EUMETSAT Satellite Application Facility on Climate Monitoring

Algorithm Theoretical Basis Document

MSG Surface Radiation

Edition 1

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Surface Incoming Shortwave Radiation	**CM-53**
Surface Net Shortwave Radiation	**CM-68**
Surface Outgoing Longwave Radiation	**CM-75**
Surface Downward Longwave Radiation	**CM-82**
Surface Net Longwave Radiation	**CM-89**
Surface Radiation Budget	**CM-96**
Cloud Radiative Effect SW	**CM-102**
Cloud Radiative Effect LW	**CM-103**

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Applicable documents

Reference	Title	Code
AD 1	CM SAF Product Requirement Document	SAF/CM/DWD/PRD/2.0

Reference documents

Reference	Title	Code
RD 1	Product User Manual Surface Radiation Manual	SAF/CM/DWD/PUM/SFCRAD
RD 2	ATBD Meteosat (MVIRI) Solar Surface Irradiance and effective Cloud Albedo Climate Data Sets	SAF/CM/DWD/VAL/MVIRI_HEL

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1 The EUMETSAT SAF on Climate Monitoring (CM SAF)

The importance of climate monitoring with satellites was recognized in 2000 by EUMETSAT Member States when they amended the EUMETSAT Convention to affirm that the EUMETSAT mandate is also to “contribute to the operational monitoring of the climate and the detection of global climatic changes". Following this, EUMETSAT established within its Satellite Application Facility (SAF) network a dedicated centre, the SAF on Climate Monitoring (CM SAF, http://www.cmsaf.eu).
The consortium of CM SAF currently comprises the Deutscher Wetterdienst (DWD) as host institute, and the partners from the Royal Meteorological Institute of Belgium (RMIB), the Finnish Meteorological Institute (FMI), the Royal Meteorological Institute of the Netherlands (KNMI), the Swedish Meteorological and Hydrological Institute (SMHI), the Meteorological Service of Switzerland (MeteoSwiss), and the Meteorological Service of the United Kingdom (UK MetOffice). Since the beginning in 1999, the EUMETSAT Satellite Application Facility on Climate Monitoring (CM SAF) has developed and will continue to develop capabilities for a sustained generation and provision of Climate Data Records (CDR’s) derived from operational meteorological satellites.
In particular the generation of long-term data sets is pursued. The ultimate aim is to make the resulting data sets suitable for the analysis of climate variability and potentially the detection of climate trends. CM SAF works in close collaboration with the EUMETSAT Central Facility and liaises with other satellite operators to advance the availability, quality and usability of Fundamental Climate Data Records (FCDRs) as defined by the Global Climate Observing System (GCOS). As a major task the CM SAF utilizes FCDRs to produce records of Essential Climate Variables (ECVs) as defined by GCOS. Thematically, the focus of CM SAF is on ECVs associated with the global energy and water cycle.

Another essential task of CM SAF is to produce data sets that can serve applications related to the new Global Framework of Climate Services initiated by the WMO World Climate Conference-3 in 2009. CM SAF is supporting climate services at national meteorological and hydrological services (NMHSs) with long-term data records but also with data sets produced close to real time that can be used to prepare monthly/annual updates of the state of the climate. Both types of products together allow for a consistent description of mean values, anomalies, variability and potential trends for the chosen ECVs. CM SAF ECV data sets also serve the improvement of climate models both at global and regional scale.
As an essential partner in the related international frameworks, in particular WMO SCOPE-CM (Sustained COordinated Processing of Environmental satellite data for Climate Monitoring), the CM SAF - together with the EUMETSAT Central Facility, assumes the role as main implementer of EUMETSAT’s commitments in support to global climate monitoring. This is achieved through:

- Application of highest standards and guidelines as lined out by GCOS for the satellite data processing,
- Processing of satellite data within a true international collaboration benefiting from developments at international level and pollinating the partnership with own ideas and standards,
- Intensive validation and improvement of the CM SAF climate data records,
- Taking a major role in data set assessments performed by research organisations such as WCRP (World Climate Research Program). This role provides the CM SAF with deep contacts to research organizations that form a substantial user group for the CM SAF CDRs,

- Maintaining and providing an operational and sustained infrastructure that can serve the community within the transition of mature CDR products from the research community into operational environments.

A catalogue of all available CM SAF products is accessible via the CM SAF webpage, www.cmsaf.eu. Here, detailed information about product ordering, add-on tools, sample programs and documentation is provided.

2 Introduction

This CM SAF Algorithm Theoretical Basis Document (ATBD) provides information on the processing algorithm implemented for the retrieval of surface radiation parameters from the SEVIRI / GERB instruments on-board of MSG. For the shortwave surface radiation the same algorithm is applied as used for the generation of the MVIRI long term data set. For the retrieval of the longwave surface radiation the algorithm is based on cloud information derived from satellite, reanalysis data, and topographic information.
More information on the basic accuracy requirements are defined in the product requirements document [AD 1]. The MSG surface radiation data set contains multiple parameters:

Surface Incoming Shortwave Radiation – CM-53, Section 3.1.1

Surface Net Shortwave Radiation – CM-68, Section 3.1.2

Surface Outgoing Longwave Radiation – CM-75, Section 3.2.2

Surface Downward Longwave Radiation – CM-82, Section 3.2.1

Surface Net Longwave Radiation – CM-89, Section 3.2.3

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Cloud Radiative Effect SW – CM-102, Section 3.3.2

Cloud Radiative Effect LW – CM-103, Section 3.3.3

3 Retrieval Algorithms of the MSG Surface Radiation Products

In the following the retrieval algorithms used to generate the surface radiation products in the CM SAF MSG data set will be described. The retrieval of the shortwave surface radiation products (SIS, SNS) is presented in Section 3.1, Section 3.2 presents the algorithms used to derive the longwave surface radiation data sets (SDL, SOL, SNL). The algorithms to calculate the surface radiation budget (SRB) and the shortwave and longwave cloud effects (CFS, CFL) are presented in Section 3.3.

