EUMETSAT Satellite Application Facility on Climate Monitoring

Algorithm Theoretical Basis Document

CM SAF Cloud, Albedo, Radiation data record, AVHRR-based, Edition 3 (CLARA-A3)

Surface Radiation

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	CDR	ICDR
Surface Incoming Shortwave Radiation	**CM-11202**	**CM-6211**
Surface Downward Longwave Radiation	**CM-11262**	**CM-6261**
Surface Radiation Budget	**CM-11272**	**CM-6271**
Surface Net Shortwave Radiation	**CM-11281**	**CM-6281**
Surface Net Longwave Radiation	**CM-11291**	**CM-6291**

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Applicable documents

Reference	Title	Code
AD 1	CM SAF Product Requirement Document	SAF/CM/DWD/PRD/4.0

Reference documents

Reference	Title	Code
RD 1	Algorithm Theoretical Baseline Document, CLARA-A3, Cloud Products	SAF/CM/DWD/ATBD/CLARA/CLD v3.3
RD 2	Algorithm Theoretical Baseline Document, CLARA-A3, TOA Radiation	SAF/CM/RMIB/ATBD/CLARA/TOA /1.5
RD 3	Validation Report, CLARA-A2.1, Surface Radiation Products	SAF/CM/DWD/VAL/GAC/RAD/2.4

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The EUMETSAT SAF on Climate Monitoring

In 2000 the EUMETSAT Member States 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". Already in 1999, recognizing the importance of climate monitoring with satellites, 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 Recherché Scientifique (CNRS). 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 Thematic Climate Data Records (CDRs) for 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, i.e. FCDRs and CDRs, 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, i.e. Interim Climate Data Records (ICDRs). 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 within research programmes such as WCRP. 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.

1 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 AVHRR Global Area Coverage (GAC) data. The AVHRR-carrying satellites from 1979 onwards used in the generation of the CLARA-A3 climate data record are shown in Figure 2-1 of the CLARA-A3 Cloud Products ATBD [RD 1]. The algorithm for the retrieval of the shortwave surface radiation is based on a look-up-table approach that related the reflected solar radiation to the atmospheric transmittance as presented by Mueller et al., 2009. The estimation of the downwelling longwave surface radiation and the surface radiation budget make use of the corresponding data from the ERA-5 reanalysis system, ensuring, however, the consistency with the cloud coverage and the derived shortwave radiation from CLARA-A3.

More information on the basic accuracy requirements are defined in the product requirements document [AD 1]. The CLARA-A3 surface radiation data set contains five parameters each for the CDR and ICDR:

	CDR	**ICDR**
Surface Incoming Shortwave Radiation	**CM-11202**	**CM-6211**
Surface Downward Longwave Radiation	**CM-11262**	**CM-6261**
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2 Retrieval Algorithms of the CLARA Surface Radiation Products

In the following the retrieval algorithms used to generate the surface radiation products in the CM SAF CLARA data set will be described. The retrieval of the shortwave surface radiation products (SIS) is presented in Section 2.1, Section 2.2 presents the algorithms used to derive the longwave surface downwelling and the surface radiation budget data sets (SDL, SRB).

2.1 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 in the generation of the CM SAF CLARA-A3 data record is based on a look-up-table approach that related the reflected solar radiation to the atmospheric transmittance as presented by Mueller et al. (2009).

The underlying fundamental assumption of retrieving the surface solar irradiance from satellite observations is that the reflected solar 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:

Equation 2-1

$$SIS = E_0 \cos(\Theta_0)\, T$$

where E_0 is the incoming solar flux at the top-of-the-atmosphere (E_0 = 1361 W/m^2, annual average) and Θ_0 the solar zenith angle. The solar flux is assumed to vary only with the Earth's distance from the sun; changes in the solar flux due to the solar activity are considered to be very minor for the satellite-based estimation of the surface irradiance and are neglected here.

2.1.1 The MAGIC clear-sky model

The clear-sky Mesoscale Atmospheric Global Irradiance Code (MAGIC, https://sourceforge.net/projects/gnu-magic/) is used to estimate the clear-sky surface irradiance. Details of this radiative transfer model are provided in Mueller et al (2009); the underlying fundamental principles are provided in the following.

Look-up-tables (LUTs) form the basis of the MAGIC clear-sky model. However, the basic look-up-tables are constructed only for those parameters that do have a non-linear impact on surface irradiance; other parameters that influence the surface irradiance, but that have an (almost) linear effect on surface irradiance (i.e., the eigenvectors, see Mueller et al., 2009) are considered by linear corrections. The determination and the application of the look-up-table only for the non-linear components of the solar radiative transfer substantially reduces the dimensions of the look-up-tables without a relevant reduction in the accuracy.

The effect of the solar zenith angle on the transmission / solar irradiance, is considered by the use of the Modified Lambert Beer (MLB) function, discussed in detail in Mueller et al. (2004, 2009), and allows the consideration of the solar zenith angle effect on surface irradiance by a non-linear correction to the surface irradiance at 0° solar zenith angle.

