for longer averaging times. Only SAM

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measurements meeting the condition

$$|t - t_0| < \Delta t \quad (18)$$

were considered.

Before comparing CSR values for a 2.5° FOV the measurements were filtered: only time steps were considered with a positive cirrus cloud detection from MSG. Furthermore we required the total irradiance $I_{\text{tot},\alpha=2.5^\circ}$ calculated from the averaged SEVIRI measurements to be above 200 W m^{-2} as in Sect. 3.2 to ensure relevance for CST plants.

Excerpts of the filtered time series are shown in Fig. 11. Three days which stood out were selected since they alone contain about 42 % of the evaluated data. Most other days show large time gaps between scattered data points so that a temporal evolution of the CSR can hardly be observed. From the figure it becomes apparent that the temporal evolution of the CSR measured by SAM is in general captured by the satellite time series but there are timing and amplitude errors so that the CSR values at a given time often disagree.

The following validation measures were calculated using the N remaining CSR tuples in the time series: the relative bias, the mean absolute deviation (MAD), the root-mean-square deviation (RMSD), the Pearson correlation r (Wilks, 2005, Eq. 3.23) and the Spearman rank correlation r_{rank} (Wilks, 2005, Eq. 3.28). We show the RMSD and the Pearson correlation since they are widely used validation measures, however it should be noted that they have to be interpreted with care because neither the deviations between SAM and the satellite retrieved values are normally distributed, nor do we expect a truly linear relationship between the CSR from SAM and from our method. This is because errors in Δk or τ_s will not propagate linearly (comp. Eq. 15). The Spearman rank correlation r_{rank} is simply the Pearson correlation applied not on the data, but on the ranks of the data. It is not a measure of linear relationship but of monotone relationship. The Pearson correlation is neither robust nor resistant, the Spearman rank correlation is – it requires no assumption about the kind of monotone relationship (e.g. linear) and

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is not unduly influenced by few outliers (Wilks, 2005, Chap. 3).

$$\text{Bias} = \frac{\sum_{i=1}^N \text{CSR}_{\text{SEVIRI},i} - \sum_{i=1}^N \text{CSR}_{\text{SAM},i}}{\sum_{i=1}^N \text{CSR}_{\text{SAM},i}} \quad (19)$$

$$\text{MAD} = \sum_{i=1}^N \frac{|\text{CSR}_{\text{SEVIRI},i} - \text{CSR}_{\text{SAM},i}|}{N} \quad (20)$$

$$\text{RMSD} = \sqrt{\sum_{i=1}^N \frac{(\text{CSR}_{\text{SEVIRI},i} - \text{CSR}_{\text{SAM},i})^2}{N}} \quad (21)$$

In Table 2 the different validation measures are listed. The rank correlation between 0.54 and 0.60 and the MAD between 0.10 and 0.12 show that there are considerable differences between the time series if we look at instantaneous values. To provide context, the rank correlation between the slant path optical thickness values retrieved with APICS and measured by SAM r_{rank,τ_s} is also listed in Table 2. The rank correlation for CSR is similar to the one for slant path optical thickness. We do not expect much better validation results for the CSR than for the optical thickness since it is the main driving parameter for CSR (see Eq. 15).

After a manual inspection of the data series and sky images from an automated camera positioned besides the SAM instrument it was suspected that presence of cumulus clouds might compromise the results. The cumulus clouds – also if only covering a SEVIRI pixel partly – will increase the reflectivity in the 0.6 μm channel. This will result in APICS retrieving an increased optical thickness for the cirrus. Therefore the data were filtered manually leaving only slots without cumuli visible in the sky camera images. The numbers for the validation of the manually filtered data stand within parentheses in Table 2. The validation measures improve after this manual filtering: the rank correlation and the Pearson correlation increase, the MAD values decrease and also the Bias is reduced. For example, the three extreme runaway values in Fig. 11 around

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12:00 UTC on 6 June 2011 are removed through the cumulus screening. A cloud detection excluding cumulus contaminated pixels would thus be desirable for future applications.