3.1 Shortwave Surface Radiation

The retrieval algorithm of the surface shortwave radiation (i.e., the surface radiation in the wavelength region between 200 nm and 4000 nm) used for the processing of the MSG data is based on the algorithm used in the generation of the MVIRI Climate Data Record [RD 2].
The underlying fundamental assumption of retrieving the surface solar irradiance from satellite observations is that the reflected radiance, as measured by the satellite instrument, is related to the broadband atmospheric transmission, T. From the atmospheric transmission the surface incoming solar radiation, SIS, can be derived:

$$SIS = E_0 \cos(\Theta_0)\, T, \qquad \text{(Eq. 3-1)}$$

where E_0 is the incoming solar flux at the top-of-the-atmosphere (E_0 = 1368 W/m^2) and Θ0 the solar zenith angle. The net surface solar radiation is defined as the difference between the incoming and the reflected surface solar radiation:

$$SNS = SIS - SOS, \qquad \text{(Eq. 3-2)}$$

where SNS is the net surface solar irradiance and SOS the reflected surface solar radiation.

3.1.1 SIS Algorithm

The algorithm used here to derive SIS from the MSG data set is based on the application of a look-up-table to derive the atmospheric transmission for cloud free sky. The cloud effect on the solar surface irradiance is considered by the effective cloud albedo.
The details of the algorithm are given in [*R Mueller et al.*, 2009] and [Posselt et al. 2011]. Here, the basic layout and the fundamental assumptions of the algorithm are presented.

The solar surface irradiance is mainly determined by the solar zenith angle, the effective cloud albedo, the vertically-integrated water vapour and the aerosol optical depth.
The solar zenith angle (SZA) is determined by the rotation of the Earth, the tilting of the Earth axis and their movement around the sun; the SZA can be accurately calculated. While satellite-based information on the integrated water vapour is available from microwave instruments (e.g., the ATOVS package), these instruments / satellite channels are not available from the MSG data set. Hence for water vapour external data sources have to be consulted to calculate the transmission and the surface solar incoming radiation. For the aerosol information the same data source as for MVIRI has been used.
The main information that is used from the MSG satellite data is the information on effective cloud albedo.

The retrieval algorithm used to derive the surface incoming solar radiation consists of two steps. First, the broadband GERB based top of atmosphere albedo is used to derive information on effective cloud albedo for each pixel using the GERB top of atmosphere data as input. In case, no cloud is detected (i.e., the effective cloud albedo is zero), the surface solar irradiance is calculated by radiative transfer modelling using information on the integrated water vapour and the aerosol optical depth from auxiliary sources without the use of additional satellite observations. In the case the cloud retrieval algorithm detects the presence of a cloud, the pixel is considered '*cloudy*' and the atmospheric transmissivity and subsequently the surface solar irradiance is derived using the method described in Section 3.1.1.2.

3.1.1.1 Cloud-free conditions

The calculation of the surface solar irradiance under cloud-free conditions does not require any additional information from satellite, but is performed using the clear-sky Mesoscale Atmospheric Global Irradiance Code (MAGIC, http://gnu-magic.sourceforge.net/). Figure 1 presents the flow-chart of the calculation of the surface incoming solar radiation under clear-sky conditions using MAGIC.

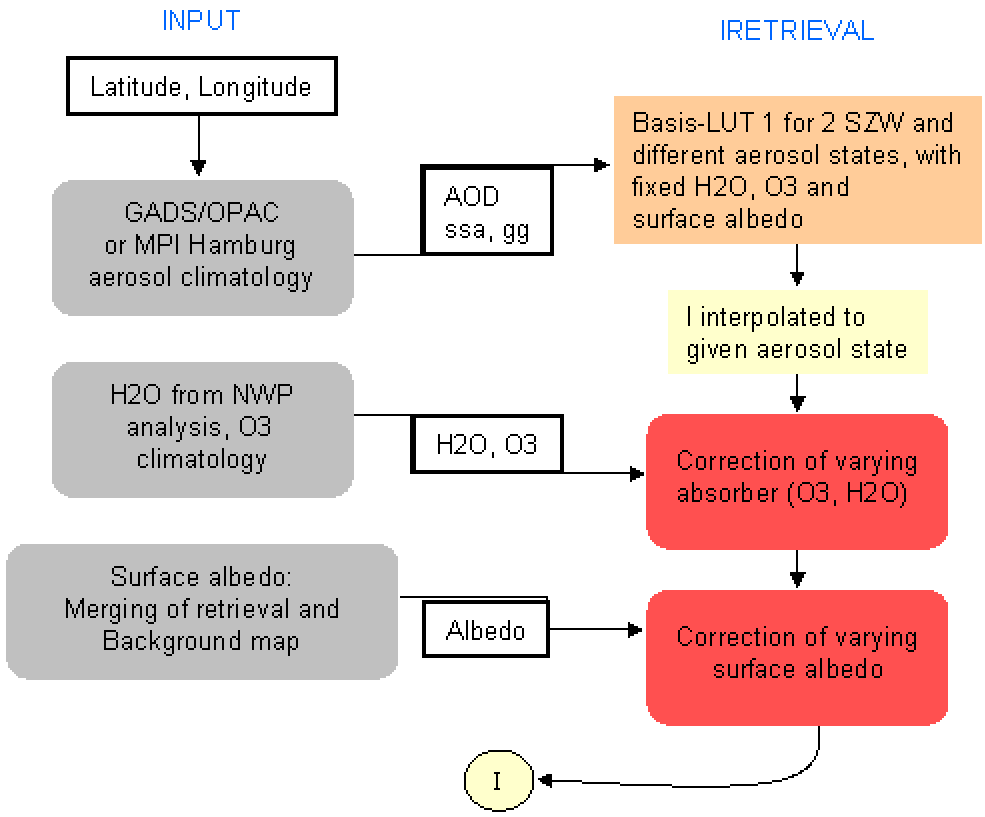

Figure 1: Flow-chart of the calculation of the surface incoming solar radiation under clear-sky conditions. The required input data is shown on the left side of the diagram, the right part represents the calculation of the surface solar irradiance using the MAGIC clear-sky model. The figure is taken from [*R Mueller et al.*, 2009].

