DNICast
Direct Normal Irradiance Nowcasting methods for optimized operation of concentrating solar technologies

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[Methods for the estimation of the Direct Normal Irradiation (DNI)]

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Keywords: Circumsolar radiation, aerosol, cirrus clouds, radiative transfer.
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1. Method overview

Within the EU FP7 project SFERA a method was developed to derive circumsolar radiation from satellite cloud measurements and modeled aerosol data. This method has been adapted in a way that the contribution of circumsolar radiation to DNI can be derived from the output of the nowcasting algorithms developed in other work packages. Different nowcasting techniques deliver different aerosol and cloud parameters with different quality (WP3.1-3.3). Those nowcasted parameters which are available and possibly valuable for nowcasting of circumsolar radiation have been identified and considered in the adaptation of the circumsolar radiation forecast method. This resulted in a software module that allows deriving circumsolar radiation from the parameters identified.

1.1 Definitions

DNI in this document refers to the strict definition of direct normal irradiance that considers only photons that do not interact with the atmosphere on their way to the observer.

The circumsolar ratio $	ext{CSR} = \text{CSR}(\alpha_{cir})$ 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:

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

where $\alpha_{sun}$ is the half angle of the Sun disk ($=0.266^\circ$) as seen from the Earth and $\alpha_{cir}$ the half angle of the region around the Sun forming the annulus.

Circumsolar radiation or circumsolar irradiance is the normal diffuse irradiance coming from a circular region around the Sun defined by $\alpha_{cir}$. By definition, 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.

1.2 Origin and Effect of Circumsolar Radiation

The circumsolar radiation relevant for CST applications is mainly caused by forward scattering of sunlight by aerosol or thin cirrus layers. If these particles are evenly distributed horizontally, the radiance decreases with angular distance from the Sun. The steepness and shape of this angular gradient depends on the particles' shape, size, mass load and extinction coefficient, which in turn depends on their refractive index.

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 these simplifications has been analyzed in Reinhardt et al. (2014) by means of several radiative transfer simulations. For the largest, and therefore most sensitive, field of view (FOV) considered in this WP of \( \alpha_{\text{cir}} = 2.5^\circ \) (half angle) they show that Rayleigh scattering causes a circumsolar irradiance of less than 1 Wm\(^{-2}\) 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 \( \theta_{\text{sun}} \) between 0 and 88°. The effect of changing the surface albedo between 0 and 1 resulted in changes in diffuse irradiance always below 2 Wm\(^{-2}\) or 0.0025 in CSR.

For all concentrating solar technologies, the effect of circumsolar radiation has to be considered also for the nowcasting since large sun shapes reduce the usable solar irradiation significantly.

1.3 The apparent optical thickness method

For the determination of circumsolar radiation or CSR we make use of the following parameterisation that was developed to take into account the fact that a ground instrument with a finite FOV pointed towards the Sun always measures the sum of DNI as defined above and circumsolar radiation (the illustration follows Reinhardt et al. (2014) closely). 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. Its derivation goes as follows. The direct transmission \( T \) through the atmosphere can be decomposed into a particulate and molecular transmission: \( T = T_p \cdot T_m \). The particulate transmission \( T_p \) can be expressed as \( T_p = \exp(-\tau_p) \), where \( \tau_p \) 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.

Considering the total radiation entering the FOV of an instrument pointing toward the Sun, one may consider an apparent transmission \( \bar{T} \), which describes both the diffuse and the direct contribution. \( \bar{T} \) can also be decomposed into a particulate and molecular part: \( \bar{T} = \bar{T}_p \cdot \bar{T}_m \). Since Rayleigh scattering on molecules contributes only a negligible part to the radiation in the circumsolar region (see above), one can approximate \( \bar{T}_m = T_m \). The molecular transmission \( T_m \) will not be further discussed here, since it will cancel out later in the relevant formulas. The apparent particulate transmission \( \bar{T}_p \) can be parameterized as \( \bar{T}_p = \exp(-k \cdot \tau_p) \), 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 \( \tau_{app} = k \times \tau_s \) one obtains \( \tilde{T}_p = \exp(-\tau_{app}) \).

It is notable that the corrective factor \( k \) depends mainly on \( r_{eff} \), FOV and particle type or shape but is almost independent of \( \tau_s \) itself. This holds true as long as the optical thickness does not get too large: as long as \( 0 < \tau_s < 3 \), \( k \) varies by less than 3% if all other parameters except the optical thickness are kept constant. This is due to the fact that the effect of multi-scattering is reduced whenever scattering in the atmosphere exhibits a strong peak in the forward direction.

In our application, we will always consider cloud or aerosol optical thickness at 550 nm and include the conversion to broadband irradiance in the factor \( k \). Hence the tabulated values of \( k \) translate a slant path optical thickness at 550 nm into a broadband \textit{apparent} optical thickness. Since the dependency of the optical thickness on wavelength is considered internally in the radiative transfer model MYSTIC, the conversion factor from 550 nm to broadband cannot be given explicitly. We tabulated \( k \) from MYSTIC simulations for cirrus clouds and aerosol as a function of three parameters: the FOV which is characterized by the instrument’s opening half-angle \( \alpha \), the particle shape and the particle effective radius \( r_{eff} \).

A look-up table approach allows the fast computation of CSR(\( \alpha_{cir} \)) from the cloud parameters \( \tau_s \) and \( r_{eff} \) using this parameterization instead of solving the radiative transfer equation. Thereby \( k \) is interpolated linearly between the tabulated values.

1.4 Implementation for cirrus clouds and aerosol

For ice clouds a look-up table for the \( k \) value was used as in the publication by Reinhardt et al. (2014). Here, optical properties are considered both for clouds featuring a particle shape mixture and for clouds composed of particles of only one single shape. The particle mixtures and associated optical properties are described in Baum et al. (2005a, 2005b: hereafter called version “Baum v2.0”) and the newer version by Baum et al. (2011: hereafter called version “Baum v3.5”). The latter incorporates more particle shapes and the particle surfaces are “severely roughened” while Baum v2.0 is composed of particles with smooth surfaces – except for aggregates, which also feature a rough surface in Baum v2.0.

Further differences between Baum v2.0 and Baum v3.5 include a change of the particle-size-dependent shape mixture and an improvement in the method to calculate the single-scattering properties of the individual particles. The five different single-particle shapes that are considered here comprise solid and hollow columns, planar bullet rosettes, droxtals, and
rough aggregates composed of eight hexagonal columns. Except for the aggregates, these particles feature smooth surfaces. 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) (C. Emde, personal communication, 2012). These are referred to under the acronym HEY, the letters of which correspond to the contributors Hong, Emde and Yang. All optical property data sets cover an effective radius range of 5–90 μm except for Baum v3.5, which only extends from 5 to 60 μm.