The statistical values of CSR are more important than the instantaneous ones for long-term CST system performance prediction (e.g. Rabl and Bendt, 1982). Therefore, Fig. 12 compares the histograms of CSR from SAM and retrieved from SEVIRI using “Baum v3.5”. Although there are some differences, the histograms compare well considering the two completely different methods operating on different scales and the small sample size. It is also encouraging that the bias in the CSR mean values for “Baum v3.5” is only 11 % (see Table 2). Therefore we conclude that the presented method is suited to generate typical distributions or time series of CSR.

4 Summary and conclusions

We have developed a method to determine circumsolar radiation from measurements of the geostationary satellites of the Meteosat Second Generation family. To achieve this, several components were linked together and improved where necessary. The Monte Carlo radiative transfer model MYSTIC was extended by introducing a sun disk instead of a point source such that it can simulate the circumsolar region with high accuracy. With this tool at hand, we were able to establish a database of coefficients that enable the computation of circumsolar radiation by simple analytical expressions from cloud properties instead of performing time consuming radiative transfer simulations. This was facilitated by the development of a theoretical basis that avoids a dependence on optical thickness in the database. To obtain CSR values from satellite measurements we use the database in conjunction with the cloud property retrieval from the APICS framework. APICS was improved by creating an albedo dataset that is consistent with the cloud property retrieval algorithm and that optimizes the retrieval’s success rate. Furthermore APICS was extended with new lookup tables for individual

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ice particle shapes and the “Baum v3.5” ice particle mixture to allow for an uncertainty analysis.

Retrievals of circumsolar radiation show that the uncertainties in the complete retrieval chain due to assumptions of the ice particle shape can sum up to 50%. Nevertheless a validation of retrieved CSR values with SAM based measurements showed good agreement especially if the “Baum v3.5” optical properties were used. The mean absolute deviation is in the range of 0.10. A manual data screening indicates that the presence of subscale water clouds below the cirrus compromises the results. A detection and appropriate treatment of “mixed cloud” pixels is an open point for further development.

Despite obvious uncertainties, a retrieval of circumsolar radiation from meteorological satellite observations can complement ground measurements since it offers several unique advantages: compared to ground measurements it is cheap. Satellite data are also readily available for many regions of the world for longer time spans than any of the so far available time series of ground measurements. Furthermore the method allows to easily compare the circumsolar radiation characteristics of several sites as long as they are within the field of view of the same satellite. The further development of satellite based cloud property retrievals can improve the circumsolar radiation products since the errors in the retrieved cloud properties are a main source of uncertainty in circumsolar radiation. In particular, further information about the ice particle shape composition would help to further reduce the uncertainty.

The presented parameterization with its efficient lookup table approach can in principle be extended and applied to other data sources as well: the other significant source for CST-relevant circumsolar radiation besides cirrus clouds – aerosols – could be treated by combining the parameterization with an aerosol resolving weather forecast model.

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Supplementary material related to this article is available online at:
[http://www.atmos-meas-tech-discuss.net/6/5835/2013/
amtd-6-5835-2013-supplement.zip](http://www.atmos-meas-tech-discuss.net/6/5835/2013/amtd-6-5835-2013-supplement.zip).

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Table 1. Exemplary values of k (Eq. 7) for varying ice optical properties.

Optical Properties	$k(0.266^\circ)$	$k(2.5^\circ)$	$k(5.0^\circ)$
Baum v2.0, $r_{\text{eff}} = 10 \mu\text{m}$	0.97	0.65	0.55
Baum v2.0, $r_{\text{eff}} = 25 \mu\text{m}$	0.82	0.46	0.43
Baum v2.0, $r_{\text{eff}} = 60 \mu\text{m}$	0.52	0.33	0.32
Baum v3.5, $r_{\text{eff}} = 10 \mu\text{m}$	0.96	0.60	0.53
Baum v3.5, $r_{\text{eff}} = 25 \mu\text{m}$	0.80	0.52	0.49
Baum v3.5, $r_{\text{eff}} = 60 \mu\text{m}$	0.65	0.50	0.47

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Table 2. Results of the comparison of CSR measured from ground and retrieved from SEVIRI for different setups: rank correlation $r_{\text{rank,CSR}}$, rank correlation for the slant path optical thickness r_{rank,τ_s} , Pearson correlation r_{CSR} , mean absolute deviation MAD, root mean square deviation RMSD, bias and the number of compared data tuples N . Values in parenthesis are for manually cumulus screened date series.