As input parameters, aerosol information (i.e., aerosol optical depth, single scattering albedo, backscattering coefficient), vertically-integrated water vapour and ozone, as well as the surface albedo are required.
For the aerosol information, the monthly mean aerosol fields from the Kinne MPI climatology [Kinne *et al.*, 2006] has been used. The integrated water vapour is taken from the ERA-Interim Reanalysis [*Dee et al.*, 2011], which has recently been extended to cover the time span between 1979 and today. The vertical ozone column has been set constant to 335 DU.

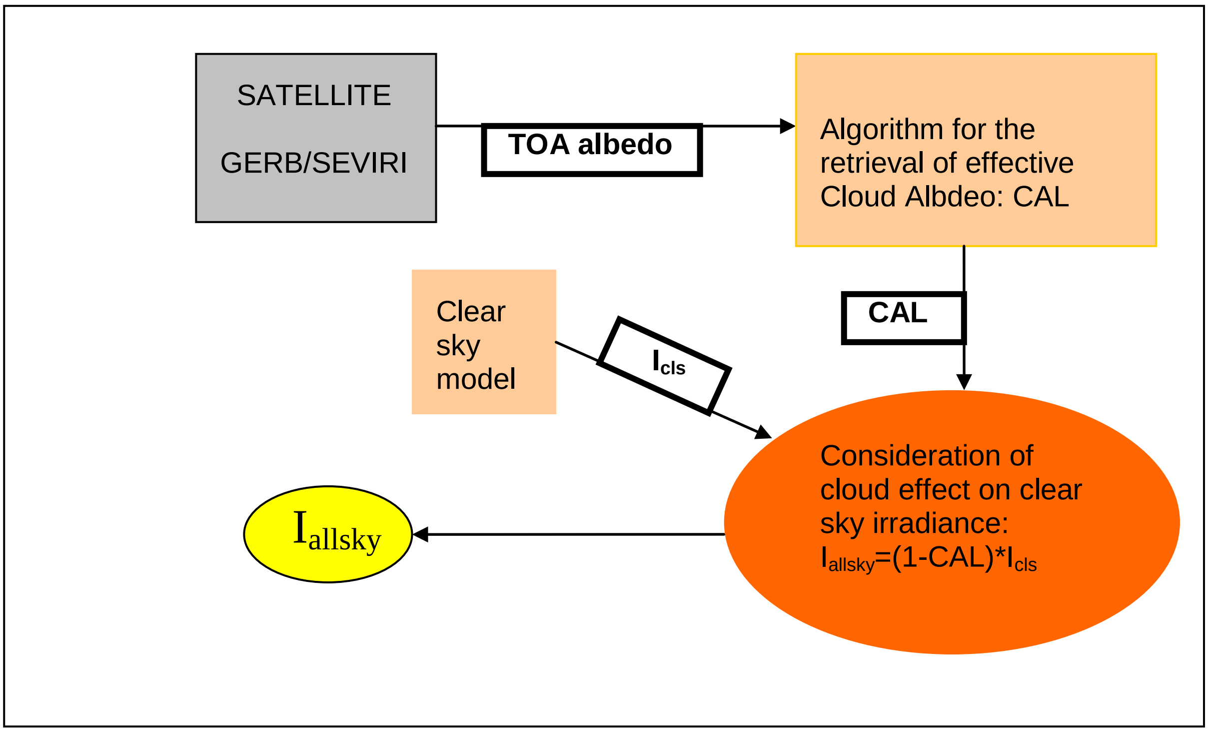

Figure 2: Diagram of the calculation of the surface solar incoming radiation under cloudy conditions. The required input data is shown on the left side of the diagram, the right part represents the calculation of the surface solar irradiance using the look-up tables for the TOA albedo. The figure is taken from[*R Mueller et al.*, 2009].

The surface albedo information is calculated based on the spatial distribution of 20 surface types. The Surface and Atmospheric Radiation Budget (SARB) working group, part of the Clouds and the Earth's Radiant Energy System (CERES) mission, provides global digital information on land cover based on scene types from the International Geosphere/Biosphere Programme (IGBP) on a 1/6 deg grid (http://www-surf.larc.nasa.gov/surf/index.html). Using the broadband albedo for each surface type, a temporally-constant global surface albedo map is generated (see Figure 3). Seasonal changes, e.g., due to snow coverage, are not considered. The variation of the surface albedo with solar zenith angle is considered [*Briegleb et al.*, 1986].
This auxiliary information is used in the MAGIC clear-sky solar radiation transfer code to derive the surface solar irradiance.