For technical reasons the wavelength range considered in the radiative transfer simulations of solar integrated values differs between the Baum (430–2000 nm) and the HEY (300–2600 nm) optical properties. The Baum and HEY spectral ranges include 82 and 98% of the extraterrestrial solar irradiance, respectively. Due to the strong absorption in the atmosphere in the UV spectrum, the figures are even higher for the solar irradiance at ground level.

For aerosol, the OPAC (Hess et al. 1998) aerosol types and optical properties are used. Since OPAC is based on spherical particles, an assumption that is usually not valid for mineral dust, asphericity was considered based on the T-matrix scattering approximation for spheroidal (oblate and prolate) particles. The aspect ratio distribution is adapted from Kandler et al. (2009). All aerosol types are tabulated in Table 1.

<table>
<thead>
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<th>Short name</th>
<th>Habit number</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>inso</td>
<td>0</td>
<td>Water insoluble aerosol consists mostly of soil particles with a certain amount of organic material.</td>
</tr>
<tr>
<td>miam</td>
<td>1</td>
<td>Mineral aerosol or desert dust is produced in arid regions. It consists of a mixture of quartz and clay minerals and is modeled with three modes to allow to consider increasing relative amount of large particles for increased turbidity. Mineral aerosol (accumulation mode).</td>
</tr>
<tr>
<td>micm</td>
<td>2</td>
<td>Mineral aerosol or desert dust is produced in arid regions. It consists of a mixture of quartz and clay minerals and is modeled with three modes to allow to consider increasing relative amount of large particles for increased turbidity. Mineral aerosol (coarse mode).</td>
</tr>
<tr>
<td>minm</td>
<td>3</td>
<td>Mineral aerosol or desert dust is produced in arid regions. It consists of a mixture of quartz and clay minerals and is modeled with three modes to allow to consider increasing relative amount of large particles for increased turbidity. Mineral aerosol (fine mode).</td>
</tr>
<tr>
<td>Aerosol Type</td>
<td>Value</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>-------</td>
<td>-------------</td>
</tr>
<tr>
<td>Relative amount of large particles for increased turbidity. This aerosol type represents the nucleation mode.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ssam</td>
<td>4</td>
<td>Sea salt particles consist of the various kinds of salt contained in seawater. The different modes are given to allow for a different wind-speed-dependent increase of particle number for particles of different size. This aerosol type represents the accumulation mode.</td>
</tr>
<tr>
<td>sscm</td>
<td>5</td>
<td>Sea salt particles (coarse mode).</td>
</tr>
<tr>
<td>suso</td>
<td>6</td>
<td>The sulfate component is used to describe the amount of sulfate found in the Antarctic aerosol. This component is not suited to describe anthropogenic sulfate aerosols that are included in the water-soluble component.</td>
</tr>
<tr>
<td>soot</td>
<td>7</td>
<td>Soot is absorbing black carbon, which is not soluble in water. In reality soot particles have a chain-like character, which of course is not accounted for in Mie calculations of optical properties. The optical properties are calculated assuming many very small spherical particles.</td>
</tr>
<tr>
<td>waso</td>
<td>8</td>
<td>Water soluble aerosol originates from gas to particle conversion and consists of various types of sulfates, nitrates, and other, also organic water-soluble substances.</td>
</tr>
<tr>
<td>minms</td>
<td>9</td>
<td>Mineral nucleation mode (variation of the mineral aerosol species containing non-spherical particles).</td>
</tr>
<tr>
<td>miams</td>
<td>10</td>
<td>Mineral accumulation mode (variation of the mineral aerosol species containing non-spherical particles).</td>
</tr>
<tr>
<td>micms</td>
<td>11</td>
<td>Mineral coarse mode (variation of the mineral aerosol species containing non-spherical particles).</td>
</tr>
</tbody>
</table>

Table 1: OPAC aerosol types implemented for CSR and their explanation.

2. Validation Data Set

The forecasted CSR is validated against surface measurements at PSA which have been carried out, evaluated and provided by DLR’s Institute of Solar Research. The sunshape measurement system consists of the Sun and Aureole Measurement (SAM) instrument, a sun photometer and post-processing software. The system is fully automated and weather proof (Figure 1). A detailed description of the Sunshape measurement system and the evaluation algorithm can be found in Wilbert et al. (2013) and Wilbert...
A summary of the system description from these references is presented in the following.

Figure 1: Photo of the SAM Series 400 next to the Cimel sun photometer at DLR's meteorological station at the Plataforma Solar de Almería (PSA). Photo from Wilbert et al. (2013).

The SAM instrument uses two cameras: one camera for the sun disk and another camera for the aureole. They are mounted on a solar tracker so that the sun-disk camera is facing the sun directly. The aureole camera takes images of a screen. A lens forms an image of the aureole on this screen while the rays coming from the sun disk itself fall onto a beam dump. The use of five exposure times per each measurement and camera provides the required high dynamic range whatever the luminosity conditions.

The results of the SAM instrument include a radial average radiance profile which is created using the information from both cameras. There is a gap for most measurements that are relevant for solar power between an angle close to the solar disk angle and 0.475° from center. This is due to the limited dynamic range of disk camera and the size of the beam dump in the screen of 0.375°. The gap is usually larger than 0.375° because the data close to the border of the beam dump is not reliable due to the roughness of the screen in this region. For high CSR no gap occurs due to the less pronounced step in the radiance profile close to the solar disk angle. The gap is filled with a power law fit after the detection of the appropriate supporting points. The measurement of the disk radiance is used as an upper limit for the resulting fitted radiance, which increases the robustness of the regression.

The SAM instrument was designed for the investigation of cloud properties, such as particle optical depth, cloud particle size distribution and effective radius (De Vore et al. 2009). Thus, SAM uses narrow band-pass filters. The cameras’ band-pass filters are centered at 670 nm with a full width at half maximum of 10 nm. The filters can be exchanged with filters centered at 440 nm and 870 nm. For these wavelengths, comparison and cross
calibration with the Cimel CE 318 (Holben et al. 1998) sun photometer is possible. The sun photometer measures spectral direct normal irradiance and spectral sky radiance at nine different wavelengths between 340 nm and 1640 nm.

