EUMETSAT Satellite Application Facility on Climate Monitoring

Product User Manual

Meteosat Solar Surface Radiation and Effective Cloud Albedo Climate Data Records

SARAH-3

DOI: 10.5676/EUM_SAF_CM/SARAH/V003

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Effective Cloud Albedo (CAL):	CM-23083	CM-5081
Surface Incoming Shortwave Radiation (SIS):	CM-23203	CM-5211
Surface Direct Irradiance (SDI):	CM-23293	CM-5291
Sunshine Duration (SDU):	CM-23283	CM-5281
Photosynthetic Active Radiation (PAR):	CM-23273	CM-5271
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	Name	Function	Signature	Date
Author	Uwe Pfeifroth Jörg Trentmann	CM SAF Scientists		24/02/2023
Review	M. Schröder	CM SAF Science Coordinator		01/03/2023
Approval	CM SAF Steering Group			
Release	Rainer Hollmann	Project Manager		

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Applicable Documents

Reference	Title	Code
AD 1	CM SAF Product Requirement Document	SAF/CM/DWD/PRD/4.1

Reference Documents

Reference	Title	Code
RD 1	Validation Report Meteosat Climate Data Records of Surface Radiation SARAH-3	SAF/CM/DWD/VAL/METEOSAT/HEL/3.2

Reference	Title	Code
RD 2	Algorithm Theoretical Baseline Document (ATBD) Meteosat Solar Surface Irradiance and effective Cloud Albedo Climate Data records SARAH-3	SAF/CM/DWD/ATBD/METEOSAT/HEL/3.4

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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), the Meteorological Service of the United Kingdom (UK MetOffice) and the Centre National de la recherche scientifique (CNRS) of France. 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 (CDRs) derived from operational meteorological satellites.

In particular the generation of long term data records is pursued. The ultimate aim is to make the resulting data records 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 records 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 records 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 records also serve the improvement of climate models both at global and regional scale.

As an essential partner in the related international frameworks the CM SAF 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 an 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 record assessments performed by research organisations such as WCRP (World Climate Research Programme),
- 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.

1 Introduction

This CM SAF Product User Manual (PUM) provides relevant information to the user on the Surface Solar Radiation Data Record – Heliosat Edition 3 (SARAH-3).

The generated 38 year long (1983-2020) continuous surface radiation climate data records are based on observations from the Meteosat First and Second Generation satellites; it is the third release of the SARAH data record (SARAH-3). The Digital Object Identifier (DOI) of this SARAH-3 data record (1983-2020) is 10.5676/EUM_SAF_CM/SARAH/V003.

Peer-reviewed publications describing previous editions of the SARAH climate data record, its generation, accuracy and stability are Müller et al., 2015b and Pfeifroth et al., 2018.

The document enables the user to perform an appropriate use of the data. This manual describes available products including example images, gives basic algorithm descriptions and a brief overview of the accuracy. It also discusses potential difficulties affecting the scientific interpretation. Additionally, a technical description of the data including information on format as well as on access and handling tools (e.g. mapping and display tools) is provided in the final sections.

CM SAF data products are distinguished between operational monitoring products, often called Interim Climate Data Records (ICDR), and data records (Schulz et al., 2009). Operational monitoring products are disseminated with appropriate timeliness for climate monitoring (8 weeks up to 5 days after observation at the latest) to support operational climate monitoring applications of National Meteorological and Hydrological Services and other services. This timeliness requirement implies that such products are not a priori suitable for monitoring of inter-annual variability and trends with high confidence. Bias errors due to e. g. sensor degradations and orbital shifts as well as inter-satellite biases are not corrected for in the operational monitoring product. However, the characterisation of relatively strong anomalies on the monthly scale should be feasible. Concerning the retrospective produced data records, errors due to sensor degradations, orbital changes and inter-satellite biases are minimised. Those data records are aimed at providing time series suitable for analysing variability at longer scales than inter-annual. This PUM describes the CM SAF Meteosat surface solar radiation climate data record SARAH-3, a CDR accompanied by a corresponding ICDR from 2021 onwards with a timeliness of 5 days or better.

Long time series are needed for climate monitoring and analysis. For this reason, there is a need to employ the satellite information of the first generation of Meteosat satellites (Meteosat-2 to Meteosat-7) to generate climate information. The MVIRI (Meteosat Visible-InfraRed Imager) instrument on-board the Meteosat First Generation satellites is a passive imaging radiometer with three spectral channels a visible channel covering 0.5-0.9 microns , and infra-red channel covering 5.7-7.1 microns and 10.5-12.5 microns. MVIRI comes with a spatial resolution of 2.5km for the visible and 5km for the IR channels, sub-satellite point respectively.

The second generation of Meteosat satellites is equipped with the Spinning Enhanced Visible and InfraRed Imager (SEVIRI) and the Geostationary Earth Radiation Budget (GERB) instrument. The GERB instrument is a visible-infrared radiometer for earth radiation budget studies. It provides accurate measurements of the shortwave (SW) and longwave (LW) components of the radiation budget at the top of the atmosphere. SEVIRI employs twelve spectral channels, which provide more information of the atmosphere compared to its forerunner. Several retrieval algorithms have been developed in order to use the additional information gained by the improved spectral information of MSG mainly for now-casting applications (e. g. Nowcasting SAF algorithm, Mueller et al., 2009). However, these algorithms can not be applied to the MVIRI instrument on-board the Meteosat First Generation satellites as they use spectral information that is not provided by MVIRI.

Hence, in order to be able to provide a long time series covering more than 30 years there is a need for a specific climate algorithm that can be applied to the Meteosat First and Second Generation satellite instruments. Moreover, the retrieved climate variable must have climate quality. This is the reason why the same algorithm used for MVIRI is also applied to SEVIRI.

The algorithm consists of two parts, the modified Heliosat method, described in section 3.2.2, is used for the retrieval of the effective cloud albedo CAL (section 3.2). In a second step the MAGIC approach, described in section 3.3.2, is used for the calculation of the all sky surface radiation based on CAL (section 3.3 and 3.4). The combination of these methods is referred as MAGICSOL. The surface solar radiation climate data records generated with MAGICSOL are referred as SARAH: Surface Solar Radiation Data records – Heliosat.

The MAGICSOL method does meet the above mentioned requirements for the generation of climate data records and is in detail described in RD 2. The method provides the effective cloud albedo, the solar surface irradiance, and direct surface solar radiation parameters, sunshine duration, and the spectrally-resolved surface solar irradiance.

Version history since CDOP

The following table lists product versions according to the release history of the Meteosat climate data records from the first release in January 2011 to the respective latest release. The version history is also available for each product at www.cmsaf.eu.

The table follows the official versioning of the CM SAF work plan and of the Web User Interface. However, for the version 2 of the CM SAF surface radiation climate data records a specific name was assigned to this data record, SARAH-1. Within this document, the latest data record SARAH-3 is described.

Table 2-1: History of Meteosat-based CM SAF Climate Data Records of Surface Radiation parameters

Version	Name	Document code	Time range	Major changes
1		MVIRI_HEL	Jan 1983 – Dec 2005	• First version based on modified Heliosat version 1.0 • MAGIC version 0x86
2	SARAH-1	METEOSAT_ HEL	Jan 1983 – Dec 2013	• Second version of data record covering MFG and MSG time period, hence longer time period covered. • Improved algorithms & accuracy. • Improved aerosol information. • Name of the data record: SARAH
3	SARAH-2	METEOSAT_ HEL	Jan 1983 – Dec 2015	• Second release of the SARAH CDR • Includes SRI • Includes SDU • Improved treatment of water vapour • Geometry correction for high viewing angles • Improved temporal stability
	SARAH-2.1	METEOSAT_ HEL	Jan 1983 – Dec 2017	• Extension of SARAH-2 in time (until 2017) -> SARAH-2.1 consists of SARAH-2 plus 2016, 2017.
4	SARAH-3	METEOSAT_ HEL	Jan 1983 – Dec 2020 + ICDR (from 2021 onwards)	• Improved treatment of snow-covered surfaces • Improved surface albedo for clear-sky surface radiation • Includes PAR, DAL data record; SRI data record deleted

2 Description of Meteosat climate data records

The Meteosat processing provides climate data records of the effective cloud albedo, the solar surface irradiance, the surface direct irradiance, and the sunshine duration. The applied method, i. e., MAGICSOL described in detail in the Algorithm Theoretical Baseline document RD 2 (SAF/CM/DWD/ATBD/METEOSAT/HEL/3.2), provides also information on the clear sky reflection. The effective cloud albedo, the solar surface irradiance, the surface direct irradiance, and the sunshine duration are available on a regular 0.05x0.05 degree grid. The spatial coverage covers the Meteosat disk up to a scanning angle of 68 degree as illustrated in Figure 3-1. The data records CAL, SIS, SDI, PAR, and DAL are available as 30-min instantaneous, daily and monthly means. The sunshine duration (SDU) is provided as daily and monthly sums. All SARAH-3 climate data records are introduced in Table 3-1 with associated acronyms and units. Table 3-2 provides an overview of all available surface irradiance and effective cloud albedo data records and products. From 2021 onwards the SARAH-3 data records are generated and delivered as ICDR data records, which are available in near-realtime.

In cooperation with the PV GIS team from the EU Joint Research Centre (EU JRC) the Meteosat IODC observations from 1999 to 2016 have been used to generate a surface solar radiation data record (SARAH-E), this climate data record is available at http://dx.doi.org/10.5676/DWD/JECD/SARAH_E/V001_01

Table 3-1: Overview of SARAH-3 data records discussed in this PUM.

Acronym	Product title	Unit
SIS	Surface Incoming Shortwave Irradiance	W / m^2
CAL	Effective Cloud Albedo	Dimensionless
SDI	Surface Direct Irradiance	W / m^2
SDU	Sunshine Duration	h
PAR	Photosynthetic Active Radiation	$\mu mol/(m^2 s)$
DAL	Daylight	kLux

Table 3-2: Overview of CM SAF surface irradiance and effective cloud albedo products and data records. Entries in blue are discussed in this document.