Optical Properties	$r_{\text{rank,CSR}}$	r_{rank,τ_s}	r_{CSR}	MAD	RMSD	Bias	N
Baum v2.0	0.60 (0.73)	0.64 (0.68)	0.53 (0.71)	0.12 (0.09)	0.16 (0.12)	39 % (22 %)	208 (114)
Baum v3.5	0.54 (0.71)	0.62 (0.66)	0.44 (0.66)	0.10 (0.07)	0.14 (0.10)	11 % (–3 %)	194 (113)

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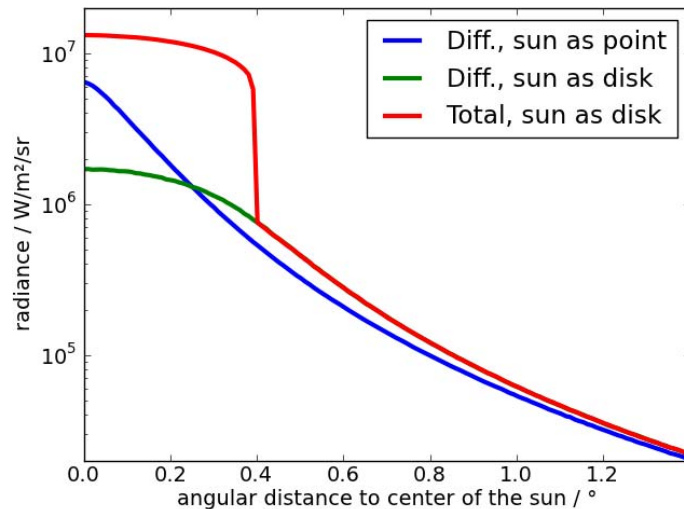


Fig. 1. Simulated broad band sunshape (integrated solar) for a cirrus cloud with optical thickness 0.5 and with the sun in the zenith. Blue: diffuse radiance for a point source. Green: diffuse radiance for a disk source. Red: direct and diffuse radiance for a disk source.

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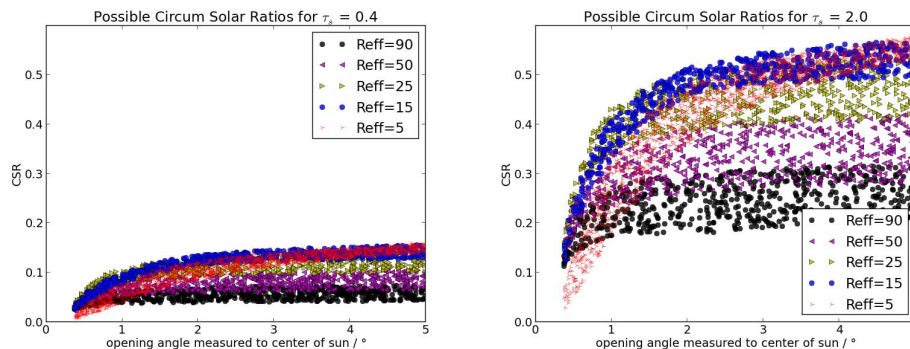


Fig. 2. Possible CSR-values as a function of the limiting angle α for a variety of cirrus clouds, each composed of a random mixture of the five particle shapes and the two particle mixtures (described in Sect. 2.3). Left: $\tau_s = 0.4$. Right: $\tau_s = 2.0$. Different symbols denote different effective radii (labeled Reff, units μm).

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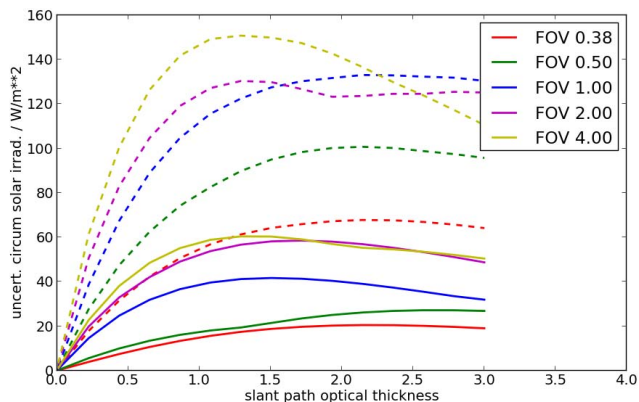


Fig. 3. Uncertainty in circumsolar irradiance for certain FOVs (legend gives opening half angle in degrees). Solid lines: for $r_{\text{eff}} = 25 \mu\text{m}$ and undefined ice particle shape. Dashed lines: for undefined r_{eff} and ice particle shape.