Scattering, and thus the resulting spectral sunshapes, are wavelength dependent. Therefore, the measured absolute spectral radiance profile at 670 nm might be different from the broadband sunshape that is required for CSP applications. The spectral sunshape is thus transformed to obtain the broadband sunshape. This post processing involves the co-located, sun-photometric determination of aerosol properties.

The spectral transformation is based on spectral extraterrestrial radiance profiles, calculations with a clear sky radiative transfer model and a transformation for the forward scattering of light in clouds. The used clear sky radiative transfer model is a version of SMARTS 2.9.5 (Gueymard 2001).

The input values for the model are for the most part from PSA's cloud-screened AERONET data (at Level 2 whenever available, otherwise at Level 1.5):

- spectral aerosol optical depth
- precipitable water
- aerosol single scattering albedo
- asymmetry factor
- atmospheric pressure
- ozone concentration
- aerosol phase function

Alternatively, estimates of the aerosol data can be used. Also ambient temperature and relative humidity from the co-located meteorological station are used. The modified version of the SMARTS 2.9.5 code can process tuples of user defined values for the single scattering albedo, the asymmetry factor and Angström’s wavelength exponents together with the selection of the phase function model. Thus, the solar spectrum and the spectral CSR for pure aerosol scattering are calculated. The transformation includes a further step if clouds masked the sun. Clouds are detected based on the deviation of particle and aerosol optical depth, the temporal variation of the particle optical depth and the monotonicity of the radiance profile. In the case that clouds were detected, the spectral aureole profile is calculated for several wavelengths assuming that the scattering is dominated by diffraction.

If clouds were detected the resulting spectral CSR and spectral sunshapes are calculated using the cloud and aerosol optical depth and the
assumption that the cloud scattering occurred above that by aerosol particles.

The validation data set consists of 585660 SAM measurements at PSA between 2013 and 2015 with a typical temporal resolution of 40-60 s. A large fraction of it (489957 measurements, 84%) is with CSR. A part of it, approximately a third (157547 measurements, 32%) is labeled as cloudy using the cloud detection method from (Wilbert, 2014). The rest (332410 measurements, 68%) is labeled as cloud free, i.e. the atmosphere contains only aerosol. Their distribution is shown in Figure 2.

![Figure 2: Distribution of CSR as a function of DNI during the entire measurement period for cloudy samples (top) and cloud free samples (bottom). The color bar shows the number of occurrence in linear and log scale (left and right resp.).](image)

3. Uncertainties

Uncertainties must be classified according to their origin. Three main sources of errors can be identified:

1. uncertainties related to the method of the apparent optical thickness
2. uncertainties due to the application of the method to the given data set
3. uncertainties due to the non-perfect forecast skill of the given method.
The first aspect relates to the fact that the method used in this WP for the determination of CSR is subject to limitations, simplifications and assumptions such that even a perfect input data set would only provide an approximate CSR. The second set of uncertainties is due to the characteristics of the single model/instrument and to the algorithms and assumptions used for the derivation of the required parameters. Of course, some methods do not even allow the determination of all required input parameters such that additional assumptions must be made. The last aspect refers to uncertainties due to the fact that the accuracy of a forecast is always limited.

Unfortunately, it is virtually impossible to disentangle these three aspects when forecast data is used. In particular, uncertainties related to item 2 and 3 can hardly be separated. Thus, we will start with a detailed investigation of the first aspect, the inherent uncertainties of the CSR parameterization, to better assess the source and magnitude of the uncertainties of the CSR resulting from the various data types.

### 3.1 Uncertainties of the method

The method by Shiobara and Asano (1994) allows parameterising circumsolar radiation in an accurate way by avoiding cpu time consuming 3D radiative transfer calculations. At the same time, the method requires the representation of the atmospheric components in one atmospheric column by means of two sets of two optical parameters (optical thickness and effective radius), one set for ice clouds and one set for aerosol. The knowledge of cloud and aerosol optical properties not only allows computing circumsolar radiation but also DNI in a consistent way.

The method has been applied to whole-sky imager data, to satellite products and to NWP model output. In all cases, the parameters provided by these tools have been translated into optical properties that can be used for the determination of the apparent optical thickness.

#### 3.1.1 Uncertainties due to effective radius

The effective radius is a quantity that is difficult to derive and must be, in many cases, parameterized. Even when it can be obtained from observations, it is subject to uncertainties, particularly for optically very thin clouds. The ice particle shape cannot at all be retrieved with passive remote sensing methods and is also not available from weather models. Thus, the impact of effective radius on CSR is illustrated in this section. The work presented here is a summary of selected results from the SFERA project and Reinhardt et al. (2014) which are required for the further overall uncertainty estimation in this work. Since the method applied to different data sets for the estimation of CSR in DNICast is the one first developed in
the context of the SFERA project, its inherent uncertainties / characteristics can be obtained from the corresponding work cited above and applies to this WP as well.

In Figure 3 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 slant optical thickness $\tau_{s} = 0.4$, 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 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 CSR 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 CSR 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 $\tau_{s}$ and $r_{\text{eff}}$.

For the slant path optical thickness range of $0 < \tau_{s} < 3$ uncertainties are also depicted in Figure 4 and Figure 5. The first figure shows the maximum difference between possible values of the circumsolar irradiance $\Delta I_{\text{cir}}$ in Wm$^{-2}$ depending on the FOV and the optical thickness $\tau_{s}$ considering varying particle shapes.
Figure 4: Uncertainty in circumsolar irradiance for certain fields of view (legend gives the outer boundary half-angle in degrees). Solid lines: for $r_{\text{eff}} = 25\,\mu\text{m}$ and undefined ice particle shape. Dashed lines: for undefined $r_{\text{eff}}$ and ice particle shape. (Reinhardt et al. 2014).

The latter shows the relative uncertainties in CSR $\delta_{\text{CSR}}$ for the same parameters, computed as

$$\delta_{\text{CSR}} = \frac{\text{CSR}_{\text{max}} - \text{CSR}_{\text{min}}}{0.5 (\text{CSR}_{\text{max}} - \text{CSR}_{\text{min}})}.$$ 

In both graphs solid lines stand for a fixed $r_{\text{eff}}$ of 25$\mu$m and dashed lines for an undefined effective radius. Again knowledge about the effective radius considerably reduces the uncertainties.

Figure 5: Relative uncertainty $\delta_{\text{CSR}}$ for certain fields of view (legend gives outer boundary half-angle in degrees). Solid lines: for $r_{\text{eff}} = 25\,\mu\text{m}$ and undefined ice particle shape. Dashed lines: for undefined $r_{\text{eff}}$ and ice particle shape. (Reinhardt et al. 2014).