Acronym / Identifier	Product title	Type	Satellite & Instrument	Period & Coverage
SIS CM-54	Surface Incoming Shortwave Radiation	Data record	MFG MVIRI	1983-2005 Meteosat disk

Acronym / Identifier	Product title	Type	Satellite & Instrument	Period & Coverage
SIS CM-49	Ditto	Product	MSG SEVIRI/GERB	2007-today Meteosat disk
SIS CM-48	Ditto	Product	MSG SEVIRI/GERB	2005-2007 Europe
SIS CM-50	Ditto	Product	NOAA AVHRR	2005-today Europe
SIS CM-51	Ditto	Product	MSG/NOAA merged	2007-today Meteosat disk & Northern Europe
SIS CM-23201	Ditto	Data record	MFG/MSG	1983-2013 Meteosat disk
SIS CM-23202	Ditto	Data record	MFG / MSG	1983 – 2015 Meteosat disk
SIS CM-23205	Ditto	Data record	MFG / MSG	1983 – 2017 Meteosat disk
SIS **CM-23203 / CM-5211**	**Ditto**	**Climate / Interim Climate Data record**	**MFG / MSG**	**1983 – 2020; 2021 onwards; Meteosat disk**
CAL CM-111	Effective Cloud Albedo	Data record	MFG MVIRI	1983-2005 Meteosat disk
CAL CM-23081	Ditto	Data record	MFG/MSG	1983-2013 Meteosat disk
CAL CM-23082	Ditto	Data record	MFG/MSG	1983-2015 Meteosat disk

Acronym / Identifier	Product title	Type	Satellite & Instrument	Period & Coverage
CAL CM-23085	Ditto	Data record	MFG/MSG	1983-2017 Meteosat disk
CAL **CM-23083 / CM-5081**	**Ditto**	**Climate / Interim Climate Data record**	**MFG/MSG**	**1983 - 2020; 2021 onwards; Meteosat disk**
SID CM-106	Direct Irradiance at Surface	Data record	MFG MVIRI	1983-2005 Meteosat disk
SID CM-105	Ditto	Product	MSG SEVRI/GERB	2009-today Meteosat disk
DNI CM-23231	Direct Normal Irradiance at surface	Data record	MFG/MSG	1983-2013 Meteosat disk
SDI (SID,DNI) CM-23291	Surface Direct Irradiance	Data record	MFG/MSG	1983-2015 Meteosat disk
SDI (SID,DNI) CM-23295	Ditto	Data record	MFG/MSG	1983-2017 Meteosat disk
SDI (SID,DNI) **CM-23293 / CM-5291**	**Ditto**	**Climate / Interim Climate Data record**	**MFG/MSG**	**1983 - 2020; 2021 onwards; Meteosat disk**
SRI CM-23241	Spectrally Resolved Irradiance	Data record	MFG/MSG	1983-2015 Meteosat disk
SRI CM-23245	Ditto	Data record	MFG/MSG	1983-2017 Meteosat disk
SDU CM-23281	Sunshine Duration	Data record	MFG/MSG	1983-2015 Meteosat disk

Acronym / Identifier	Product title	Type	Satellite & Instrument	Period & Coverage
SDU CM-23282	Ditto	Data record	MFG/MSG	1983-2017 Meteosat disk
SDU CM-23283 / CM-5281	**Ditto**	**Climate / Interim Climate Data record**	**MFG/MSG**	**1983-2020; 2021 onwards; Meteosat disk**
PAR CM-23273 / CM-5271	**Photosynthetic Active Radiation**	**Climate / Interim Climate Data record**	**MFG / MSG**	**1983-2020; 2021 onwards; Meteosat disk**
DAL CM-23253 / CM-5251	**Daylight**	**Climate / Interim Climate Data record**	**MFG / MSG**	**1983-2020; 2021 onwards; Meteosat disk**

Figure 3-1 gives an overview of the processed and available area.

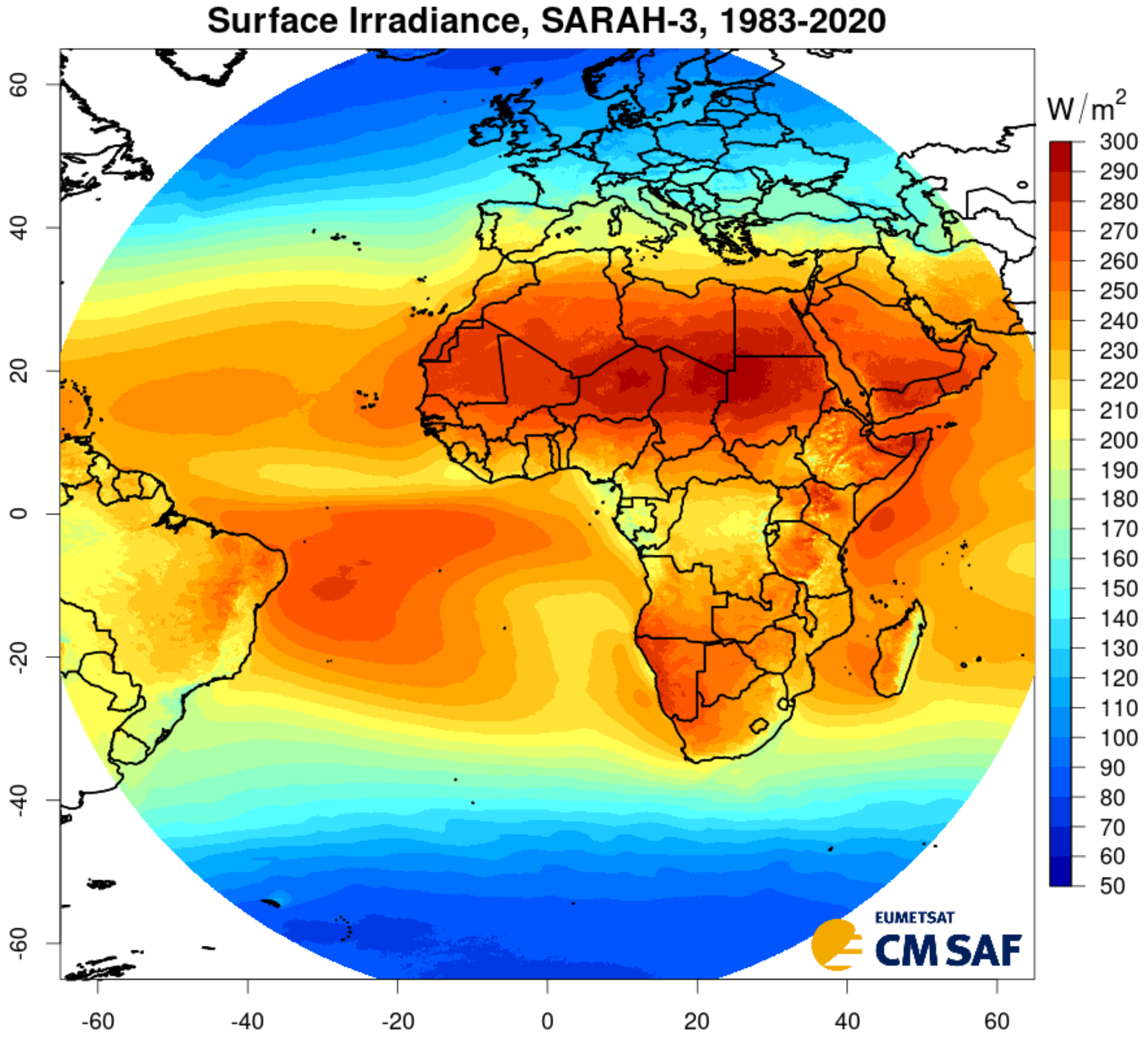

Figure 3-1: Area coverage for CM SAF SARAH-3 climate data records; shown is the SIS climatological mean.

2.1 Basic processing of Meteosat images

The processing of the METEOSAT data is done in satellite projection. The results are transferred to the regular latitude-longitude-grid using a subroutine of SPECMAGIC (Mueller et al., 2009). For the retrieval of the effective cloud albedo, the Heliosat algorithm is used (Hammer et al., 2003). The original version of the Heliosat method has been modified to generate a data record that meets climate quality. The effective cloud albedo derived with the modified Heliosat version is used in combination with the clear sky surface radiation model SPECMAGIC (Mueller et al., 2009; Mueller et al., 2012) to derive the surface radiation products from the MVIRI and SEVIRI instruments on board the geostationary Meteosat satellites number 2 to 10. The derived parameters and methods are described in more detail in the following sections. The complete model (cloudy and clear sky) is called MAGICSOL and is described in more detail in the CM SAF Algorithm Theoretical Baseline Document (ATBD, RD 2).

The Heliosat method does not require calibrated radiances as input, but is directly based on image counts. To consider the aging of the satellite instruments and the transitions between the satellites of the Meteosat series a self-calibration method has been developed and applied. The self-calibration method overcomes the need for well calibrated radiances.

From the Heliosat algorithm the effective cloud albedo is derived. Together with information about the atmospheric clear sky state (water vapour, aerosols, ozone) the effective cloud albedo is used as input for the SPECMAGIC method to calculate the direct irradiance and the solar surface irradiance.

In the following sub-sections a brief description of each individual surface radiation product is given with associated information on averaging methods, validation procedures and known limitations.

2.2 Effective Cloud Albedo (CAL)

2.2.1 Product Definition

The effective cloud albedo is defined as the amount of reflected irradiance for all sky relative to the amount of reflected irradiance for clear sky. The effective cloud albedo is the central cloud information used to derive the solar surface irradiance. It is dimensionless. CAL is provided for the Meteosat disk, covering Europe and Africa on a regular 0.05x0.05 degree latitude-longitude grid. The data record compiles monthly and daily means, as well as 30-min instantaneous data covering the period 1983-2020.

It is important to note that the effective cloud albedo depends on the cloud reflectivity and the surface albedo. The same cloud has a larger effective cloud albedo over a dark surface (e.g., ocean) than over a bright surface (e.g., desert). For the assessment of the radiative impact of clouds on the reflected solar radiation the effective cloud albedo is the relevant cloud radiative property.