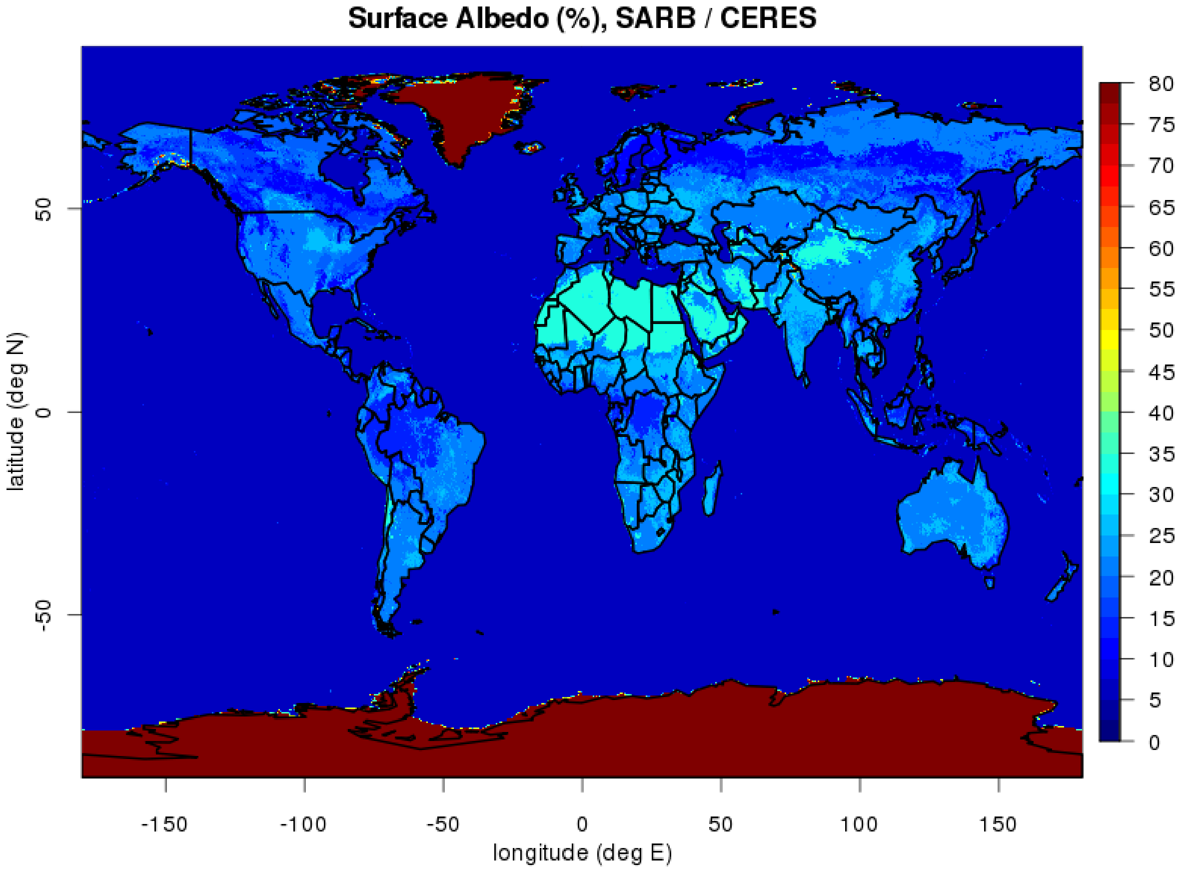

Figure 3: Spatial distribution of the surface albedo used in the calculation of the clear-sky surface radiation.

Look-up tables form the core of the MAGIC clear-sky model. They have has been pre-calculated for several aerosol optical depths and types, 2 sun zenith angles (0 and 60 degree) with fixed values of surface albedo (0.2), integrated water vapour column (15 mm) and ozone (345 DU) using the RTM model libRadtran [*Mayer and Kylling*, 2005].
To calculate the surface solar radiation for the current atmospheric state (i.e., SZA, water vapour, ozone, surface albedo) correction formulas are applied that consider the difference between the reference value of the parameter (i.e., the value used to derive the look-up-table) and the current value of the parameter. The sensitivity of the clear-sky surface irradiance to the surface albedo is small, i.e., a change of the surface albedo by a factor of 2 (e.g., from 0.2 to 0.4) induces only a 2% change on the surface downwelling clear-sky irradiance [*Mueller et al.*, 2009, Figure 4]. The Modified Lambert-Beer (MLB) function is used to derive the dependency of the surface solar radiation from the solar zenith angle based on only 2 pre-calculated solar-zenith angles [*R W Mueller et al.*, 2004]. These optimisations reduce the number of required radiation transfer calculations substantially by a factor of 10.000 compared to 'traditional' look-up table approaches. The computational efficiency of the algorithm makes it perfectly suited for the satellite retrieval of the surface solar radiation under clear-sky conditions. No additional information (e.g., the top-of-the-atmosphere reflectance) is used from the satellite measurement.

3.1.1.2 Cloudy Condition

Under cloudy conditions the effective cloud albedo is used to calculate the cloud transmission of the clear sky irradiance.

The effective cloud albedo is related to the solar irradiance via the clear sky index. The clear sky index is defined as

$$k = SIS/SIS_{cls} , \qquad \text{(Eq. 3-3)}$$

Here SIS_{CLS} is the solar irradiance for cloud free skies. The relation between the effective cloud albedo CAL and the clear sky index is mainly given by:

$$CAL = 1-k , \qquad \text{(Eq. 3-4)}$$

This relation is defined by physics, in detail by the law of energy conservation (Dagested, 2005). However, above a CAL value of 0.8 empirical corrections are needed in order to consider:

- The effect of statistical noise, which could lead to CAL values above 1 and below 0 (occurs very seldom, however have to be considered).
- The effect of saturation occurring in optical thick clouds.

In this regions the n-CAL relation was determined from the statistical regression using the ground-based measurements at European sites and fitted to get the best performance at all the ground sites. Eq. 3-5 provides the complete n-CAL relation for all possible CAL values. It is important to note that the empirical fit has been performed in the 80s and used since then without refitting. The RMSD of the empirical fit is 0.1.

$$CAL < -0.2, \quad k = 1.2 , \qquad \text{Eq. 3-5}$$

$$-0.2 \le CAL \le 0.8, \quad k = 1 - CAL ,$$

$$0.8 < CAL \le 1.1, \quad k = 2.0667 - 3.6667 * CAL + 1.6667 * CAL^2 ,$$

$$1.1 < CAL , \quad k = 0.05 .$$

As a consequence of the definition of the clear sky index, the surface solar irradiance for the full-sky situation (G) is given by,

$$SIS = k * SIS_{cls} , \qquad \text{(Eq. 3-6)}$$

where SIS_{CLS} is the clear-sky surface solar irradiance calculated using the MAGIC code (Mueller et al., 2004, 2009), described in section 3.1.1.1.

The auxiliary input data is identical to the input data used to calculate the clear-sky surface radiation, i.e., surface albedo, vertically-integrated water vapour and ozone, and aerosol information. In addition to this auxiliary input data, also satellite data is used to derive the surface radiation under cloudy conditions.
The algorithm uses the satellite-derived top-of-the-atmosphere broadband albedo in the shortwave spectral region as input parameter for the retrieval of the effective cloud albedo (see Figure 2). This quantity is provided by RMIB.