### 3.1.2 Uncertainties due to multiple scattering layers

The parameterization presented in Sect. 1.3 allows calculating circumsolar radiation caused by a single layer of scattering particles composed of ice crystals or aerosol. However, at times more than one layer has to be dealt with; be it in the case of a cirrus above an aerosol layer or when an external mixture of aerosols is to be considered, which can be regarded as multiple individual layers as well. The latter is not the case in this project and will be neglected, however the first situation occurs often. The optical thickness of
scattering layers is additive, and since the parameterization is based on the apparent optical thickness, it is obvious to test whether circumsolar radiation is additive as well.

To this end, a test scenario was considered where cirrus clouds are placed over aerosol layers. The reference simulations were performed with MYSTIC, treating the multiple layers explicitly. The sum of the parameterized values of apparent optical thickness for the individual layers computed according to our parameterization was then compared to these simulations. The summation of \( \tau_{\text{app}} \) values of individual layers or components is called “adding method” in the following. The tests shown in the following were performed for a field of view of 3.0°. The standard deviation in \( \tau_{\text{app}} \) derived from the MYSTIC reference simulations due to Monte Carlo noise is always smaller than 0.8%. The cirrus clouds were always composed of HEY solid-columns. The ice optical thickness at 550 nm was varied between the three values of 0.1, 0.5 and 1.2 and the effective radius was set to 5 μm, 10 μm, 20 μm, 30 μm, 40 μm, 50 μm, 70 μm or 90 μm. For the aerosol layer optical properties for the three different size bins of the dust aerosol were variantly used at aerosol optical thickness values at 550 nm of 0.1, 0.3 and 1.2. In total \( 3 \times 8 \times 3 \times 3 = 216 \) scenes were created. Figure 6 compares the resulting broad band apparent optical thickness values as well as the resulting CSR values. The error in the apparent optical thickness due to simply adding values of two layers instead of explicitly simulating it remains below 4%. All cases with errors > 1.1% employ aerosol with the highest AOT considered of 1.2. The error in the CSR is in general higher than in the apparent optical thickness since for its calculation two \( \tau_{\text{app}} \) values need to be determined which are both prone to errors. The addition of apparent optical thickness values seems to introduce a negative bias in the CSR since for over 90% of the considered test cases the parameterized CSR is smaller than the MYSTIC reference value.

Considering the results of this test one can assume that the error in CSR due to application of the “adding method” is on average below 5%. For individual setups the tests showed errors in the range of up to 15%. These errors seem to be acceptable if one considers the greatly enhanced flexibility obtained by the adding method. Note that if linearity can be assumed, i.e. \( \Delta k_a \tau_s \ll 1 \), also the CSR is additive and CSR contributions of the individual layers can be separated.
Figure 6: Values of apparent optical thickness (left) and CSR (right) for 216 setups of a two layer scene with a cirrus over an aerosol layer. The cirrus is composed of HEY “solid columns” of varying \( r_{\text{eff}} \) and an ice optical thickness at 550nm of 0.1, 0.5 or 1.2. The aerosol layer is composed either of the small, medium or large dust component of the OPAC aerosol with an aerosol optical thickness of 0.1, 0.3 or 1.2. The diagrams are primarily sorted by increasing combined optical thickness (aerosol + cirrus) at 550nm (\( \tau_{550\text{nm}} \)) and secondly by apparent optical thickness. Upper left: Broad band apparent optical thickness explicitly simulated with MYSTIC (blue), apparent optical thickness (bb) obtained by adding apparent optical thickness values of the individual layers computed using the \( k - \)LUTs, combined optical thickness \( \tau_{550\text{nm}} \) (red). Lower left: Relative deviation of the parametrized apparent optical thickness to the MYSTIC reference. Upper right: Resulting CSR values. Lower right: Relative deviation of the parametrized CSR to the MYSTIC reference.

### 3.1.3 Uncertainties due to solar zenith angle

The developed CSR parameterization accounts only indirectly for the sun zenith angle \( \theta_{\text{sun}} \). It is considered in the conversion from optical thickness to slant path optical thickness \( \tau_s = \tau / \cos(\theta_{\text{sun}}) \). However, the MYSTIC simulations to determine \( k \) were always performed with \( \theta_{\text{sun}} = 0^\circ \). In the following the impact of this simplification is evaluated with additional simulations. To this end, CSR values calculated from simulations at \( \theta_{\text{sun}} = 0^\circ \) were compared to CSR values at \( \theta_{\text{sun}} \neq 0^\circ \) but for equal slant path optical thickness values. Limiting angles \( \alpha_{\text{cir}} \) of 0.5\(^\circ\), 1.0\(^\circ\), 2.0\(^\circ\), 3.0\(^\circ\) and 5.0\(^\circ\) were
considered. The simulations for cirrus clouds were performed with HEY solid-column particles at $r_{\text{eff}} = 5 \, \mu m$, $20 \, \mu m$, $40 \, \mu m$ and $90 \, \mu m$ and $\tau_s$ varying between 0.2 and 4.0. Simulations for aerosol were performed for the aerosol components miam and ssam from OPAC as well as the different dust and sea salt components from the IFS with $\tau_s$ varying between 0.1 and 3.0.

Figure 7: Relative deviation of CSR calculated at $\theta_{\text{sun}} = 0^\circ$ and $\theta_{\text{sun}} \neq 0^\circ$ but for the same slant path optical thickness for HEY solid-columns. For detailed description see text.

![Graph showing relative deviation of CSR for cirrus clouds](image)

Figure 8: Relative deviation of CSR calculated at $\theta_{\text{sun}} = 0^\circ$ and $\theta_{\text{sun}} \neq 0^\circ$ but for the same slant path optical thickness for several aerosol components. For detailed description see text.

![Graph showing relative deviation of CSR for aerosol](image)

The relative deviation of the CSR calculated from simulations at $\theta_{\text{sun}} = 0^\circ$ to the reference simulations with $\theta_{\text{sun}} \neq 0^\circ$ are shown in Figure 7 for cirrus clouds and in Figure 8 for aerosol. Considering the cirrus clouds, the
deviations stay mostly confined to ±5%. The largest calculated deviation amounts to -21% so that it can be concluded that deviations in the order of 20% must be expected for individual cases. While for cirrus clouds the deviations are distributed around the ±0, an overestimation of the CSR at high sun zenith angle was diagnosed for most aerosol setups. To avoid introducing a bias in the results, k-values for aerosol were additionally tabulated at $\theta_{\text{sun}} = 60^\circ$, 70° and 80°. In the computation of CSR this requires an additional linear interpolation step in $\theta_{\text{sun}}$.