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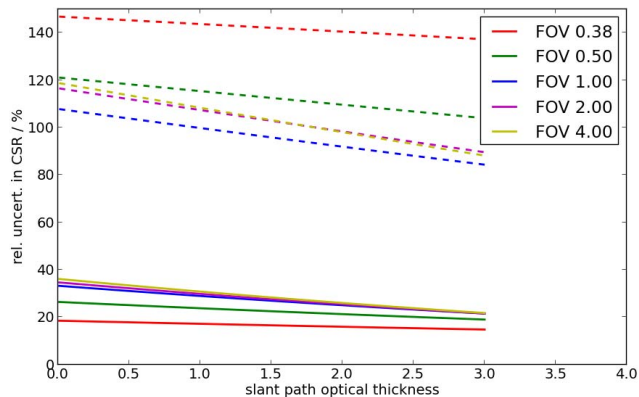


Fig. 4. Relative uncertainty δ_{CSR} for certain FOVs (legend gives opening half angle in degrees). Solid lines: for $r_{\text{eff}} = 25 \mu\text{m}$ and undefined ice particle shape. Dashed lines: for undefined r_{eff} and ice particle shape.

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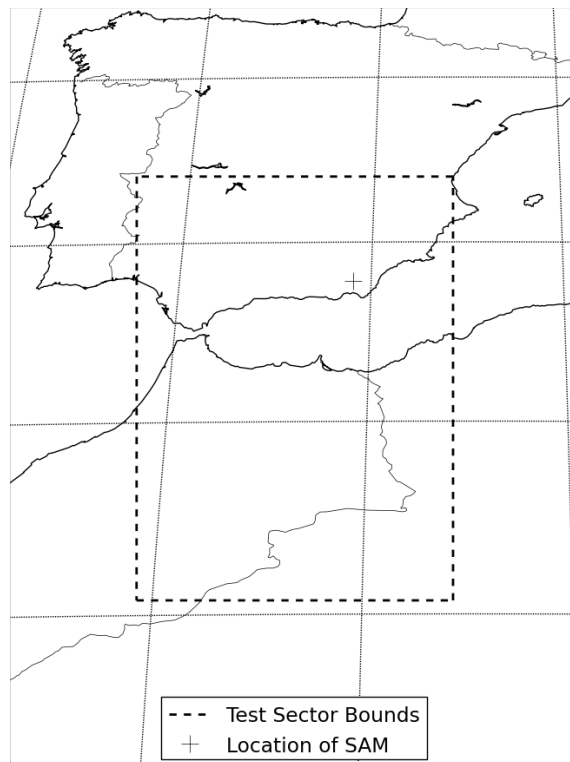


Fig. 5. Map covering the test sector. SEVIRI pixels are evaluated inside the sector (only over land). The cross marks the location of the SAM instrument at the Plataforma Solar de Almería (Sect. 3.3).

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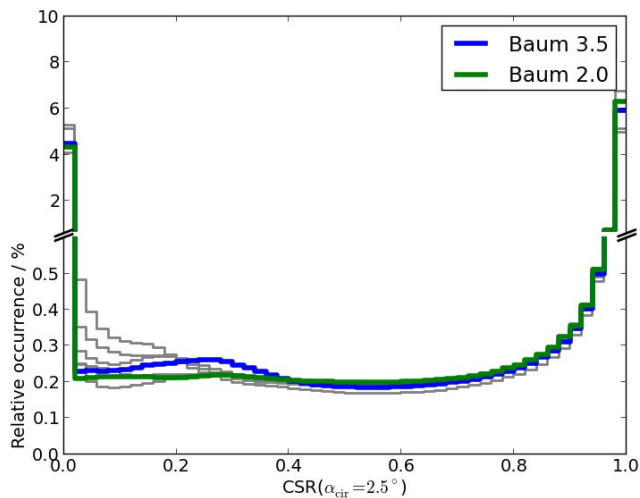


Fig. 6. Histograms of the relative occurrence of CSR values in case of cirrus clouds with respect to the total number of SEVIRI measurements with $\theta_{\text{sun}} < 80^\circ$ for one year within the test sector considering the different ice particle shapes. The “Baum” ice particle mixtures are shown colored. The different individual ice particle shapes from HEY are shown in grey.