3.1.1.3 Calculation of gridded averages

The daily mean is calculated following the method by [*Moser and Raschke*, 1984]:

$$I_{dm} = I_{clr,dm} * \frac{\sum I_i}{\sum I_i^{clr}}, \qquad \text{(Eq. 3-7)}$$

here I_{dm} is the daily mean of the surface solar irradiance, $I_{clr,dm}$ is the daily mean of the clear sky surface solar irradiance, I_i is the retrieved surface radiation from the satellite retrieval and I_i^{clr} is the clear-sky surface solar radiation that corresponds to I_i. I_i^{clr} is calculated for each satellite pixel during the processing of the satellite data using the MAGIC clear-sky radiation transfer model. The daily mean of the clear-sky surface solar irradiance, $I_{clr,dm}$, is calculated on the 0.05° grid using the MAGIC radiation transfer model.

The monthly mean data of the surface solar irradiance are calculated as averages from the daily mean values. Only those grid boxes are considered that have more than 20 valid daily means of the surface solar radiation.

3.1.1.4 Known Limitations and their Implications

Known limitations and shortcomings of this algorithm to derive the surface solar irradiance:

- The application of the temporally-constant SARB/CERES surface albedo map limits the quality of the data set in regions with varying surface albedo, i.e., in Canada, Alaska, Russia, and Scandinavia, during the times when the surface albedo is greatly different from the value assumed in the SARB/CERES albedo map.

- The algorithm requires broadband solar fluxes at the top-of-the-atmosphere to retrieve the atmospheric transmissivity and subsequently the surface solar radiation. The conversion of the satellite-observed radiances to broadband solar fluxes requires assumptions on the bidirectional reflectance distribution function (BRDF), which can introduce large uncertainty into the satellite retrieval under cloudy conditions.

- The uncertainty in the relation between solar surface irradiance and effective cloud albedo is higher over bright surfaces.

- The application of monthly climatological aerosol information limits the accuracy of the data set, especially in regions with high inter-annual and sub-monthly aerosol variability, e.g., desert regions.

The mentioned limitations will be addresses and improved in future versions of the CM SAF MSG surface solar radiation data set.

3.1.2 SNS Algorithm

The CM SAF MSG data set of the net surface shortwave radiation (SNS) is derived directly from the CM SAF MSG data sets of the surface solar irradiance (SIS) and the surface albedo (SAL).

The net surface radiation is defined as the difference between the incoming solar surface radiation (SIS) and the outgoing surface radiation (SOS):

$$SNS = SIS - SOS = SIS\ (1 - SAL), \qquad \text{(Eq. 3-8)}$$

with

$$SOS = SAL * SIS. \qquad \text{(Eq. 3-9)}$$

For the generation of the CM SAF MSG SNS data set this calculation is conducted on the 0.05 deg grid based on the monthly means of SIS.

3.1.2.1 Known Limitations

The accuracy of the CM SAF MSG SNS data set depends on the accuracy of the CM SAF MSG SIS and SAL data set and the limitations of their algorithms also apply to the SNS data set (see Section 3.1.1.4 for the limitations of the SIS retrieval algorithm).

Additionally, the following limitations apply:

- The surface albedo in the SAL data set describes the directional-hemispherical reflectance (direct radiation) at a solar zenith angle of 60° and does not consider bi-hemispherical reflectance (diffuse radiation). Applying the SAL data set to the monthly mean surface incoming solar radiation data set introduces temporally- and spatially-dependent uncertainties.

In future releases of the CM SAF MSG SNS data set, these limitations will be addressed.

3.2 Longwave Surface Radiation Products

This section describes the algorithms to derive the surface longwave radiation products of the CM SAF MSG data set: The surface downwelling longwave radiation (SDL), the surface outgoing longwave radiation (SOL), and the surface net longwave radiation (SNL).

The longwave surface radiation budget is decoupled from the visible and infra-red radiation at the top-of-the-atmosphere [*Ellingson*, 1995], which limits the suitability of the MSG data to retrieve the longwave surface radiation components.
The surface downwelling longwave radiation is, under cloud-free conditions, mainly determined by the temperature and water vapour in the lowest kilometre of the atmosphere [*Ohmura*, 2001]. Under cloudy conditions, the height of the cloud base determines the surface downwelling longwave radiation. In both cases, the AVHRR satellite signal alone does not contain enough relevant information to retrieve the surface longwave downwelling radiation within sufficient accuracy.
The surface outgoing longwave radiation is dominated by the surface temperature, which can, under cloud-free conditions, be derived from the AVHRR satellite observations. No information on the surface temperature, and hence the surface outgoing longwave radiation, is present in the satellite measurements under cloudy conditions.

To overcome this fundamental limitation, data from the ERA-Interim data set is used to generate the CM SAF MSG surface longwave radiation data set. The ERA-Interim data set is generated at the spectral T255 horizontal resolution, corresponding to approximately 79 km spacing on a reduced Gaussian grid [*Dee et al.*, 2011]. To reduce spin-up effects of the reanalysis model, the monthly means of the surface longwave radiation data based on the 12-to-24 h forecasts are used.
The information on the cloud fraction from the CMSAF MSG CFC data set and additional topographic information is used to provide the high spatial resolution of the CM SAF MSG surface longwave radiation data sets.

3.2.1 SDL Algorithm

The CM SAF algorithm to derive the surface downwelling longwave (SDL) radiation from the MSG data set is based on the monthly mean surface downwelling longwave radiation data from the ERA-Interim data set. The CM SAF MSG cloud fraction (CFC) data set and high-resolution topographic information are used to generate the CM SAF MSG SDL data set on the 0.05° grid.