2.2.2 Basic Retrieval approach

The original Heliosat method is described in several publications, e. g. in Hammer et al., 2003, and Cano et al., 1986. It is used to retrieve the effective cloud albedo. The effective cloud albedo describes the amount of reflected irradiance for all sky relative to the amount for clear sky, normalised to the maximum cloud reflection, and is defined as:

$$CAL = \frac{R - R_{\text{sfc}}}{R_{\max} - R_{\text{sfc}}} \qquad \text{Equation 3-1}$$

Here R_{max} is a measure for the maximum cloud reflection, R_{sfc} is the clear sky reflection, dominated by the surface albedo and R is the observed irradiance. R_{max} and R_{sfc} are determined by statistical methods from the observed radiance (R) on a monthly basis. Hence all quantities are based on the observation of the reflections. No additional information (e. g., from a model) is required for the basic retrieval of the effective cloud albedo. The change in sensitivity of the satellite instruments over time is considered by the temporal evolution of the maximum cloud reflection, R_{max} .This so-called 'self-calibration' technique ensures the generation of a homogenous data record even with un-calibrated satellite radiances.

The newly-developed HelSnow algorithm is designed to identify snow-covered pixels and to correct the clear-sky reflection, R_{sfc}, accordingly, hence preventing the misclassification of snow-covered pixels as cloudy pixels. The basic principle of the HelSnow algorithm is the identification of bright and moving areas using an Optical Flow numerical method. These information is used to derive a daily snow mask and update the clear sky reflection at the snow-covered pixels. To avoid a misclassification of stationary clouds, e.g., fog, as snow a binary snow mask derived from ERA5-Land and ERA-5 information is also applied.

The methods are described in detail in the ATBD (RD 2).

2.2.3 Details on processing, gridding and averaging

Monthly and daily means are calculated by arithmetic averaging, using Equation 3-2.

$$CAL_{mean} = \frac{\sum_{i=1}^{n} CAL_i}{n} \qquad \text{Equation 3-2}$$

Here i is a loop over the 30-min instantaneous effective cloud albedo data for the calculation of the daily means and a loop over daily means for the calculation of monthly means.

Information on the number of daylight observations used for the generation of the CAL daily means is delivered as an additional layer in the CAL daily mean NetCDF-files. This number of observations holds also as background information for the SIS and SDI daily mean data.

The conversion from the irregular satellite projection to the regular 0.05x0.05 degree grid is done with a SPECMAGIC subroutine.

2.2.4 Input data

METEOSAT 1st generation (MFG) images of the broadband channel in openMTP format; Level 1.5 rectified image data of digital counts (not radiances) are used. The respective data are called "Rectified Image Data" and provided by EUMETSAT (EUM TD 06). Calibrated or inter-calibrated radiances are not needed by the applied Heliosat method, the respective issues are resolved by an implemented self-calibration method, described in more detail in the ATBD [RD 2].

Data from all operational MFG and MSG satellites (Meteosat-2 to Meteosat-11) at 0.0 degree position have been used. Further details of the METEOSAT input data are described in EUMETSAT documentations (EUM TD 06 and EUM TD 04). From 2006 onwards the data from the MSG satellites carrying the Spinning Enhanced Visible and Infrared Imager (SEVIRI) is used. A more detailed table of the used METEOSAT data is given in Table 3-3. SEVIRI is a radiometer that measures the Earth's disk every 15 min in 12 spectral bands spanning visible and infrared wavelengths. For consistency reasons the SEVIRI data is used only every 30 min.

Table 3-3: Major operational periods for the used Meteosat satellites

Satellite	Instrument	From	To
Meteosat 2	MVIRI	16 Aug 1981	11 Aug 1988
Meteosat 3	MVIRI	11 Aug 1988	19 Jun 1989
Meteosat 4	MVIRI	19 Jun 1989	24 Jan 1990
Meteosat 3	MVIRI	24 Jan 1990	19 Apr 1990
Meteosat 4	MVIRI	19 Apr 1990	4 Feb 1994
Meteosat 5	MVIRI	4 Feb 1994	13 Feb 1997
Meteosat 6	MVIRI	13 Feb 1997	3 Jun 1998
Meteosat 7	MVIRI	3 Jun 1998	31 Dec 2005
Meteosat 8	SEVIRI	1 Jan 2006	10 Apr 2007
Meteosat 9	SEVIRI	11 Apr 2007	20 Jan 2013
Meteosat 10	SEVIRI	21 Jan 2013	20 Feb 2018
Meteosat 11	SEVIRI	21 Feb 2018	31 Dec 2020

For this purpose the two narrow band visible channels are used. They are located at around 0.6 µm (VIS006) and 0.8 µm (VIS008) and have a spatial resolution of around 3 km at nadir. Further details and evaluation of the approach are given in Posselt et al., 2014. The SEVIRI data is provided in High Rate Information Transmission (HRIT) format. This is a CGMS standard format, agreed upon by satellite operators, for the dissemination of digital data, originating from geostationary satellites to users, via direct broadcast. For more details on the format see http://www.eumetsat.int/website/home/Data/Products/Formats/index.html.

For the generation of the daily snow reflectivity a daily snow mask is used to reduce the false classification of snow, e.g., due to fog. The daily snow mask used for the retrieval of CAL within SARAH-3 is based on ERA5-Land (Muñoz-Sabater et al., 2021, snow coverage) and ERA-5 (Hersbach et al., 2020, sea ice fraction).

2.2.5 Product example

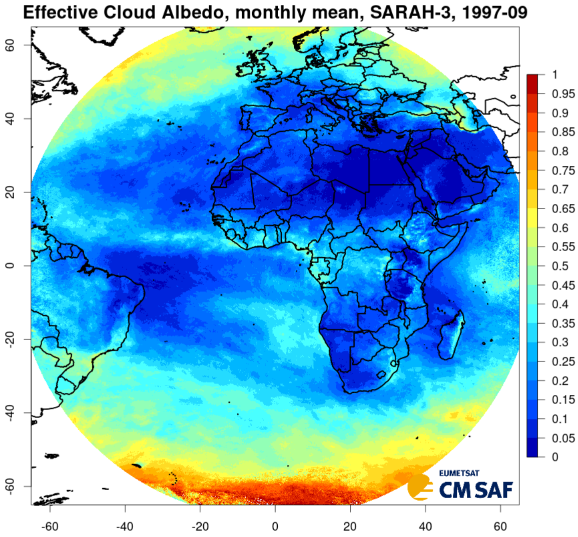

Figure 3-2: Monthly mean effective cloud albedo for September 1997 from the SARAH-3 data record.

Figure 3-2 provides an example of the monthly mean CAL product for September 1997.

2.2.6 Validation

The Product Requirement Document (PRD) [AD 1] lists specific product requirements which have to be fulfilled by the products. The achieved accuracy for the CAL product is summarized in Table 3-4. CAL cannot be directly validated against ground measurements, which is a limitation of the validation.

Table 3-4: Accuracy achieved for CAL. The 90 % limit compiles all regions, no region is excluded.

Product	Summary on mean error (absolute)
CAL (METEOSAT)	*90 % of absolute bias values below 0.1 for monthly means, 0.15 for daily means respectively.* *Bias below 0.15 for instantaneous data.*

The detailed results of the validation are presented in the CM SAF Validation Report [RD 2: SAF/CM/DWD/VAL/METEOSAT_HEL]. The numbers given in Table 3-3 are worst case accuracies derived from the accuracy of SIS summarised in Table 3-4.

2.2.7 Limitations

Below is a list of known deficiencies and limitations of the CAL CDR:

- R_{sfc} can only be retrieved accurately if a certain amount of clear sky cases are present within each month. In some regions and seasons, this is not always the case. In regions and periods with long-lasting clouds higher uncertainties occur. Here cloud contamination of R_{sfc} leads to lower values of CAL, hence to significant errors in CAL. This artefact occurs pre-dominantly for slant geometries (edges of the Meteosat coverage, or wintertime above a latitude of +/- 60 degrees). It is expected that the target accuracy of 0.1 (0.15) for monthly (daily) means is not met any more in those regions and higher uncertainties might occur. The sensitivity of this artefact on CAL accuracy is discussed in more detail in the ATBD (RD 2). However, as long-lasting clouds are a pre-requisite for the occurrence of this artefact, the effect on solar irradiance is usually rather small.
- Unidentified surface snow coverage will result in an overestimation of the effective cloud albedo; this limitation mainly effects mountainous regions, e.g., the Alpine region, but also the Eastern part of Europe.
- Fog, which is wrongly classified and treated as snow-covered surfaces, will result in an underestimation of the effective cloud albedo. The limitation is mainly occurring in fall (winter in localized humid regions, e.g., river valleys).
- The neglect of the anisotropy of the cloud reflection leads to enhanced uncertainties in the effective cloud albedo, in particular for the case of high level ice clouds.

2.3 Surface Incoming Solar Radiation (SIS)

2.3.1 Product definition

The surface incoming solar (SIS) radiation is the radiation flux (irradiance) reaching a horizontal plane at the Earth surface in the 0.2 – 4 µm wavelength region. It is expressed in Wm^{-2}, i.e, representing the instantaneous and the mean radiation fluxes, respectively. The daily and monthly mean fluxes can be converted into daily and monthly sums by multiplication with the length of the time interval, i.e., to convert the daily mean surface radiation data ($W\ m^{2}$) into daily sums ($J\ cm^{-2}$) a factor of 8.64 s should be applied (24 * 3600 s / 10000).

2.3.2 Basic Retrieval approach

The surface incoming solar radiation (SIS) is retrieved using the Heliosat method. The Heliosat method is based on the conservation of energy. As a consequence the basic relation between the solar irradiance and the effective cloud albedo is as follows:

$$SIS = SIS_{CLS} \cdot (1 - CAL) \quad \text{Equation 3-3}$$

Here, SIS is the solar surface irradiance, SIS_{CLS} the clear sky irradiance and CAL is the effective cloud albedo, also called cloud index, n, in former publications (e. g. Cano et al, 1986). For effective cloud albedo values higher than 0.8 the Equation 3-3 is modified in order to consider the saturation and absorption effects within optically thick clouds. The modification of the equation for small and large values of CAL is based on ground measurements and is described in detail in the ATBD [RD 2] and given in the Appendix, Section 7.2, of this document.