3.1.4 Sensitivity of the CSR Parameterization on the Scattering Layer's Geometry

If not stated otherwise, cirrus clouds were always placed in a layer between 10 km and 11 km above the ground in the MYSTIC simulations. Aerosol was always evenly distributed in a layer of one kilometer depth directly above the ground. This was founded on the assumption that circumsolar radiation is caused mainly due to single scattering and that Rayleigh scattering contributes only negligibly to the signal. For example, Lohmann et al. (2006) also reported that the cloud geometrical thickness has negligible influence on global horizontal and direct irradiance at the surface. Here this is verified in regard to circumsolar radiation for some scenes by exemplary calculations of the CSR ($\alpha_{\text{cir}} = 3^\circ$). Considering clouds, the cloud height and the cloud thickness were varied in the control simulations. For aerosol, only impact of a change of the thickness of the aerosol layer was assessed, because most of the aerosol will normally be concentrated in the atmospheric boundary layer and not in elevated layers. Ice clouds composed of HEY solid columns were simulated in a layer 0 km and 1 km above ground. The simulations were then compared to the original simulations. This was done for 92 combinations of slant path optical thickness varying between 0.2 and 4.0, effective radius varying between 5 μm and 90 μm and sun zenith angle varying between 0° and 78°. The deviations from the originally calculated CSR (i.e. for the cirrus in 10 km height) were always below 2% or 0.003 which is below the calculated Monte Carlo uncertainty for most simulations performed for this sensitivity study. Furthermore cirrus clouds of only 300m thickness between 10.0 km and 10.3 km were simulated using the same parameter combinations. The deviations in CSR from the original simulations with clouds of 1000 m thickness were again below 2% or 0.003. miam, ssam and sscm aerosol from OPAC was simulated in a 300 m thick layer above ground. Following, the CSR ($\alpha_{\text{cir}} = 3^\circ$) was compared to the original simulation with a 1 km thick aerosol layer. In the simulations slant path optical thickness values between 0.1 and 3.0 were considered. The sun zenith angle was varied between 0° and 78°. In total simulations for 90 parameter combinations were compared. In all cases the simulations for the thin aerosol layers deviate by
less than 1% from the simulations for the thick aerosol layer. These exemplary verification simulations confirm that the circumsolar radiation is not unduly sensitive to the geometry of the scattering layer.

**3.1.5 Summary and implications of the uncertainties of the method**

The largest uncertainties of the method are due to the cirrus cloud particle effective radius and the ice crystal microphysical model. Unfortunately, ice particle shape and size depend on the thermodynamical and synoptical conditions in which the clouds are formed in a non-trivial way. Thus, it is virtually impossible to select the most suitable model case by case. Not even weather models are nowadays able to determine the most likely ice crystal model from physical principles. As a consequence, in the application of the CSR model to the various data sources the parameterization by Baum et al. (2005) is selected since it represents a sort of “climatological” mean because it is based on many field campaigns. As far as effective cloud particle radius is concerned, this quantity is not always available from measurements and virtually never from models. To relieve this issue, effective radius is either set per default to a plausible value or it is determined in a consistent way from the weather models.

**3.2 Application to whole-sky imager data**

Whole-sky imagers provide a detailed view of the cloud and aerosol conditions at one site and are thus particularly interesting. However, the derivation of optical properties of clouds and aerosol is very challenging since these instruments are usually not calibrated. Nevertheless, a sophisticated approach has enabled the determination of important parameters that serve as basis for the determination of DNI and CSR.

**3.2.1 Aerosol observations (UniPatras)**

Aerosol optical depth (AOD) values have been derived from a methodology based on the comparison of modeled calculated radiances for cloud free situations and image RGB values. The time series includes the date and time (UTC) of images taken, the corresponding solar zenith angle and AOD value at 500nm for cloud-free cases. Aerosol type cannot be derived with this methodology and must be assumed for the application of the apparent optical thickness method. These observations could be validated against surface measurements for clear days during the months June to October 2014 as shown in Figure 9.
Figure 9: Temporal evolution of CSR as measured at PSA (red, all sky situations) and the corresponding CSR values derived from the whole-sky camera (blue, only cloud free days).

Excluding all cloudy measurements from the comparison still 1623 whole-sky measurement times are left that are compared to CSR values measured at PSA (averaged over 1 min around the time of the whole-sky picture) in a scatter plot in Figure 10, left. Although the CSR computed from the whole-sky aerosol optical thickness data shows an underestimation, the correlation coefficient is very high and exceeds 0.8. The whole-sky data is of course not a forecast but if one assumes that aerosol optical thickness variability in time is not high, the observed value of aerosol optical thickness could be adopted for a given time after the time of it measurement. This result about CSR shows that with such a method reliable CSR values could be determined this way. DNI is also highly correlated (Figure 10, right).

Figure 10: Scatter plot of CSR (left) and DNI (right) for PSA against whole-sky camera derived quantities for clear measurements.

3.2.2 Cloud observations (Paris Mines/UniPatras)

The sector of the image containing the Sun or close to it is particularly important since clouds located here directly affect DNI and circumsolar
radiation. Unfortunately, a quantitative evaluation of this portion of the image is very challenging due to saturation of the sensor and missing contrast between pixels with different cirrus cloud optical thickness. Nevertheless, it is possible to distinguish between the situation where the Sun disk is fully covered, partially covered or clear. Furthermore, information about cloud type in this circumsolar region can also be extracted such that it is possible to determine whether a thin or thick cloud is affecting radiation between the ground based camera and the Sun. Since no optical parameters can be provided for these clouds, assumptions had to be made:

1. For thick clouds an optical thickness of 20 was assumed. Since a thick cloud blocks both direct radiation and circumsolar radiation, the exact optical thickness value is not critical as soon as it larger than 10. Effective radius and thermodynamic phase are of no concern such that a value of 25 micron for ice clouds was selected.
2. Thin clouds are assumed to consist of ice crystals. For them, an optical thickness value of 1 and an effective radius of 25 micron was assumed. The impact of this arbitrary choice will be assessed during validation and might be further tunes to achieve better results.

Since the cloud products from whole-sky imagers are expected to a later stage, only a limited validation with initial sample days could be performed.
Figure 11: Temporal evolution of CSR as measured at PSA (red) and the corresponding CSR values derived from the whole-sky camera (blue).