3.2.1.1 Calculation of the Cloud Correction Factor

In a preparatory step, the sensitivity of the surface downwelling longwave radiation to cloud coverage is determined from the ERA-Interim data set. The cloud correction factor (CCF) is defined as the ratio of the difference between the clear-sky and all-sky surface longwave downwelling radiation to the cloud fraction:

$$CCF = \frac{\Delta SDL}{CFC_{ERA}} = \frac{SDL_{allsky} - SDL_{clr}}{CFC_{ERA}} \qquad \text{(Eq. 3-10)}$$

The cloud correction factor describes the sensitivity of the surface downwelling longwave radiation to changes in the cloud fraction. The CCF is determined from the ERA-Interim monthly mean data by linear regression between *ΔSDL* and *CFC* for each grid box. The calculation of the regression is conducted separately for each month resulting in a CCF data set for each month of the year based on the 31 years of ERA-Interim data.
All grid boxes with a mean total cloud fraction of more than 20 % and mean *ΔSDL* below 3% of SDL are set to zero. In these grid boxes (only in tropical regions), the impact of cloud coverage on the surface downwelling longwave radiation is negligible. The cloud correction factor is derived from the linear regression for grid boxes that exhibit a CFC variability of more than 10 % and for grid boxes with a correlation coefficient between *ΔSDL* and *CFC* above 0.6. For the remaining grid boxes, CCF is extrapolated from neighbouring grid boxes.

In the tropical regions, clouds have no impact on the surface downwelling longwave radiation, i.e., the differences of the monthly means of the clear-sky and the all-sky surface downwelling longwave radiation is close to zero, even though cloud coverage is larger than 0. The impact of clouds on the surface longwave downwelling radiation is largest over the Southern Oceans, especially over the Pacific, where clouds can add more than 100 W/m^2 to the clear-sky surface longwave radiation.

3.2.1.2 Calculation of SDL

The surface downwelling longwave radiation from the MSG data set is calculated from the monthly mean of the clear-sky surface downwelling longwave radiation derived from ERA-Interim and the cloud correction term, i.e., the *CCF* multiplied with the cloud cover derived from the CM SAF MSG CFC data set:

$$SDL_{MSG} = SDL_{clr} + CFCmsg * CCF = SDL_{clr} + CFC_{MSG} * \frac{\Delta SDL}{CFC_{ERA}}, \qquad \text{(Eq. 3-11)}$$

here SDL_{clr} denotes the monthly mean clear-sky surface downwelling longwave radiation from ERA-Interim and CFC_{MSG} is the cloud fraction from the CM SAF MSG data set. By the application of the cloud correction using the MSG CFC data set the spatial resolution of the data is substantially improved and corresponds to the spatial resolution of the CM SAF MSG CFC data set. To ensure the conservation of the absolute values from the ERA-Interim data the SDL_{MSG} data is rescaled after this step to reproduce the SDL data from ERA-Interim on the coarse ERA-Interim grid.

Topography substantially modifies the surface longwave downwelling radiation, because of the change in near-surface temperature induced by changes in altitude. Based on observations, [*Wild et al.*, 1995] found that the surface downwelling longwave radiation decreases on average by 2.8 W/m^2 per 100 m in elevation. To account for this effect when generating the CM SAF MSG SDL data set, the Global Land One-km Base Elevation Project (GLOBE) database has been used to calculate the topography on the 0.05° MSG disk grid. The GLOBE data set is a global 1-km gridded, quality-controlled Digital Elevation Model (DEM) accessible from the National Geophysical Data Centre at NOAA (http://www.ngdc.noaa.gov/mgg/topo/globe.html). Using the topography information from the ERA-Interim data set, the surface downwelling longwave radiation (SDL_{MSG}) has been corrected according to [*Wild et al.*, 1995] to account for the differences in the surface elevation between the two grids The conservation of the surface downwelling longwave radiation on the original ERA-Interim grid is taken into account during the topographic correction.

The CM SAF MSG data set of the surface downwelling longwave radiation is available as monthly means from 1982 to 2009 with a grid point distance of 0.05°.

3.2.1.3 Known limitations

Known limitations and shortcomings of this algorithm to derive the surface downwelling longwave radiation:

- The cloud correction factor (CCF) is determined on a monthly basis by linear regression using ERA-Interim data between 1979 and 2010. By using linear regression to determine CCF, Equation (Eq. 3-11) is only valid in an 'average' sense and no interannual variability is considered. For a given year and month the cloud correction of the surface downwelling longwave radiation is (slightly) different to the climatological correction factor for this months. This introduces some uncertainties into the calculation of the CM SAF MSG SDL data set.

- The topography correction of the surface downwelling longwave radiation is based on measurements obtained in the European Alpine region [*Wild et al.*, 1995]. By analysing the differences between ERA-Interim-derived SDL and global surface observations from the Baseline Surface Radiation Network (BSRN), no improved topographic correction could be determined based on the available observations (Sebastian Limbach, pers. comm.). Dedicated surface observations of the altitudinal dependence of the surface downwelling longwave radiation are required to improve the topographic correction term for the surface downwelling longwave radiation for the global scale. The application of one constant value for the topographic correction in the calculation of the CM SAF MSG SDL data set is a limitation, which introduces uncertainty.

These limitations will be addressed in future versions of the CM SAF MSG SDL data set.

3.2.2 SOL Algorithm

The surface outgoing longwave radiation (SOL) is primarily determined by the surface temperature and the emissivity of the surface. In the longwave spectral region, the emissivity of the Earth surface is close to unity, resulting in a very small contribution of the reflected surface downwelling longwave radiation to the surface outgoing longwave radiation.

The ability to retrieve the surface outgoing longwave radiation from satellite observations alone is limited by the ability to retrieve the surface temperature with high accuracy. Direct retrieval of the surface temperature from satellite using VIS / IR channels is fundamentally restricted to clear-sky conditions. The high sensitivity of the surface outgoing longwave radiation to the surface temperature (SOL is proportional to T_{srf}^4 .) results in large uncertainties in the outgoing longwave radiation even under perfect conditions.

Here, we use ERA-Interim data to generate the CM SAF MSG data set of the surface outgoing longwave radiation. To prepare the CM SAF MSG data set on the 0.05° grid, the ERA-Interim data is corrected to account for differences in the terrain elevation and the emissivity between the ERA-Interim grid and the CM SAF MSG grid.