When CAL is known, SIS can be calculated from the clear sky solar irradiance. The algorithm to calculate the clear sky solar surface irradiance uses RTM based LUTs for the calculation of SIS_{CLS}.

The radiative transfer model (RTM) libRadtran (Mayer and Kylling, 2005) was used for the generation of the LUT. The LUT contains SIS values for a wide range of atmospheric states and 32 spectral bands. The SIS value for the actual atmospheric state is then calculated by interpolation between the states. The atmospheric states cover different values for water vapour, ozone, aerosol optical depth, aerosol single scattering albedo, and asymmetry parameter. Several aerosol types were included (Hess et al., 1998). Additionally, Modified Lambert Beer (MLB)-LUTs are used (Mueller et al., 2004). A specific aerosol optical thickness and aerosol type can be assigned to each pixel depending on the provided aerosol background map (based on MACC data in the case of SARAH-3). The aerosol optical thickness and type is assigned to each pixel depending on the aerosol map derived from the aerosol information provided by the European Centre for Medium-Range Weather Forecasts (ECMWF), see Benedetti et al., 2009 and Morcrette et al., 2009 for further details. Vertically-integrated water vapour and ozone columns (daily means) are taken from ERA-5 reanalysis provided by the ECMWF. The interpolation between the LUTs is done with a linear interpolation scheme.

2.3.3 Details on processing, gridding and averaging

Daily averages are calculated following a method by Möser (1983) (also published in Diekmann et al., 1988), see Equation 3-4 for calculation of SIS mean.

$$SIS_{DA} = SIS_{CLSDA} \frac{\sum_{i=1}^{n} SIS_i}{\sum_{i=1}^{n} SIS_{CLS\,i}} \qquad \text{Equation 3-4}$$

SIS_{DA} is the daily average of SIS. SIS_{CLSDA} is the daily averaged clear sky SIS, SIS_i the calculated SIS for satellite image i and $SIS_{CLS\,i}$ the corresponding calculated clear sky SIS, n is the number of images available during a day.

The applied equation for averaging accounts for data gaps (missing values) and zero values. However, the larger the number of available images per day, the better the daily cycle of cloud coverage can be resolved, increasing the accuracy of the daily average of SIS. The daily average is derived only if more than 25% of the possible daylight images are available for a specific pixel. The monthly average is calculated from the corresponding daily means at pixel level with a required number of 20 existing daily means and maximum number of 5 subsequent missing daily means.

2.3.4 Input data

- CAL from METEOSAT processing, available for each pixel in satellite resolution, CAL is described in detail section 3.2 of this document.
- Daily means of the vertically-integrated water vapour and ozone from the ERA-5 Reanalysis (Hersbach et al., 2020) have been used with a spatial resolution of 0.25° x 0.25°. These data have been topographically corrected to account for sub-grid topography to a spatial resolution of 0.05° x 0.05°.
- Lookup tables.
- Spectral surface albedo from MODIS used for the estimation of clear sky surface radiation based on Blanc et al., 2018.

Information about the aerosol optical thickness and type is derived from the aerosol information MACC (Monitoring Atmospheric Composition and Climate) provided by the European Centre for Medium-Range Weather Forecasts (ECMWF). The MACC data results from a data assimilation system for global reactive gases, aerosols and greenhouse gases. It consists of a forward model for aerosol composition and dynamics (Morcrette et al., 2009) and the data assimilation procedure described in detail in (Benedetti et al., 2009). MACC has been evaluated to perform significantly better than Kinne et al., 2013, and the GADS/OPAC climatology (Hess et al., 1998, Köpke et al. 1997), within the Magicsol processing; see Mueller and Träger-Chatterjee (2014) and Mueller et al., 2015a for further details. The aerosol input is used as monthly long-term means on a 0.5x0.5 degree latitude-longitude grid. The pixel value is derived by spatial interpolation and assignment of the respective monthly mean

2.3.5 Product example

Figure 3-3 provides an illustration of the SIS product.

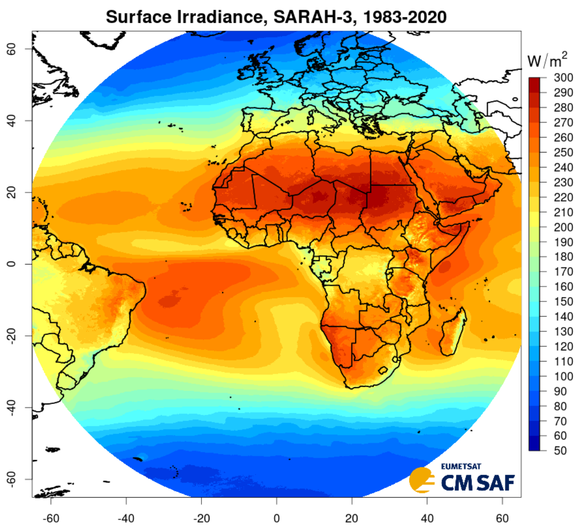

Figure 3-3: Illustration of the SARAH-3 SIS product. Long-term mean 1983-2020.

2.3.6 Validation

The Product Requirement Document (PRD) [AD 1] lists specific product requirements which have to be fulfilled by the products. The achieved accuracy for the SIS product is summarized in Table 3-5.

The validation has been performed against reference ground measurements of the Baseline Surface Radiation Network (BSRN). The measurements of the BSRN stations start in 1993 and the density of the network over Africa is relative thin. Hence, the BSRN validation results do not cover the complete time series of the CDR and do not cover all climate regions in Africa. This is a limitation of the CDR validation.

Table 3-5: Accuracy achieved for SIS. The 90 % limit includes all regions, no region is excluded.

Product	**Summary on mean error (absolute)**
SARAH-3 SIS	*Mean Absolute Bias of about 5.3 W/m² and almost 90 % of absolute bias values below 10 W/m² for monthly means.*

The detailed results of the validation are presented in the CM SAF Validation Report [RD 1]. Here the main validation results are given in Table 3-6.

Table 3-6: Summary of validation results for SIS: N Number of comparisons. MAB: mean of absolute bias values for monthly / daily means. SD: standard deviation. AC: Correlation of anomalies. $Frac_{mon}$: Fraction of cases (months/days) with a MAB greater than the target accuracy (target level used for the assessment shown in brackets). Basis of the results has been the comparison with 17 BSRN stations. For comparison the values of validation of the first version of the SARAH data record is also shown.

SIS	**N**	**Bias [W/m²]**	**MAB [W/m²]**	**SD [W/m²]**	**AC**	**$Frac_{mon}$ > thrshold. accuracy [%]**
SARAH-3						
Monthly Mean	2863	2.25	5.32	6.75	0.93	12.2 (> 10 W/m²)
Daily mean	84789	2.18	10.9	15.8	0.96	19.6 (> 17 W/m²)
SARAH-2.1 + ICDR						
Monthly mean	2863	1.6	5.15	6.87	0.92	11.1 (> 10 W/m²)
Daily mean	84815	1.52	11.5	16.8	0.95	21.4 (> 17 W/m²)

Using measurements from the GEBA archive from Europe the temporal stability of the SARAH-3 SIS CDR has been investigated. The decadal temporal stability between 1983 and 2017 has been determined to be -0.6±0.4 W/m²/dec. see Figure 3-4 documenting the high stability of the SARAH-3 data record. Pfeifroth et al., 2018 provides further information on variability and trends of global radiation of SARAH-2 and surface measurements.

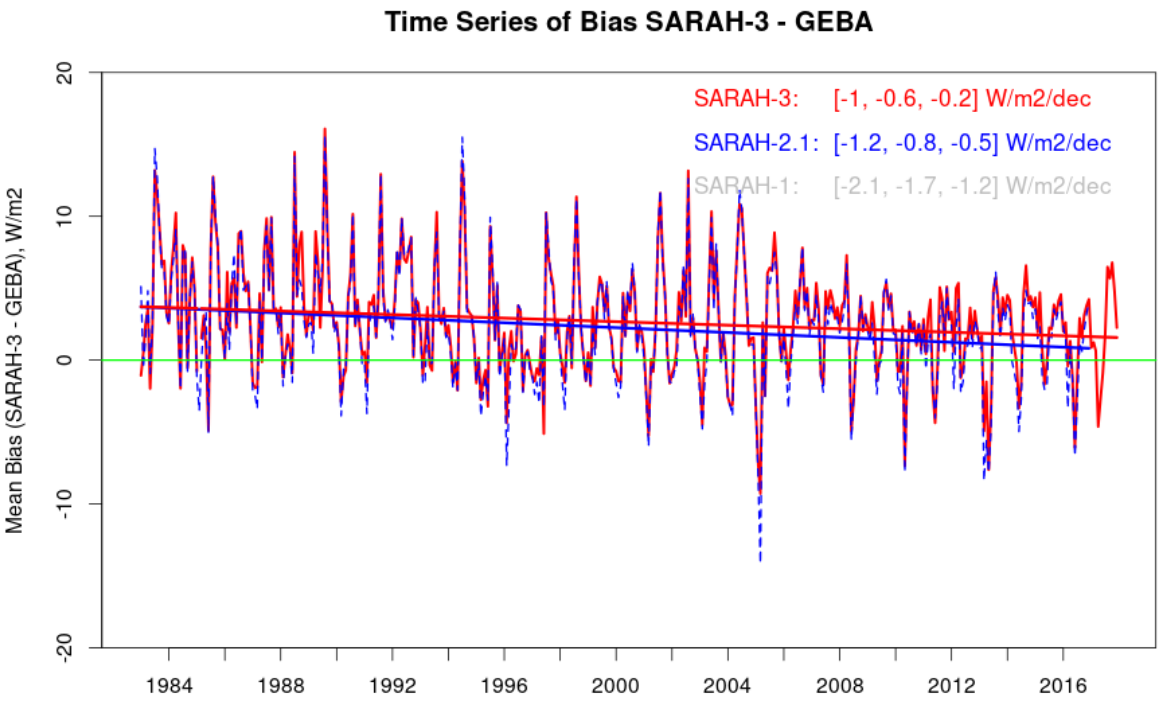

Figure 3-4: Comparison of SARAH-3 SIS CDR with GEBA ground measurements. Compared to GEBA there is no significant trend apparent, which indicates the temporal stability of the SIS CDR.