Although the whole-sky camera is located very close to the SAM instrument and it can observe the Sun directly, the method implemented for CSR computation starting from the cloud classification provided by Paris Mines/UniPatras turns out to be too simple. A contribution to the CSR is only provided when the Sun has been found to partially or fully covered by clouds and these clouds are thin. In that case, an ice cloud with optical thickness 1 is assumed. In all other cases (no cloud/thick cloud) no CSR is derived as the AOT is neglected. Figure 11 shows seven sample days with various cloudiness. The CSR behavior could not be reproduced satisfactorily in none of these cases. Several enhancements are possible, but not further explored here. One option is to derive CSR from DNI in a similar way as for MSG/SEVIRI for meteotest as explained below since DNI determination takes into account the actual attenuation of the solar radiation.

3.3 Application to satellite data

Satellite data from imagers provide information mainly about the horizontal distribution of clouds over large areas with moderate to high spatial resolution. Hyperspectral sounders can be usually employed to infer the vertical structure of the temperature and water vapour of the atmosphere. Due to their high spectral resolution they can also be used to detect clouds and aerosols and to make an accurate distinction between liquid water clouds, ice clouds and aerosols. However, spatial resolution is lower than for passive imagers. In the following, we have analysed cloud, aerosol and radiative products from SEVIRI aboard Meteosat Second Generation (MSG) and IASI aboard MetOp.

3.3.1 Cloud observations with MSG/SEVIRI (DLR/PA)

Cloud optical properties are obtained from MSG/SEVIRI observations by application of two retrievals. The APICS algorithm (Bugliaro et al., 2011) implements a cloud detection based on reflectance and temperature threshold techniques. The COCS algorithm (Kox et al. 2014) detects high ice clouds. From a combination of both algorithms a cloud mask and a cloud phase mask can be compiled. Optical thickness of thin cirrus is further provided by COCS from thermal channels while optical thickness of thick ice clouds and water clouds is computed by APICS based on the work by Nakajima and King (1990) adapted to SEVIRI channels 1 and 3 in the solar spectrum (centered at 0.6 and 1.6 μm). Thus, optical thickness of clouds is provided by the algorithms and can be used directly to compute CSR. Effective radius is taken from APICS when available, while a standard value of 25 μm is selected when no measurement is provided.
Forecasts were started at every full hour with a forecast horizon of 2 hours. For the evaluation of the algorithm we used forecast data that is at most 1 hour old. This CSR forecast data from MSG/SEVIRI is plotted for March 2013 in Figure 12 in blue on top of the surface measurements performed at PSA when clouds were present (according to the PSA instruments). Please notice that MSG values were not always available, as well as PSA values. One can notice that the CSR derived from MSG is usually lower than the one measured at the surface. This is confirmed in Figure 13 where a scatter plot of the two data sets is shown. The correlation coefficient for these 430 samples amounts to 0.476. For this comparison CSR values from PSA were averaged over 5 minutes around the MSG/SEVIRI acquisition time, while the MSG-derived CSR was averaged over 5x5 pixels to partially take into account parallax effects. These effects consist in 1) clouds over PSA are observed by MSG located above the Equator, and 2) the clouds relevant for circumsolar radiation are those between PSA and the Sun.

Figure 12: Temporal evolution of CSR as measured at PSA (red) and the corresponding CSR values derived from MSG/SEVIRI (blue).

Figure 13: Scatter plot of CSR for PSA against MSG/SEVIRI derived CSR.
3.3.2 Cloud observations with MSG/SEVIRI (DLR/DFD)

Cloud detection and characterisation for MSG/SEVIRI at DLR/DFD is based on the APOLLO retrieval (Kriebel et al. 2003) originally developed for the AVHRR instrument aboard the NOAA polar orbiting satellites. It provides cloud detection as well as detailed cloud typing information.

The APOLLO methodology delivers cloud mask, cloud classification, cloud optical depth, liquid and ice water path, cloud top temperature and infrared emissivity as cloud parameter. Additionally, a cloud classification scheme delivers information on vertically extended cold, very thick cloud-layers, thin clouds, warm and thick water clouds, multi-layer clouds and stratiform clouds (http://andromeda.caf.dlr.de/data-products/clouds/seviriapollo).

Thus, low clouds can be separated from high thin clouds that are assumed to consist of ice crystals. Their optical thickness is computed according to the parameterisation of Stephens et al. (1984).

Direct measurements were used for validation as no forecasted data were available at the time of the comparison.

The temporal evolution of the CSR at PSA from the surface (red) and from MSG/SEVIRI (blue) is shown in Figure 14.

![Figure 14: Temporal evolution of CSR as measured at PSA (red) and the corresponding CSR values derived from MSG/SEVIRI (blue).](image)

In this case, CSR values from MSG/SEVIRI are very low when compared to SAM measurements. This might be due to a bunch of reasons: 1) the assignment of an ice cloud optical thickness is difficult since the cloud retrieval provides a cloud classification and a cloud optical thickness but no differentiation between water and ice clouds; 2) thin ice clouds might have been missed by the cloud retrieval; 3) another ice model should be used for the determination of CSR that better fits to the cloud model of the cloud retrieval; 4) since the cloud retrieval provides information at one point in space (at PSA in this case) it is difficult to take care of parallax effects. Thus, the application of the apparent optical thickness method for this type of cloud retrieval should be verified.
3.3.3 *Cloud and aerosol observations with MetOp/IASI (DLR/DFD)*

The hyperspectral Infrared Atmospheric Sounding Interferometer (IASI) instrument has been used for the determination of the aerosol (mineral dust) and the ice cloud optical thickness. This sensor has a very high spectral resolution that enables the characterisation of the observed objects as ice clouds or mineral dust and the determination of their properties. Daily observations by the IASI aboard Metop-A were collected to a regular 0.25° lat/lon projection. For every box, the information about optical thickness and effective radius can be extracted for both aerosol and clouds together with their relative pixel coverage. Thus, for both aerosol and clouds DNI and circumsolar radiation were derived and averaged according to their relative weight to provide a mean surface value of DNI and circumsolar radiation.

Forecast of clouds and aerosol is not expected with this method such that direct measurements were used for validation. Since the MetOp satellite is polar orbiting, only one measurement per day is available. The comparison is performed over the months March-May 2013 and September-November 2013. However, due to SAM data gaps, mainly the first period could be evaluated.