As a first step, the surface temperature that corresponds to the monthly mean surface outgoing longwave radiation from ERA-Interim is calculated:

$$T_{srf} = \sqrt[4]{\frac{SOL_{ERA}}{\varepsilon \cdot \sigma}}, \qquad \text{(Eq.3-12)}$$

where SOL_{ERA} is the monthly mean surface outgoing longwave radiation from ERA-Interim, ε is the emissivity of the ERA-Interim grid box, and σ is the Stefan-Boltzman constant ($\sigma = 5.67\ 10^{8}\ Wm^{-2}\ K^{-4}$).

The surface emissivity on the ERA-Interim grid is based on land cover types provided by the Global Land Cover 2000 (GLC2000) and Global Land Cover Characteristics (GLCC) data bases. Both data sets are derived from analysis of satellite observations and provide the data at a spatial resolution of 1 km. The GLC2000 data set is mainly based on observations from the VEGETATION instrument onboard the SPOT 4 satellite and covers most of the globe, expect Antarctica [*Bartholome and Belward*, 2005]; the GLCC data is based on AVHRR measurements [*Loveland et al.*, 2000]. Here, the GLCC is used in regions where GLC2000 information is not available. The land cover types are converted to land type classes and the broadband emissivity is calculated based on the data given in *Wilber et al.* [1999] (See Figure 4). The emissivity derived on the original resolution of the land type data are then averaged onto the ERA-Interim grid.

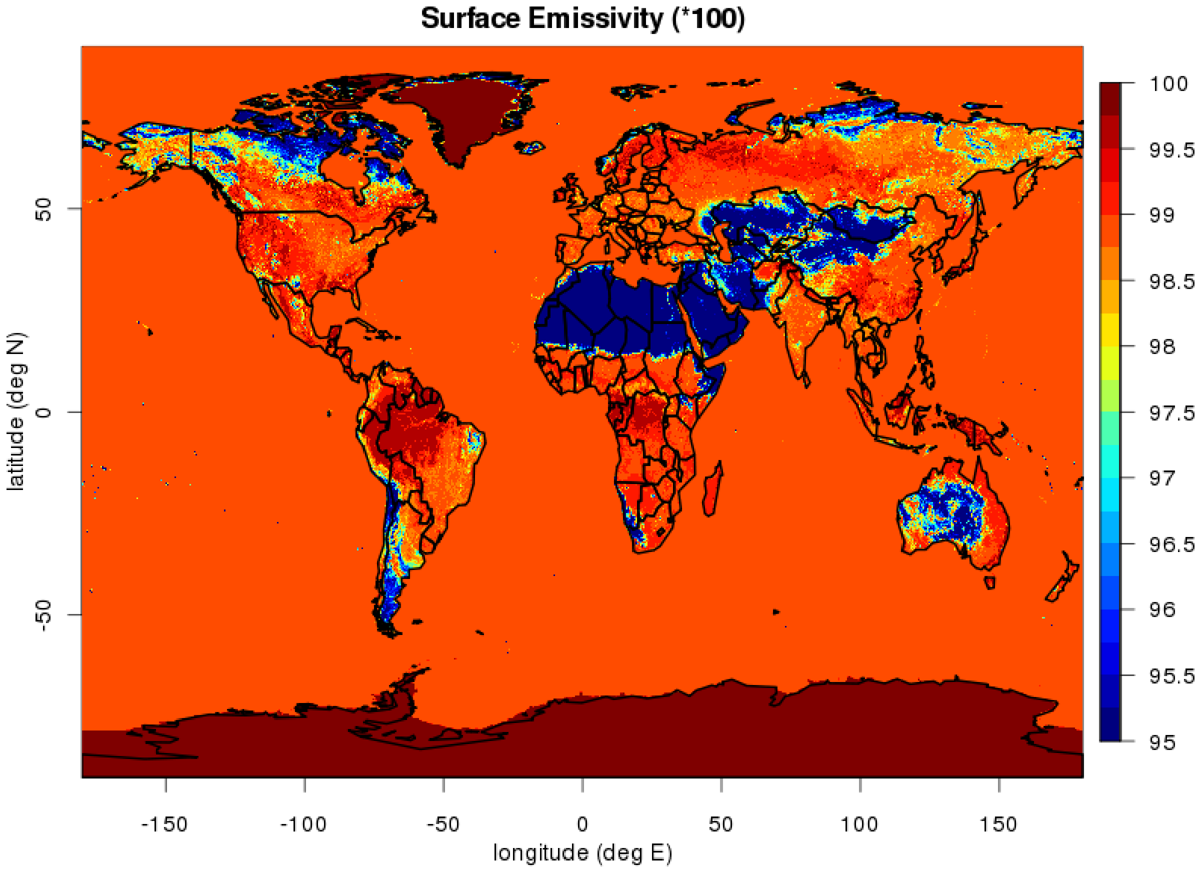

Figure 4: Surface Emissivity Map derived from land cover types.

The SOL-consistent surface temperature from ERA-Interim is adjusted to account for differences between the terrain elevation on the ERA-Interim grid and the elevation on the global 0.05°-grid by applying the dry-adiabatic temperature gradient of $\Delta T = -9.81$ K / km:

$$\Delta T_{srf} = \Delta h * \Delta T, \qquad \text{(Eq.3-13)}$$

where Δh is the difference in terrain elevation between the 0.05° MSG grid and the ERA-Interim grid in kilometres. The surface outgoing longwave radiation on the global 0.05° grid can then be calculated:

$$SOL = \varepsilon * \sigma * (T_{srf} + \Delta T_{srf})^4 \qquad \text{(Eq.3-14)}$$

in the calculation of the SOL data set on the global 0.05° grid, it is ensured that the SOL values on the ERA-Interim grid are conserved. The surface outgoing longwave radiation is positively defined in the CM SAF MSG SOL data set.