2.3.7 Limitations

Below is a list of known deficiencies and limitations of the SIS product:

- The high clear sky reflection over bright surfaces (e. g., desert regions) reduces the contrast between clear sky reflection and cloudy-sky reflection. This leads to higher uncertainties in CAL and errors in the calculation of SIS.
- The accuracy of aerosol information is not well defined in several regions of the world due to missing ground measurements. Any uncertainty in the aerosol information affects the accuracy of SIS, especially in regions that are dominated by cloud free sky. For the current Heliosat data record a climatology has been used. Monthly, daily and hourly variations in the aerosol optical depth are therefore not considered.

2.4 Surface Direct irradiance (SDI)

2.4.1 Product definition

The surface direct irradiance contains two radiation products, the direct normalized irradiance (DNI) and the surface incoming direct radiation (SID). The direct normal irradiance (DNI) is the radiation flux (irradiance) at the surface normal to the direction of the sun in the 0.2 - 4 µm wavelength region. It is derived by normalisation of the direct irradiance, SID, with the cosine of the solar zenith angle (see Equation 3-6). SID is the radiation flux (irradiance) reaching a horizontal plane in the 0.2 – 4 µm wavelength region at the surface directly without scattering. Both parameters are expressed in Wm^{-2}, i.e, representing the instantaneous and the mean radiation fluxes, respectively. The daily and monthly mean fluxes can be converted into daily and monthly sums by multiplication with the length of the time interval, i.e., to convert the daily mean surface radiation data ($W\ m^{-2}$) into daily sums ($J\ cm^{-2}$) a factor of 8.64 s should be applied (24 * 3600 s / 10000).

2.4.2 Algorithm outline

2.4.2.1 Clear sky

The algorithm for the calculation of SID under clear sky conditions is described in detail in Mueller et al., 2009 and also documented in the public license gnu-MAGIC project, http://sourceforge.net/projects/gnu-magic. It is a fast method to calculate solar irradiance (including the direct irradiance) for large areas, which uses an eigenvector hybrid LUT approach for the fast and accurate calculation of SID. The aerosol optical thickness and type is assigned to each pixel depending on the aerosol map derived from the aerosol information provided by the European Centre for Medium-Range Weather Forecasts (ECMWF). Monthly means of water vapour amounts are taken from the ERA-interim reanalysis provided by the ECMWF. The interpolation within the LUTs is done with a linear interpolation scheme. The atmospheric input and interpolation routine is identical for SIS and SID, with exception of a background surface albedo map, which is not needed for SID.

2.4.2.2 Cloudy sky situations

For the consideration of clouds on the clear sky irradiance a formula of Müller et al. (2009) is used, which describes the relation of the direct irradiance (all sky) SID_{allsky} to that of the clear sky direct irradiance SID_{clear}:

$$SID_{allsky} = SID_{clear} \cdot \left((1 - CAL) + 0.38 \cdot CAL)\right)^{2.5} \qquad \text{Equation 3-5}$$

where CAL is the effective cloud albedo. This formula is an adaptation from the diffuse model of Skartveit et al., 1998. The direct irradiance is set to zero for CAL values above 0.6. DNI is subsequently derived from SID by normalisation with the solar zenith angle:

$$DNI = SID / \cos(SZA) \qquad \text{Equation 3-6}$$

where SID is the direct irradiance and SZA is the solar zenith angle.

2.4.3 Details on processing, gridding and averaging

The calculation of the temporal averages of the SDI climate data records is conducted with the same method as for the surface irradiance (see Section 3.3.3)

2.4.4 Input data

The input is identical to that of SIS with exception of the background surface albedo map which is not needed for SDI. The input data is therefore described in Section 3.3.4. CAL, total water vapour column, ozone contend, aerosol information and look-up tables are used according to Section 3.3.4

2.4.5 Product example

Figure 3-5 provides examples of the SDI data records (DNI and SID)

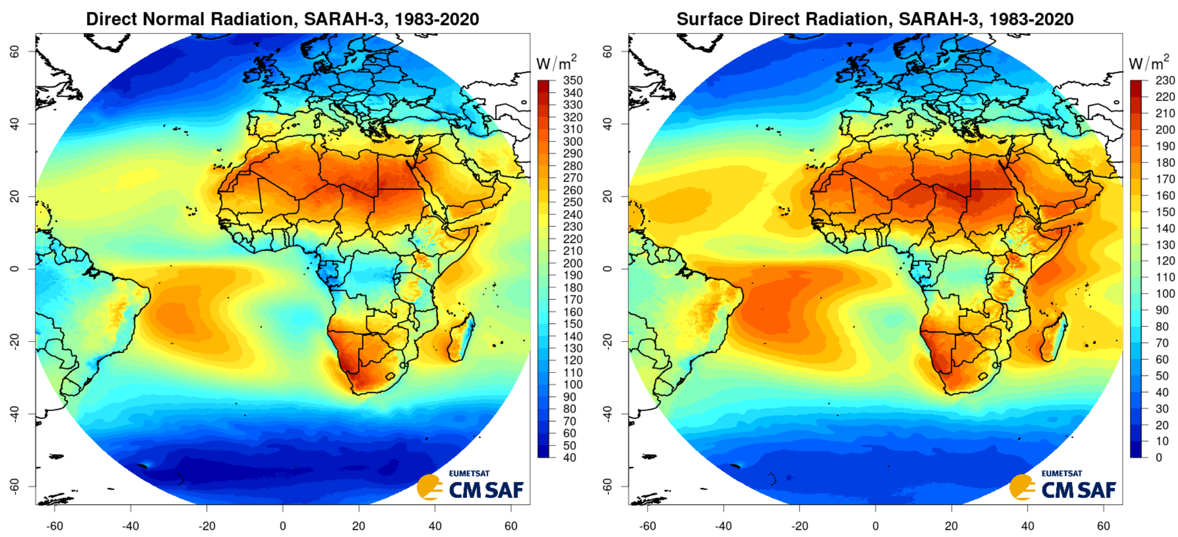

Figure 3-5: Illustration of the SDI (DNI and SID) climate data record; long term mean for 1983-2020.

2.4.6 Validation

The Product Requirement Document (PRD) [AD 1] lists specific product requirements which have to be fulfilled by the products. The achieved accuracy for the SDI data records are shown in Table 3-7. Please see section 3.3.6 for validation limitations.

Table 3-7: Accuracy achieved for SDI (SID and DNI).

Product	Summary on mean error (absolute)
SARAH-3 DNI: Direct Normal Radiaton	*Mean Absolute Bias of about 16 W/m² and more than 80 % of absolute bias values below 27 W/m² for monthly means;*
SARAH-3 SID: Surface Incoming Direct Radiaton	*Mean Absolute Bias of about 8 W/m² and almost 80 % of absolute bias values below 13 W/m² for monthly means;*

The detailed results of the validation are presented in the CM SAF Validation Report [RD 1: SAF/CM/DWD/VAL/METEOSAT_HEL].

Table 3-8: Summary of validation results for SARAH-3 SDI: N Number of comparisons. MAB: mean of absolute bias values for monthly/daily means. SD: standard deviation. AC: Correlation of anomalies. $Frac_{mon}$: Fraction of cases (months / days) with an accuracy outside of the threshold accuracy. Basis of the results has been the comparison with 17 BSRN stations.

SID	N	Bias [W/m²]	MAB [W/m²]	SD [W/m²]	AC	$Frac_{mon}$ > thrshold. accuracy [%]
SARAH-3						
Monthly Mean	2708	0.99	7.84	11.2	0.90	7.7 (>13 W/m²)
Daily mean	76537	0.92	16.0	24.0	0.93	25.3 (>20 W/m²)
SARAH-2.1 + ICDR						
Monthly mean	2708	0.70	7.78	11.2	0.90	18.2 (>13 W/m²)
Daily mean	76537	0.63	17.0	25.5	0.92	27.2 (>20 W/m²)
DNI						
SARAH-3						
Monthly mean	2627	-0.89	16.7	22.1	0.89	18.5 (>27 W/m²)
Daily mean	71331	0.33	31.1	43.3	0.93	26.1 (>44 W/m²)
SARAH-2.1 + ICDR						
Monthly mean	2627	-1.78	16.5	21.9	0.88	17.5 (> 27 W/m²)
Daily mean	71354	-0.69	33.0	46.2	0.92	28.3 (> 44 W/m²)

2.4.7 Limitations

Below is a list of some of known deficiencies and limitations of the SDI product (see also SIS limitations)

- The relatively high clear sky reflection over bright surfaces reduces the contrast between clear sky reflection and cloudy sky reflection. This leads to higher uncertainties and errors in the calculation of CAL and subsequent of DNI.
- The accuracy of aerosol information is not known in several regions of the world due to missing ground measurements.
- SDI is quite sensitive to the AOD (aerosol optical depth) in clear sky situations, which introduces a certain amount of uncertainty as the accuracy of monthly AOD can only be expected to be +/- 0.1. Moreover, for the current Heliosat data record a climatology has been used. Monthly, daily and hourly variations in the aerosol optical depth are therefore not considered, which increases the uncertainty in daily and hourly values significantly. However, due to missing ground based measurements it is not evident nor proven that information about the temporal variation of aerosols gained from satellite would perform significantly better for the generation of a long term data records of monthly and daily means than a best-of aerosol climatology. Indeed, Kinne et al. (2006) discussed the limited accuracy of aerosol information retrieved from satellites. Moreover, dynamic aerosol information with appropriate coverage does not exist for the complete period of the Heliosat data record. Hence, uncertainties in SDI introduced by uncertainties in the AOD are mainly related to the lack of accurate and homogeneous input alternatives of aerosol information (especially over land) with high spatial and temporal resolution. However, due to the relative large sensitivity of SDI on aerosol optical depth the limited accuracy of the aerosol information is a significant reason for the lower accuracy of SDI relative to SIS.