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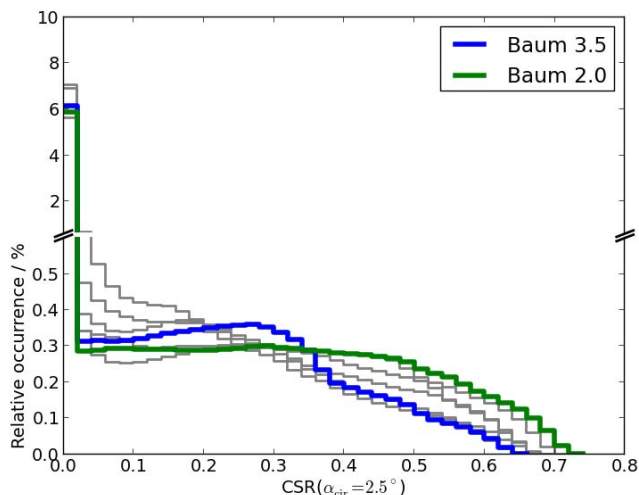


Fig. 7. Histograms of the relative occurrence of CSR values under the condition $I_{\text{tot},\alpha=2.5} > 200 \text{ W m}^{-2}$ with respect to the total number of SEVIRI measurements with $I_{\text{tot},\alpha=2.5} > 200 \text{ W m}^{-2}$ for one year within the test sector considering the different ice particle shapes. The “Baum” ice particle mixtures are shown colored. The different individual ice particle shapes from HEY are shown grey.

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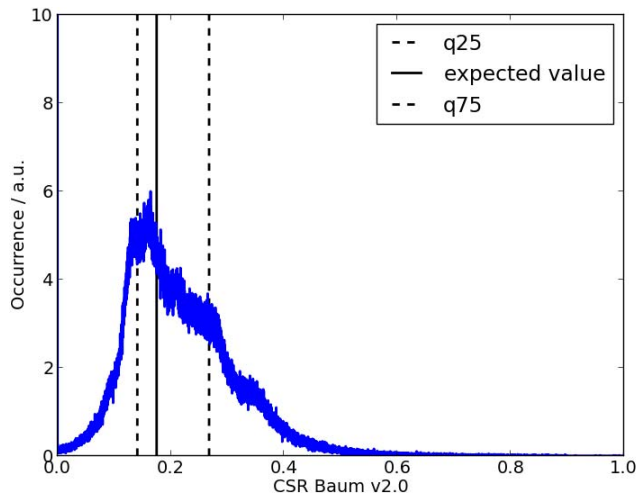


Fig. 8. Normalized distribution of retrieval results using “Baum v2.0” for SEVIRI measurements for which the retrieval with “Baum v3.5” yielded values between 0.17 and 0.18. Dashed lines mark the 25th and 75th percentiles (q_{25} and q_{75}).

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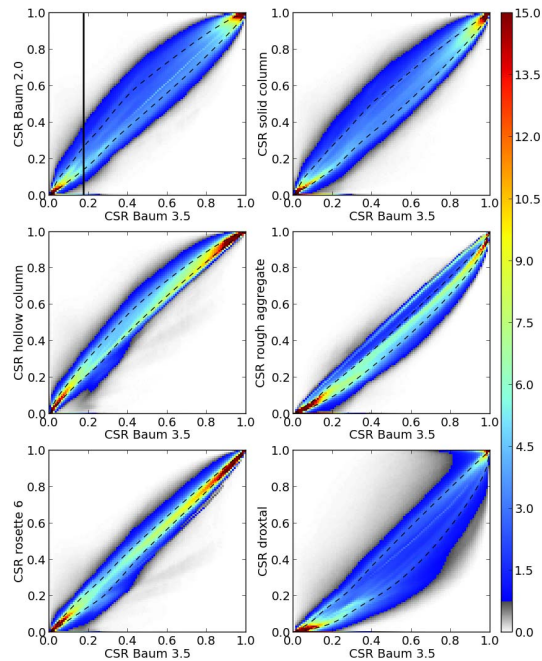


Fig. 9. Normalized CSR retrieval distributions for 100 bins of CSR from “Baum v3.5” (x-axis, bin width 0.01). Dashed lines mark q_{25} and q_{75} , i.e. they enclose 50% of the measurements. Black vertical line in upper left panel marks the cross section that is displayed in Fig. 8.