3.2.2.1 Known limitations

Here is a list of limitations of the SOL data set:

- The topographic correction of the SOL data from ERA-Interim is based on the assumption that the representative monthly mean surface temperature is modified with the dry-adiabatic temperature gradient as a function of elevation. This assumption needs to be verified and introduces some uncertainty in the current data set.
- The emissivity used to derive the surface temperature that corresponds to the monthly mean surface outgoing longwave radiation from ERA-Interim is derived from land type

classes and predefined emissivity. In ERA-Interim, the surface emissivity also depends on additional parameters, e.g., soil moisture. Hence, the calculated corresponding surface temperature is slightly different to the one used within ERA-Interim, which introduces some uncertainty in the topographic correction of the SOL ERA-Interim data. The impact on the CM SAF MSG SOL data set is considered marginal.

3.2.3 SNL Algorithm

The surface net longwave radiation is defined as the sum of the downwelling and the upwelling longwave surface radiation. Since, in the case of the CM SAF MSG surface longwave radiation data sets, the surface outgoing longwave radiation is positively defined (Section 3.2.2), the surface net longwave radiation is calculated by the difference between the downwelling and the upwelling longwave surface radiation:

$$\mathrm{SNL} = \mathrm{SDL} - \mathrm{SOL}. \qquad \text{(Eq.3-15)}$$

The calculation is based on the monthly mean CM SAF MSG data sets of the surface longwave downwelling (SDL) and upwelling radiation (SOL) and available on the 0.05 deg MSG disk grid. As SOL usually is larger than SDL, values of SNL typically are below zero.

3.2.3.1 Known limitations

Equation (Eq.3-15) to calculate the surface net longwave radiation is based on the definition of this quantity, so only the limitations of the input data sets (i.e., CM SAF MSG SDL (Section 3.2.1.3) and CM SAF MSG SOL (Section 3.2.2.1)) apply.

3.3 Surface Radiation Budget and Cloud Forcing

Based on the surface shortwave and longwave data sets the surface radiation budget and the short- and longwave surface cloud forcing are calculated.

3.3.1 SRB Algorithm

The surface radiation budget is calculated as the sum of the shortwave and the longwave net surface radiation fluxes and can be derived directly from the corresponding monthly mean CM SAF MSG data sets:

$$SRB = SNS + SNL. \qquad \text{(Eq.3-16)}$$

The calculation is based on the monthly mean CM SAF MSG data sets of the net surface longwave (SNL) and shortwave (SNS) and available on the 0.05 deg MSG disk grid.

3.3.1.1 Known limitations

The equation to calculate the surface radiation budget is based on the definition of this quantity, so only the limitations of the input data sets (i.e., CM SAF MSG SNS and CM SAF MSG SNL) apply.

3.3.2 CFS Algorithm

The shortwave cloud radiative effect is defined as the difference between the net shortwave surface radiation fluxes under all-sky and under clear sky conditions:

$$CFS = SNS - SNS_{clr}, \qquad \text{(Eq.3-17)}$$

where SNS is the net surface shortwave radiation and $\mathrm{SNS}_{\mathrm{clr}}$ the net surface shortwave radiation under clear sky conditions. Using the surface albedo, the equation can be transformed into

$$CFS = (SIS - SIS_{clr})\ (1 - SAL). \quad \text{(Eq.3-18)}$$

The clear-sky surface downwelling solar radiation is calculated in the process of generating the surface downwelling solar radiation data set (see Section 3.1.1) and also available as monthly means on the CM SAF MSG 0.05° grid. The CFS is generated by directly applying Equation (Eq.3-18) to the monthly mean CM SAF data sets of SIS and SAL and available as monthly means on the CM SAF MSG 0.05 deg grid.

3.3.2.1 Known limitations

The equation to calculate the shortwave surface cloud forcing is based on the definition of this quantity, so only the limitations of the input data sets (i.e., CM SAF MSG SIS and CM SAF MSG SAL and the monthly mean clear-sky surface radiation) apply.

3.3.3 CFL Algorithm

The longwave cloud radiative effect is defined as the difference of the net longwave surface radiation fluxes under all-sky and under clear-sky conditions:

$$CFL = SNL - SNL_{clr}\ , \quad \text{(Eq. 3-19)}$$

where SNL is the net longwave surface radiation and SNL_{clr} is the net longwave surface radiation under clear-sky conditions. With the assumption that the difference between the all-sky and the clear-sky surface outgoing longwave radiation is negligible the longwave cloud radiative can be calculated from the differences of the downwelling surface longwave fluxes under all-sky and clear-sky conditions:

$$CFL = SDL - SDL_{clr}. \quad \text{(Eq.3-20)}$$

Taking into account Equation (Eq. 3-11), CFL can be calculated from the cloud fraction and the cloud correction factor:

$$CFL = CFC * CCF. \quad \text{(Eq.3-21)}$$

The longwave cloud forcing is generated on the global CM SAF MSG grid using the monthly mean CM SAF MSG CFC data set and the cloud correction factor on the global 0.05° grid.

3.3.3.1 Known limitations

The equation to calculate the longwave surface cloud forcing is based on the definition of this quantity. The assumption that the difference between the outgoing longwave radiation under clear-sky and all-sky conditions is equivalent to the assumption that surface-reflected downwelling longwave radiation only accounts for a small contribution to the outgoing longwave surface radiation. The uncertainty introduced by this assumption is expected to be marginal. Additional limitations arise from the applications of the CM SAF MSG CFC data set and the cloud correction factor based on the ERA-Interim data set.

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5 Glossary

AVHRR: Advanced Very High Resolution Radiometer
AOD: Aerosol Optical Depth
CAL: Effective cloud albedo
COT Cloud optical depth
GADS/OPAC: Global Aerosol Data Set / Optical Properties of Aerosols and Clouds
GERB: Geostationary Earth Radiation Experiment
K: Clear sky index.
LUT: Look-up table
MVIRI: Meteosat Visible-InfraRed Imager
NOAA: National Oceanic and Atmospheric Administration
NCEP: National Center for Environmental Prediction
RTM: Radiative Transfer Model
SID: Surface Direct Irradiance (beam).
SIS: Solar Surface Irradiance
SZA: Sun Zenith Angle
SSA: Single Scattering Albedo