2.5 Sunshine Duration (SDU)

2.5.1 Product definition

The daily or monthly sunshine duration is the time per day or month at which DNI exceeds the WMO threshold of 120 W/m^2. The SDU data are provided as daily and monthly sums in hours; to convert the monthly sums of sunshine duration into mean daily sums for the given month the monthly sum has to be divided by the number of days in the specific month. The number of days per month is provided as a variable in the SDU monthly sums data files.

2.5.2 Algorithm outline

2.5.2.1 Sunshine duration

Basis for the retrieval of satellite-based sunshine duration (SDU) are the SARAH-3 DNI data and the WMO threshold for sunshine, which is defined by DNI ≥ 120 W/m^2. SDU is derived by the ratio of sunny slots to all slots during daylight multiplied by the daylength.

The daylength is calculated depending on the date, longitude and latitude using simplified clear sky surface radiation transfer model and climatological water vapor and aerosol information. The sunny slots are weigthed depending on the number of surrounding cloudy and sunny grid points, which is discussed in more detail in section 3.5.2.2 and in RD 2. The number of daylight slots describes the maximum number of Meteosat observations (slots) per grid point and per day during daylight. Daylight is defined by the time where the SEA exceeds 2.5° and the clear-sky DNI exceeds 120 W/m^2.

2.5.2.2 Weighting of sunny slots

A sunny slot corresponds to a DNI value of 120 W/m^2 or larger. SARAH-3 provides instantaneous DNI data every 30 minutes. Therefore, without weighting, one sunny slot would correspond to a 30 minutes time window. In reality this is only the case in bright weather situations. If there are clouds in the surrounding area of a grid point, there is a probability that not the whole 30 minutes are sunny. This is also valid in the opposite case, when a cloudy grid point has sunny grid points in its near surrounding's. This fact should be accounted for in the retrieval of SDU by using the information of the 24 surrounding grid points. In addition the information of two successive time steps is incorporated.

2.5.3 Details on processing, gridding and averaging

The output of the algorithm is described in section 3.5.2 for daily sums of SDU. To derive SDU monthly sums the daily sums of each month are summed up.

2.5.4 Input data

Basis for the retrieval of satellite-based sunshine duration (SDU) are the SARAH-3 DNI data.

2.5.5 Product example

Figure 3-6 provides an example of the SDU data records.

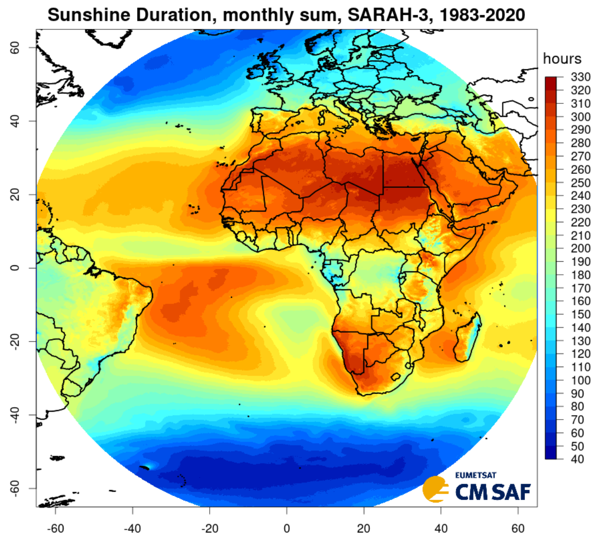

Figure 3-6: Illustration of the SDU climate data record; mean annual sum for 1983-2020.

2.5.6 Validation

The achieved accuracy for the SDU data record is shown in Table 3-9.

Table 3-9: Accuracy achieved for SDU.

Product	**Summary on mean error (absolute)**
SDU: Sunshine duration.	*Mean Absolute Difference of 15h (monthly sum) and almost 75% of absolute difference values below 20h for monthly sums.*

The detailed results of the validation are presented in the CM SAF Validation Report [RD 1: SAF/CM/DWD/VAL/METEOSAT_HEL].

Table 3-10: Summary of validation results for SDU: N Number of comparisons. MAD: mean of absolute bias values for monthly/daily sums. SD: standard deviation. AC: Correlation of anomalies. $Frac_{mon}$: Fraction of cases (months) with an accuracy outside of the threshold accuracy. Basis of the results has been the comparison with CLIMAT and ECA&D stations.

SDU	N	Bias [h]	MAD [h]	SD [h]	AC	Frac > threshold accuracy [%]
SARAH-3						
Monthly sum	139,786	6.24	15.4	20.37	0.88	26.6 (> 20 h)
Daily sum	4,579,221	0.25	1.05	1.64	0.91	23.5 (> 1.5 h)
SARAH-2.1 + ICDR						
Monthly sum	139,768	8.49	16.59	21.28	0.88	29.5 (> 20 h)
Daily sum	4,575,907	0.30	1.07	1.64	0.91	23.8 (> 1.5 h)

2.5.7 Limitations

Below is a list of some of known deficiencies and limitations of the SDU product (see also SDI limitations)

The main limitation is the reduced observation frequency of 30 min, which limits the accuracy of the sunshine duration and results in artefacts in the raster data due to the stepwise change in the number of observations across the Meteosat Disc. The latter results in latitudinal ‘stripes’ across in the sunshine duration data, in particular in cloud free regions. These features have been substantially reduced in SARAH-3 compared to SARAH-2.

2.6 Photosynthetic active radiation (PAR)

2.6.1 Product definition

The photosynthetic active radiation (PAR) is defined as the surface incoming radiation within the photosynthetically-active spectral range, i.e., the spectral regions of the solar radiation that can be used by plants, namely 400 – 700 nm. PAR is provided in µmole m^{-2} s^{-1}, which can be converted to W m^{-2} using 1 W m^{-2} ≈ 4.6 µmole m^{-2} s^{-1} (Sager and Farlane, 2017).

2.6.2 Algorithm outline

The photosynthetic active radiation (PAR) is estimated by a weighted sum of the spectral surface radiation that is estimated during the retrieval of SIS; the spectral weights are provided Section 6.1 of RD 2.

2.6.3 Details on processing, gridding and averaging

The calculation of the temporal averages of the PAR climate data record is conducted with the same method as for the surface irradiance (see Section 3.3.3)

2.6.4 Input data

The input data for the estimation of PAR is identical to the input data for the estimation of SIS and, hence, is already described in Section 3.3.4. CAL, total water vapour column, ozone content, aerosol information, surface albedo and look-up tables are used according to Section 3.3.4

2.6.5 Product example

Figure 3-7 provides an example of the PAR data record.

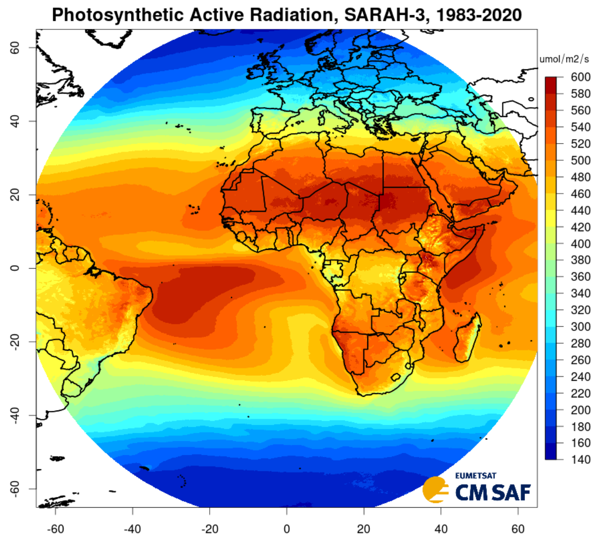

Figure 3-7: Illustration of the PAR climate data record; climatological mean for 1983-2020.

2.6.6 Validation

The achieved accuracy for the PAR data record is shown in Table 3-11.

Table 3-11: Accuracy achieved for PAR.

Product	Summary on mean error (absolute)
PAR: Photosynthetic active radiation.	*Mean Absolute Difference of about 20 µmol/m^2/s and more than 95 % of monthly absolute difference values below 46 µmol/m^2/s.*

The detailed results of the validation are presented in the CM SAF Validation Report [RD 1].

Table 3-12: Summary of validation results for PAR: N Number of comparisons. MAD: mean of absolute bias values for monthly/daily sums. SD: standard deviation. AC: Correlation of anomalies. Fracmon: Fraction of cases (months) with an accuracy outside of the threshold accuracy. Basis of the results has been the comparison with data from 10 stations.

PAR	N	Bias [μmol/m²/s]	MAD [μmol/m²/s]	SD [μmol/m²/s]	AC	Frac > target accuracy [%]
SARAH-3						
Monthly mean	1064	14.5	19.7	24.1	0.89	3.8 (> 46 μmol/m²/s)
Daily sum	31,532	14.7	26.5	32.7	0.98	3.5 (> 78 μmol/m²/s)

2.6.7 Limitations

The estimation of PAR is closely linked to the retrieval of SIS, the limitations to the retrieval of SIS also apply to PAR.

2.7 Daylight (DAL)

2.7.1 Product definition

The daylight (DAL) is defined as the surface incoming radiation that can be seen by the human eye, the maximum spectral sensitivity is around 550 nm. DAL is provided in kLux. The unit Lux can be transferred to W m^{-2} by the relation 1 W m^{-2} ≈ 683 Lux.

2.7.2 Algorithm outline

The daylight (DAL) is estimated by a weighted sum of the spectral surface radiation that is estimated during the retrieval of DAL; the spectral weights are provided Section 6.2 of RD 2.

2.7.3 Details on processing, gridding and averaging

The calculation of the temporal averages of the DAL climate data record is conducted with the same method as for the surface irradiance (see Section 3.3.3)

2.7.4 Input data

The input data for the estimation of DAL is identical to the input data for the estimation of SIS and, hence, is already described in Section 3.3.4. CAL, total water vapour column, ozone content, aerosol information, surface albedo and look-up tables are used according to Section 3.3.4.

2.7.5 Product example

Figure 3-8 provides an example of the DAL data record.