![Figure 15: Scatter plots of CSR as measured at PSA against the corresponding CSR values derived from MetOp/IASI for all measurements (left) and for the cloudy samples (right).](image)

Figure 15 shows the scatter plots of CSR for the IASI product against the SAM measurements at PSA that have been averaged over 20 minutes around the time of the IASI observation because IASI information is provided on a 0.25° x 0.25° grid. When no filtering is applied, i.e. when cloudy as well as cloud free measurements are considered, the correlation coefficient amounts to 0.341, but when only cloudy data is used, the correlation coefficient increases to 0.702.
3.3.4 Cloud observations with MSG/SEVIRI (meteotest)

At meteotest the Cloud Index (CI) is derived from MSG/SEVIRI. CI in this context is the fraction of radiation passing through the atmosphere to the ground, i.e. global (direct+diffuse) radiation at surface is the multiplication of CI with the clear-sky irradiance. Clear-sky irradiance itself depends on extraterrestrial irradiance, solar zenith angle and also on turbidity, being a measure for the aerosol load in the lower atmosphere close to the ground. DNI is then obtained from the CI and global surface irradiance.

Since this model does not provide optical cloud parameters, we first use information about solar zenith angle $\theta_0$, the extraterrestrial DNI ($\text{DNI}_0$) and the DNI to obtain the total optical thickness of the atmosphere as

$$\tau = -\ln\left(\frac{\text{DNI}}{\text{DNI}_0}\right) \cos(\theta_0).$$

This total optical thickness is then decomposed into an atmospheric (Rayleigh) optical thickness (according to a given assumption about atmospheric gas profiles), an aerosol optical thickness (a standard aerosol load is selected), and a cloud optical thickness. Since no possibility of discerning between liquid water and ice clouds is given, we always make the assumption that we are considering ice clouds. In case of thick clouds ($\tau > 10$) this phase discrimination does not play a role since both DNI and CSR are zero, for lower values it is of course crucial.

![Figure 16: Temporal evolution of CSR as measured at PSA (red) and the corresponding CSR values derived from MSG/SEVIRI (blue).](image)

When applied to data from March to May 2013 this results in Figure 16. The general features are quite well reproduced, but again an underestimation of the CSR is observed.
This is confirmed in Figure 17 where the scatter plot of PSA values averaged over 5 minutes around the MSG/SEVIRI acquisition time for PSA ae displayed against the MSG/SEVIRI values. The correlation coefficient of 0.456 is comparable to the one obtained from MSG/SEVIRI using the DLR-IPA method.

3.4 Application to NWP models

NWP models describe the physical state of the atmosphere in a set of vertical levels from the surface to a given pressure. Usually these quantities represent physical properties of the atmosphere like temperature, water vapour abundance (specific humidity of mass mixing ratio) and liquid or ice water content (also in the form of specific contents or mass mixing ratios). Optical properties are usually not directly available since they are only derived and used in the corresponding radiative transfer routines. These routines can look very different in the treatment of ice (and liquid, even if to a lesser extent) and gas properties as well as in the solution of the radiative transfer equation for fluxes and heating rates. In this work, we tried to stick to the radiative transfer routines used in the given models as close as possible. Since radiation affects the evolution of weather in a significant way, the CSR derived from these models should be as consistent as possible with the remaining radiative quantities obtained from the models.

3.4.1 COSMO-MUSCAT (Tropos)

COSMO provides physical properties of liquid water and ice clouds (specific water content) that are translated into optical properties by means of the Martin et al. (1994) and Wyser (1998) schemes respectively. In the scheme
of Geleyn and Hollingsworth (1979) used in COSMO, the fluxes are obtained through the solution of a system of linear equations in a matrix form that accounts for reflection and transmission of radiation from the cloudy and clear fraction of a model layer into the cloudy and clear fraction of the next model layer. This method was used to derive an optical thickness for each model column that was then used to derive CSR. The additional information about dust load of the atmosphere provided by MUSCAT was also used to derive CSR. However, since only historical data from 2008 with 3 hours temporal resolution are available, only statistical comparisons can be shown here. Thus, we selected the same months, days and times of the day for the PSA data as for COSMO-MUSCAT, but for the year 2014 in order to provide a first proof of plausibility of the CSR derived from this model. For bot data sets we concentrated on cloud free measurements in order to evaluate the aerosol effect on CSR.

Figure 18: Two dimensional histogram of CSR against DNI as measured at PSA during June-September 2014 (bottom) and the corresponding histogram for values from COSMO-MUSCAT during the same months in 2008 (top). In the top left diagram accumulation mode properties were assumed, in the top right diagram coarse mode properties were used.
Figure 18 shows that observed CSR values at PSA are in the same range as the modelled ones (CSR<0.3). However, DNI derived from COSMO-MUSCAT is peaked at higher values than measured DNI.

### 3.4.2 WRF (DLR/DFD)

The Weather Research and Forecasting (WRF) Model is a mesoscale numerical weather prediction system designed for both atmospheric research and operational forecasting needs. The model has been run with 5 km spatial resolution and cloud microphysics with the WDM6 (double moment scheme) from Lim and Hong (2010). Ensembles have been created, among other things, by using two radiative transfer codes. One is the scheme by Dudhia (1989) taken from MM5. From it we derived an optical thickness to be applied to the CSR method.

It is a simple downward integration of solar flux, accounting for clear-air scattering, water vapor absorption, and cloud albedo and absorption. It uses look-up tables for clouds from Stephens (1978). The other is the RRTMG_SW by Iacono et al. (2008). This code combines a 112 interval correlated-k parameterization of gas absorption with the so-called MlCA method (Monte Carlo Independent Column Approximation) to account for partial cloud cover. Since it was not possible to adapt this scheme to the apparent optical thickness method we kept the idea of the Monte Carlo scheme by applied it to the spectral interval containing 550 nm to derive an optical thickness of clouds that is input to the CSR method.

### 3.4.3 WRF/EURAD-IM (RIU)

Meteorological fields are taken from the WRF model according to the WSM6 microphysical scheme by Hong and Lim (2006). The radiation code is the RRTMG_SW by Iacono et al. (2008), see above. Thus, cloud optical thickness was derived in the same method as for the DLR-DFD WRF model. Aerosols are provided by the EURAD-IM code as a total optical thickness at 550 nm. This value was used for the application of the apparent optical thickness method.