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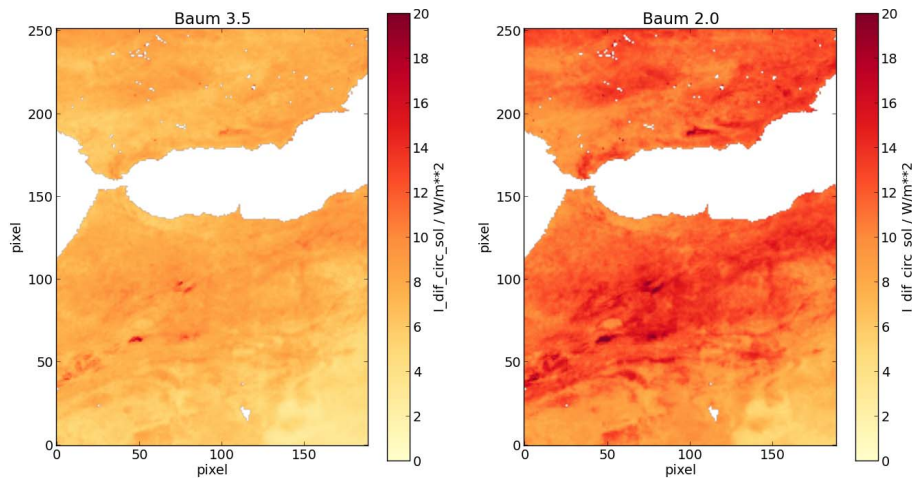


Fig. 10. Circum solar irradiance for a limiting angle of 2.5° averaged over all time steps in the test dataset with $I_{\text{tot},\alpha=2.5^\circ} > 200 \text{ W m}^{-2}$.

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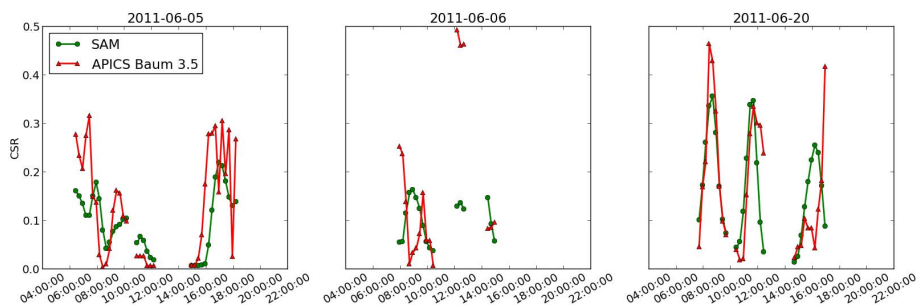


Fig. 11. Exemplary excerpt of the CSR time series used for the validation. The three selected days represent 81 of the 194 evaluated data tuples. Time is given as UTC.

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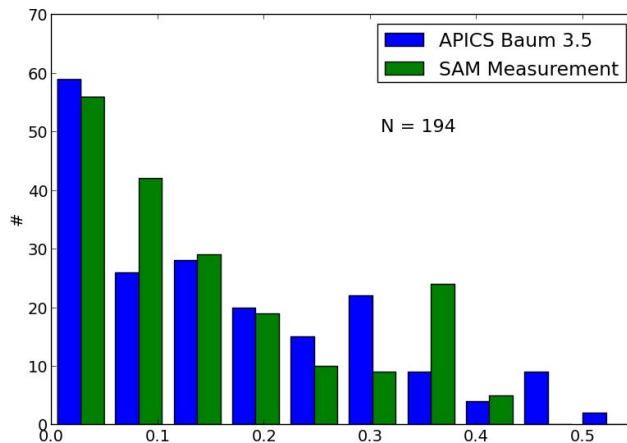


Fig. 12. Histograms of the CSR time series measured by SAM and retrieved from SEVIRI used for the validation in Sect. 3.3 (2.5° FOV, not manually cumulus screened).

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