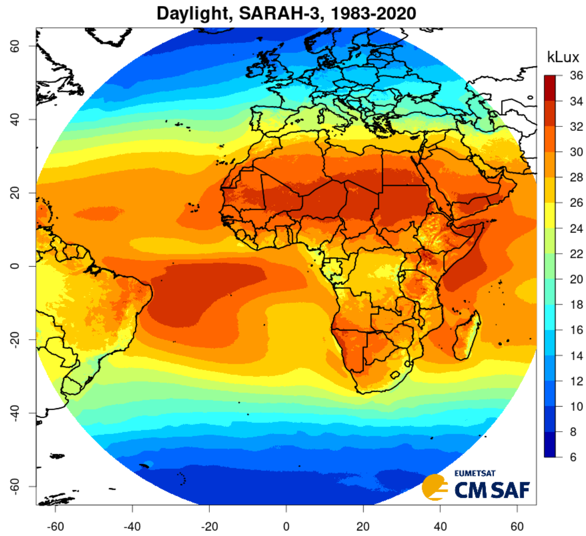

Figure 3-8: Illustration of the DAL climate data record; climatological mean for 1983-2020.

2.7.6 Validation

The achieved accuracy for the DAL data record is shown in Table 3-13.

Table 3-13: Accuracy achieved for DAL.

Product	Summary on mean error (absolute)
DAL: Daylight	*Mean Absolute Difference of 2.5 kLux and almost 60 % of absolute difference values below 2.7 kLux*

The detailed results of the validation are presented in the CM SAF Validation Report [RD 1].

Table 3-14: Summary of validation results for DAL: N Number of comparisons. MAD: mean of absolute bias values for monthly/daily sums. SD: standard deviation. AC: Correlation of anomalies. Fraction of cases (months / days) with an accuracy outside of the threshold accuracy. Basis of the results has been the comparison with data from 3 reference stations

DAL	N	Bias [kLux]	MAD [kLux]	SD [kLux]	AC	Frac > thres. accuracy [%]
SARAH-3						
Monthly sum	584	2.54	2.59	1.75	0.84	42.5 (> 2.7 kLux)
Daily sum	17,775	2.51	3.37	3.37	3.29	23.4 (> 4.8 kLux)

2.7.7 Limitations

The estimation of DAL is closely linked to the retrieval of SIS, the limitations to the retrieval of SIS also apply to DAL.

2.8 Known Issues and planned improvements

A processing bug has been found after the data have been fully generated. This bug results in the non-consideration of the snow-mask on the last day of each month. On these days, no snow mask information have been used for the generation of the surface radiation parameters. This results in an underestimation of surface radiation / sunshine duration on those days, if clear-sky conditions over snow-covered surfaces prevail. The overall impact on the data quality is considered to be small; the bug will be fixed in the next edition of the SARAH CDR.

Planned improvements in upcoming SARAH climate data records include the processing of measurements from other geostationary satellites to provide full coverage with SARAH-like data records. The use of updated aerosol information will also be considered for upcoming versions of the SARAH data records.

3 Information on the ICDR

As for the SARAH-3 predecessor (SARAH-2.1) a corresponding Interim Climate Data Record (ICDR) is generated and distributed to provide consistent near-realtime SARAH-3 products to the users. From 2021-01-01 onwards the SARAH-3 data is derived by the ICDR processing, which provides daily updates of all SARAH-3 products in a consistent manner. The data shall be delivered 5 days after observation at latest.

Even though staying as close as possible to the SARAH-3 CDR algorithm, some processing modification are needed to generate the SARAH-3 data in near-realtime. There are two main differences of the ICDR processing compared to the CDR processing:

3.1 Change of auxiliary data used as input to the algorithm

The purpose of generating very recent SARAH-3 data records requires to use data from ECMWF high resolution analysis and forecasts as input (in contrast to ERA5 data used for the CDR processing), namely total column water vapour, total ozone, snow depth and sea-ice thickness. Details on the auxillary data used for the CDR and ICDR generation are given in the Algorithm Theoretical Baseline Document (ATBD) (see RD 2).

3.2 Algorithmic changes

For the calculation of the daily snow mask the last 30 days of satellite data is used for statistics instead of the respective month. The basic processing steps of Helsnow remain unchanged. Analogue to the generation of the snow mask, the last 30 days of data are also used In the Heliosat part for the retrieval of the Effective Cloud Albedo (CAL). Based on CAL, the calculation of the radiation parameters using SPECMAGIC is identical to the CDR processing (considering the changes in the auxiliary data, see Section 4.1). As for the CDR the monthly means are calculated using the WMO criteria for the estimation of monthly averages.

3.3 CDR vs. ICDR

The described algorithmic differences cause differences in the final products between the CDR and ICDR. For the major part, the differences are very small. Larger differences can occur in mountain areas, where differences in the snow detection affect the surface radiation parameters. Further, in the southern Atlantic ocean area, larger differences occur due to the different statistical time window used to determine the Effective Cloud Albedo (see Figure 4-1) and differences in sea-ice input.

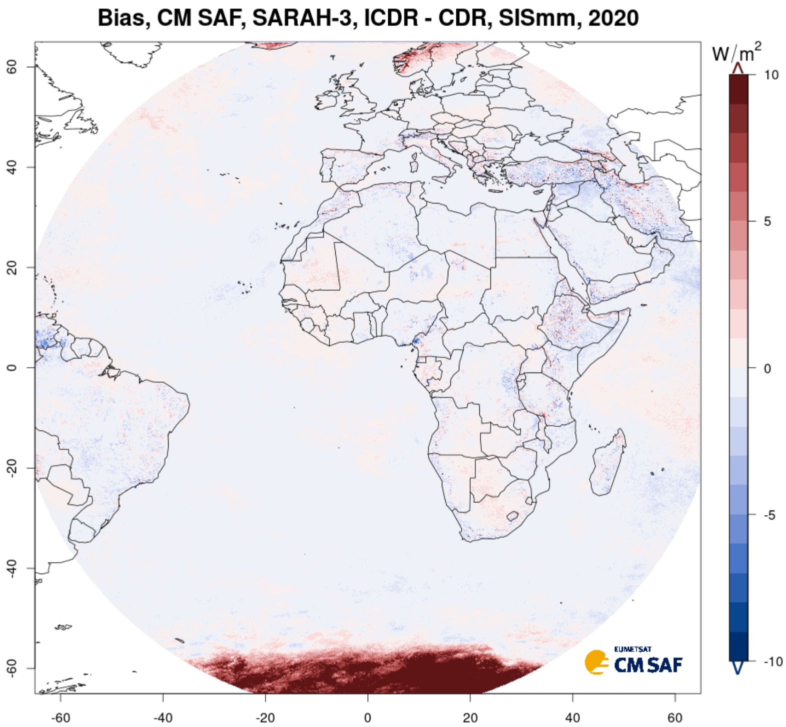

Figure 4-1: Bias of the monthly means of Surface Incoming Solar Radiation (SISmm) (ICDR minus TCDR) for 2020

Overall the data from the SARAH-3 ICDR (from 2021 onwards) in combination with the corresponding data from the CDR (1983 - 2020) enables users to derive the recent anomalies, a requirement for climate monitoring applications. However, when using the combined CDR + ICDR data record for climate trend analysis, which have a higher requirement on the stability, a closer look on the temporal stability of the times series for the specific region of interest is strongly recommended.

4 Data description

This section describes the output formats for the surface radiation parameters. Each surface radiation parameter is gridded onto a regular lat/lon grid with a size of 0.05 x 0.05° (WSG 84). The time resolution includes 30-min instantaneous values, daily mean values, and monthly mean values for CAL, SIS, SDI, PAR, and DAL; SDU is available as daily and monthly sums.

Note, that the spatial grid of SARAH-3 is shifted by half a grid box compared to the spatial grid of the SARAH-2 climate data record to provide a better consistency with other CM SAF data records, e.g., the CLAAS data record.

4.1 Product Names

Product types are:

- Surface incoming solar radiation (SIS), also known as global irradiance,
- Surface direct radiation (SDI),
- Sunshine Duration (SDU),
- Photosynthetic active radiation (PAR),
- Daylight (DAL),
- Effective cloud albedo (CAL), also known as cloud index.

Time resolution:

- Daily mean value (for SDU: daily sum),
- Monthly mean value (for SDU: monthly sum),
- 30 min instantaneous values.

4.2 Data Format and Ordering

CM SAF‘s climate monitoring products of surface radiation are provided as NetCDF (Network Common Data Format, http://www.unidata.ucar.edu/software/netcdf/) files. The NetCDF software functions as an I/O library, callable from C, FORTRAN, C++, Perl, or other language for which a NetCDF library is available. The library stores and retrieves data in self-describing, machine-independent data records. Each NetCDF data record can contain multidimensional, named variables (with differing types that include integers, reals, characters, bytes, etc.), and each variable may be accompanied by ancillary data, such as units of measure or descriptive text.

A NetCDF consists of dimensions, variables, and attributes. These components can be used together to capture the meaning of data and relations among data. The dimensions of the CM SAF radiation CDRs are longitude, latitude and time (see Table A-7-1). Each NetCDF file contains one variable (SIS, DNI, SID, PAR, DAL, SDU, or CAL) at the given time resolution (instantaneous, daily or monthly means (sums for SDU)) together with the data values for the dimensions (see Table A-7-2). The variables as well as the dimension variables are accompanied by attributes following the NetCDF Climate and Forecast (CF) Metadata Convention 1.4 (http://cfconventions.org/). The attributes that are included in the CM SAF surface radiation data records are listed in Table A-7-3.

All data records are provided in separated files, one file for each time step, with the exception of the 30-min instantaneous data, which are provided with all time steps per day in a single file. The data records cover monthly, daily and 30-min instantaneous values.

Below a list of relevant product acronyms ($product) and acronyms for the averaging period ($mean):

SIS: Surface Incoming Shortwave Radiation**.** Also called solar surface irradiance

DNI: Direct Normal Irradiance at surface

SID: Surface incoming direct radiation

SDU: Sunshine Duration

PAR: Photosynthetic active radiation

DAL: Daylight

CAL: Effective cloud albedo

As additional data layer the corresponding daily and monthly mean clear-sky surface radiation data are available.

mm: Monthly mean

dm: Daily mean

in: instantaneous

ms: Monthly sum

ds: Daily sum

Within the CAL daily mean NetCDF files an additional layer called "Nobs" is included that gives the number of used satellite observations in the visible spectral range per pixel, at the given day.