### 3.4.4 Harmonie (SMHI)

Harmonie in the setup for DNICast uses the IFS core version c25R1 (2002). The radiation scheme in HARMONIE has six SW spectral bands: three bands in the ultraviolet and visible spectral ranges and three bands in the solar infrared spectral range. Specifically, these six spectral bands are defined by the wavelengths 0.185–0.25–0.44–0.69–1.19–2.38–4.00 μm. The radiative transfer calculations are done using the delta-Eddington approximation (Joseph et al., 1976; Fouquart and Bonnel, 1980).
The effective radius of the liquid water cloud particles is computed from the cloud liquid water content using the diagnostic formulation of Martin et al. (1994) and specified concentrations of cloud concentration nuclei over land and ocean. For ice clouds, the effective dimension of the cloud particles is diagnosed from temperature using the formulation by Ou and Liou (1995). Shortwave optical properties are obtained from Fouquart (1987) for liquid water clouds and from the Ebert and Curry (1992) parameterization for ice clouds.

Cloud overlap is treated in the following way. Considering an atmosphere where a fraction $C_{\text{cltot}}$ (as seen from the surface or the top of the atmosphere) is covered by clouds (the fraction depends on which cloud-overlap assumption is assumed for the calculations), the final fluxes $F$ at the surface are given as a weighted average of the fluxes in the clear sky and in the cloudy fractions of the column

$$ F = C_{\text{cltot}} \cdot T_{\text{cl}} + (1 - C_{\text{cltot}}) \cdot T_{\text{clr}}, $$

where the subscripts clr and clt refer to the clear-sky and cloudy fractions of the layer, respectively. In contrast to the scheme of Geleyn and Hollingsworth (1979), the fluxes are not obtained through the solution of a system of linear equations in a matrix form. Rather, assuming an atmosphere divided into homogeneous layers, the upward and downward fluxes at a given layer interface are given by

$$ F = F_0 \prod_{i=j}^{N} T_{\text{bot}_i}, $$

where $T_{\text{bot}_i}$ is the transmittance at the bottom of the $i$-th layer and $F_0$ is the incoming solar irradiance. Computations of transmittance start at the top of the atmosphere and work downward. $T_{\text{bot}_i}$ account for the presence of cloud in the layer

$$ T_{\text{bot}_i} = c_i \cdot T_{\text{cl}} + (1 - c_i) \cdot T_{\text{clr}}, $$

where $c_i$ is the cloud fractional coverage of the layer $i$ within the cloudy fraction $C_{\text{cltot}}$ of the column. The total cloud cover $C_{\text{cltot}}$ is computed under the assumption of maximum random overlap.

This procedure has been adapted to derive cloud optical thickness for the cloudy part of the column $C_{\text{cltot}}$ and for the application of the apparent optical thickness method. Since the data available for approx. 10 days in January 2010 was not suitable for a comparison due to the lack of surface measurement in this period, it is skipped at this stage.
4. Summary and discussion

The method for the computation of CSR from Shiobara and Asano (1994) in the form developed during the FP7 project SFERA has been applied to products from whole-sky imagers, satellite observations and weather model data. The necessary input data for the determination of the apparent optical thickness has been derived from these products in a way as consistent as possible to the features of the instrument/model used.

In general, an underestimation of CSR is observed using this method. For a more detailed description of the results, the three groups of nowcasting methods used in the DNICast approach (whole-sky imagers, satellite instruments, weather models) are reviewed in the following.

For the determination of CSR from cloud observations of whole-sky imagers it turned out that the derivation of optical thickness from information of cloud coverage of the circumsolar region is not able to reproduce the CSR variability. To improve this result, one should either tune the method to find out more reasonable connections between cloud coverage and cloud optical properties or exploit additional knowledge about radiation extinction through the cloud to the surface camera (not available at the moment). For aerosol instead, the determination of the aerosol optical thickness from whole-sky cameras produced a very high correlation coefficient (0.8) under cloud free conditions.

Satellite products, mainly of cloud optical properties, from geostationary (MSG/SEVIRI) and polar orbiting instruments (MetOp/IASI) show generally speaking a good potential for the determination of CSR. Of course, geostationary data comes with a good temporal resolution that enables the forecast of CSR while forecasts of CSR from polar orbiting platforms surely require sophisticated methods to deal with one to three observations per day at selected sites (and is not part of the DNICast project). Both CSR forecast methods by DLR-IPA and meteotest based produce (Pearson) correlation coefficients (with CSR surface measurements) in the range 0.45-0.50. In Reinhardt et al. (2014) the DLR-IPA method has been applied to one year of measurements (May 2011 - April 2012, i.e. temporally separated from the sampling period used here) and resulted in a correlation coefficient of 0.44. A shorter time series (1 May 2011 - 30 June 2011) could reach a correlation coefficient of 0.58 and this same short time period resulted in an increased correlation coefficient of 0.67 when satellite data was visually screened for a better detection of low liquid water clouds. This shows that the CSR from forecast satellite data (no direct measurement like in Reinhardt et al. 2004!) shows a very good correlation with surface measurements. The satellite-based method by DLR-DFD using MetOp/IASI
showed a very high correlation coefficient of approx. 0.7 when only cloudy
days were observed.

For weather models, the creation of the required input parameters is much
more complicate due 1) the lack of optical parameters and 2) the provision
of vertical profiles of physical cloud properties. The method seems to
provide realistic results but also in this case it underestimates CSR.

With respect to the uncertainties related to the effective radius and
microphysical model for ice clouds, it could be favorable to test different
parameterizations to check whether the observed underestimation of CSR
can be alleviated.

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6. References

Baum, B., Heymsfield, A., Yang, P., and Bedka, S.: Bulk scattering models for
the remote sensing of ice clouds, Part 1: Microphysical data and models, J.

Baum, B., Yang, P., Heymsfield, A., Platnick, S., King, M. D., Hu, Y. X., and
Bedka, S.: Bulk scattering models for the remote sensing of ice clouds, Part

Baum, B. A., Yang, P., Heymsfield, A. J., Schmitt, C. G., Xie, Y., Bansemer, A.,
Hu, Y.-X., and Zhang, Z.: Improvements in shortwave bulk scattering and
absorption models for the remote sensing of ice clouds, J. Appl. Meteorol.

Bugliaro, L., Zinner, T., Keil, C., Mayer, B., Hollmann, R., Reuter, M., and
Thomas, W.: Validation of cloud property retrievals with simulated satellite
radiances: a case study for SEVIRI, Atmos. Chem. Phys., 11, 5603-5624,

DeVore, J., Stair, A., LePage, A., Rall, D., Atkinson, J., Villanucci, D.,
Rappaport, S., Joss, P., and McClatchey, R.: Retrieving Properties of Thin
Clouds From Solar Aureole Measurements, Journal of Atmospheric and