Ordered files will follow the following naming convention

$Product$mean$Year$MonthDayHour$Version

Further details on the naming are given in the Web User Interface and the naming convention document available at the CM SAF web page: www.cmsaf.eu -> Products -> "Naming convention" item.

4.3 Data ordering via the Web User Interface (WUI)

Information on the CM SAF services are provided through the CM SAF homepage www.cmsaf.eu. The web page includes information and documentation on the CM SAF and the CM SAF products, information on how to contact the user help desk. It provides also the link to the WUI (http://wui.cmsaf.eu), which allows to search the product catalogue and to order products.

On the WUI "webpage" (http://wui.cmsaf.eu), a detailed description how to use the web interface for product search and ordering is given. The user is referred to this description since it is the central and most up to date documentation. However, some of the key features and services are briefly described in the following sections.

Copyright note:

All intellectual property rights of the CM SAF products belong to EUMETSAT. The use of these products is granted to every interested user, free of charge. If you wish to use these products, EUMETSAT's copyright credit must be shown by displaying the words "copyright (year) EUMETSAT" on each of the products used.

4.3.1 Product ordering process

You need to be registered and logged in to order products. A login is provided upon registration, all products are delivered free of charge. After the selection of the product, the desired way of data transfer can be chosen. This is either via a temporary ftp account (the default setting), or by CD/DVD or email. Each order will be confirmed via email, and the user will get another email once the data have been prepared. If the ftp data transfer was selected, this second email will provide the information on how to access the ftp server.

4.4 Data volume

The data amount depends on the data request of the user, in detail on the size of the selected region and the duration of the covered time period. The user will be informed about the data volume of his request within the WUI ordering process.

Below the maximum values for one parameter covering the complete Meteosat disk and time period are given:

Monthly Means: ~2 GB

Daily Means: ~80 GB

30-min Instantaneous: ~3 TB

4.5 Contact User Help Desk staff

In case of questions the contact information of the User Help Desk (e-mail address contact.cmsaf@dwd.de, telephone and fax number) are available via the CM SAF main webpage (www.cmsaf.eu or the main page of the Web User Interface.

4.6 Feedback/User Problem Report

Users of CM SAF products and services are encouraged to provide feedback on the CM SAF product and services to the CM SAF team. Users can either contact the User Help Desk (see Chapter 4.5) or use the “User Problem Report” page. A link to the “User Problem Report” is available either from the CM SAF main page (www.cmsaf.eu) or the Web User Interface main page.

4.7 Service Messages / log of changes

Service messages and a log of changes are also accessible from the CM SAF main webpage (www.cmsaf.eu) and provide useful information on product status, versioning and known deficiencies.

5 Tools and Auxiliary data

This section describes currently available tools to read, display, re-project and modify the CM SAF products. All tools and auxiliary data shortly described here, are accessible from the CM SAF main webpage (www.cmsaf.eu).

All tools and auxiliary data described are free of charge. They come with no warranty and are based on best effort basis. When encountering problems, please contact the User help desk (Section 4.5).

5.1 Climate data operators (CDO)

To allow easy access to CM SAF data records the possibility to import CM SAF data has recently been integrated into the ‚climate data operators' (CDO) which is a well-established conversion tool in the climate modelling community (https://code.zmaw.de/projects/cdo).

This package was originally developed for processing and analysis of data produced by a variety of climate and numerical weather prediction models (e. g. for file operations, simple statistics, arithmetic, interpolation or the calculation of climate indices). Besides the conversion between different file formats, cdo offers possibilities for pre-processing the data for validation studies, especially interpolation to other grid types and selection of regions, including methods for interpolation of non-continuous data records such as e. g. cloud types.

The CM SAF Meteosat climate data records are provided on a regular latitude longitude grid, whereby the latitude and longitude are given and described in the netCDF-files. CDO employs this information for spatial operations on these final products. A link to this tools is available on the CM SAF web site (www.cmsaf.eu/tools/). CDO has been used for the averaging of CAL, for the generation of SARAH-3 monthly means, and for modifications of the NetCDF metadata settings.

Please refer to the CDO-manual for detailed instructions how to import and process CM SAF products.

5.2 CM SAF R Toolbox

The CM SAF R TOOLBOX is an easy-to-use tool to prepare, analyze and visualize CM SAF NetCDF data. The Toolbox comes as part of the cmsaf R-package, which is a collection of more than 100 functions for analysis and manipulation of CM SAF NetCDF formatted data. The CM SAF R Toolbox is based on an R-shiny graphical user interface, which guides through all options. Thus, no R or scripting experience is needed. The Toolbox as well as numerous documentation is freely available at www.cmsaf.eu/R-Toolbox.

5.3 Auxiliary Data

This section gives an overview of available auxiliary data records which will be helpful for further processing and interpretation of CM SAF products. All auxiliary data records are accessible via the webpage www.cmsaf.eu in the drop-down menu “Products” – “Auxiliary Data” or on request.

- Acquisition time difference for instantaneous products: Time difference between the time provided in the instantaneous data files and the local observation time at the corresponding grid box. Note that the time difference is different for the years prior to 2005 (i.e., data based on the MVIRI instrument) and after 2005 (i.e., data based on the SEVIRI instruments) due to a change in the reference time.
- Elevation / Land-Sea Mask / Land-cover: Elevation, Land-Sea Mask and land-cover for the SARAH-3 spatial grid.

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7 Appendix

7.1 Appendix A: Description of the netCDF file format

The netCDF metafile definitions follows the cf 1.9 convention, please see http://cfconventions.org/ for details

Table A-7-1: Dimensions in the SIS, SID, DNI, PAR, DAL, CAL, SDU netCDF files

Dimension	Size	Description
lon	2600	Longitude
lat	2600	Latitude
time	1	Time
bnds	2	

Table A-7-2: Variables in the netCDF SIS, SID, DNI, PAR, DAL, CAL, SDU files

Variable	Type	Dimension	Description
lat	float	(lat)	Longitude [°E]
lon	float	(lon)	Latitude [°N]
time	double	(time)	Time [hours since 01.01.1983]
SIS, SID, DNI, PAR, DAL, or CAL	short	(time,lat,lon)	Radiation or Effective Cloud Albedo
SDU	short	(time,lat,lon)	Sunshine duration

Table A-7-3*:* Variable attributes in the netCDF files

Attribute name	Type	Description
units	string	the units of the variable
long_name	string	a more descriptive variable name
standard_name	string	a pre-defined variable name according to the standard name table in order to enable users of data from different sources to determine whether quantities were in fact comparable

Attribute name	Type	Description
_FillValue	same as variable	This value is considered to be a special value that indicates undefined or missing data; it is used to pre-fill disk space allocated to the variable.
missing_value	same as variable	deprecated, included for backward compatibility, describes the same as the [_FillValue]
cell_methods	string	Indicates if a data value is a temporal mean, a temporal sum, or instantaneous data (point in time)

For the daily mean SIS,SID,DNI,PAR, and DAL data, also the clear-sky values are given as an additional field in the netcdf data. Note that the clear-sky radiation is no official CM SAF parameter and meat as auxillary information.

7.2 Appendix B: Complete equations for the effective cloud albedo - solar irradiance relation

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

$$k=SIS/\ SIS_{CLS}$$

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:

$$k = 1-CAL$$

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 has to be considered).
- The effect of saturation occurring in optically thick clouds.

In these 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. The equations given below provide 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.

$$
\begin{aligned}
CAL < -0.2 &: k = 1.2, \\
-0.2 \le CAL \le \ 0.8 &: k = 1 - CAL, \\
0.8 < CAL \le \ 1.1 &: k = \ 2.0667 - 3.6667 \cdot CAL + 1.6667 \cdot CAL^2, \\
CAL > \ 1.1 &: k = 0.05
\end{aligned}
$$

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

$$SIS = k \cdot SIS_{CLS} \ ,$$

where SIS_{CLS} is the clear sky surface solar irradiance calculated using the MAGIC code (Mueller et al., 2004, 2009, 2012).

8 Glossary – List of Acronyms in alphabetical order

AVHRR	Advanced Very High Resolution Radiometer
AOD	Aerosol Optical Depth
BSRN	Baseline Surface Radiation Network
CAL	Effective Cloud Albedo
CDOP	Continuous Development and Operational Phase
CDO	Climate Data Operators
CDR	Climate Data Record
CLIMAT	Measurements from Surface Climate Stations
CM SAF	Satellite Application Facility on Climate Monitoring
DAL	Daylight
DWD	Deutscher Wetterdienst
DNI	Direct Normal Irradiance
ECMWF	European Centre for Medium-Range Weather Forecast
ECV	Essential Climate Variable
ERA	ECMWF Reanalysis
FRAC	Fraction of days larger than the target value.
GADS/OPAC	Global Aerosol Data Set / Optical Properties of Aerosols and Clouds
GCOS	Global Climate Observing System
GEBA	Global Energy Balance Data Archive
GERB	Geostationary Earth Radiation Experiment
GEWEX	Global Energy and Water Cycle Experiment
ICDR	Interim Climate Data Record
K	Clear sky index
LUT	RTM based Look-Up-Table
MAD	Mean of absolute deviation over several days or months
MVIRI	Meteosat Visible and InfraRed Imager

MACC	Monitoring Atmospheric Composition and Climate
NOAA	National Oceanic and Atmospheric Administration
PAR	Photosynthetic Active Radiation
PRD	Product Requirement Document
PUM	Product User Manual
RTM	Radiative Transfer Model
SARAH	Surface Solar Radiation Data records – Heliosat
SEVIRI	Spinning Enhanced Visible and Infrared Imager
SD	Standard deviation
SDI	Surface Direct Irradiance (consist of SID and DNI)
SDU	Sunshine Duration
SEA	Sun Elevation Angle
SEVIRI	Spinning Enhanced Visible and InfraRed Imager
SID	Surface Incoming Direct radiation, commonly called direct irradiance
SIS	Surface Incoming Solar radiation, commonly called global irradiance or surface solar irradiance
SRI	Spectral Resolved Irradiance
SSA	Single Scattering Albedo
SZA	Solar Zenith Angle