The atmospheric parameters that have a non-linear effect on the surface irradiance are the aerosol parameters, i.e, aerosol optical depth (AOD), single scattering albedo (ssa), and asymmetry parameter (gg). Look-up-tables have been pre-calculated for 10 values of aerosol optical depths, 3 values of the single scattering albedo and 2 values of the asymetry parameter. The impact of the surface albedo, the vertically–integrated water vapor and ozone are considered through a linear correction from the LUT anchored at a surface albedo of 0.2, water vapour and ozone columns of 15 mm and 345 DU, respectively. All simulations to generate the LUTs have been performed using the libRadtran RTM model (Mayer and Kylling, 2005). All these optimisations reduce the number of required radiation transfer calculations substantially by a factor of 10,000 compared to 'traditional' look-up table approaches without any loss in the accuracy. The computational efficiency of the algorithm makes it perfectly suited for the satellite retrieval of the surface solar radiation under clear-sky conditions.

Figure 2-1 presents the flow-chart of the calculation of the surface incoming solar radiation under clear-sky conditions using MAGIC. In a first step to estimate the surface irradiance for a location / satellite pixel, the pre-calculated clear sky fluxes from the LUTs are interpolated towards the optical aerosol information derived for the location and the time under investigation (see Sections 2.1.2.1.1.1 and 2.1.2.3 for the aerosol information used in the generation of CLARA-A3). Subsequently, correction formulas are applied that consider the difference between the reference values (i.e., the values used to derive the look-up-table) of the other atmospheric parameters (i.e, water vapour, ozone, albedo) and the current values of the parameter (see Sections 2.1.2.1.1.2 and 2.1.2.3 for the information used in the generation of CLARA-A3). 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). The Modified Lambert-Beer (MLB) function is used to derive the dependency of the surface solar radiation on the solar zenith angle (Mueller et al., 2004).

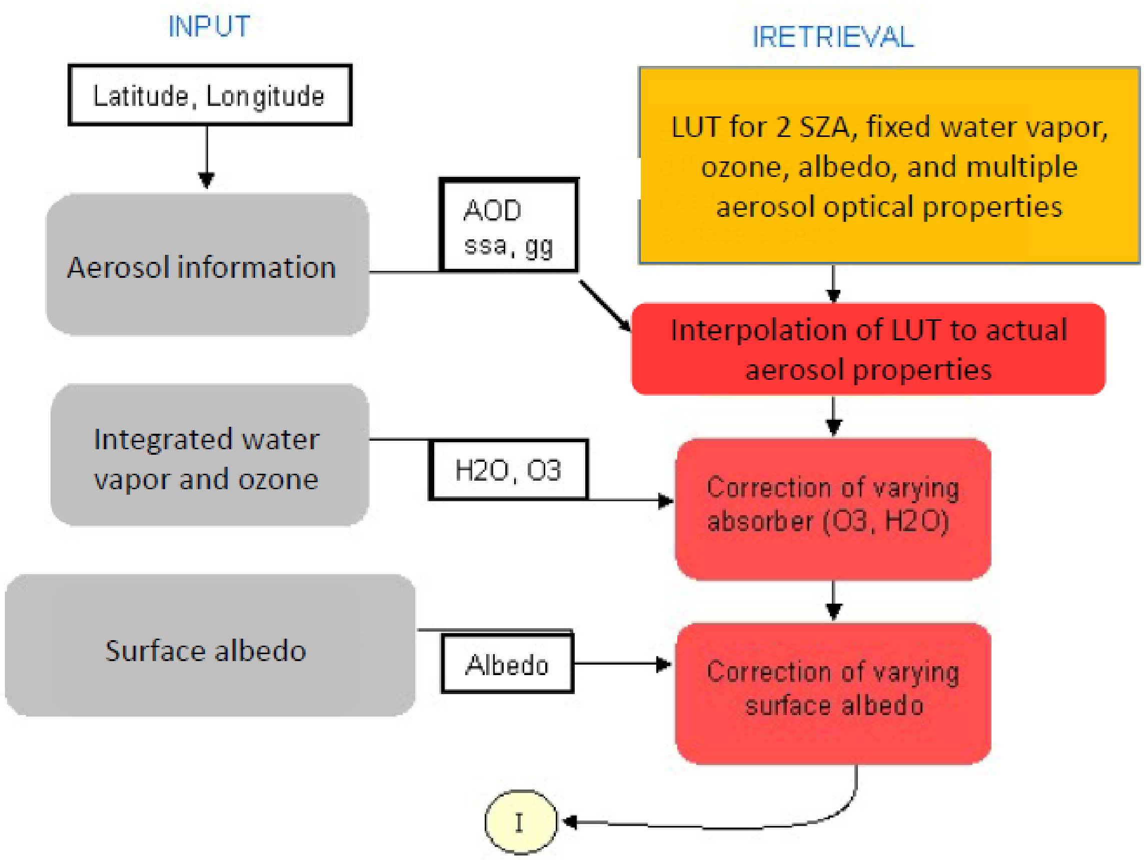

Figure 2-1: Flow-chart of the calculation of the surface incoming solar radiation under clear-sky conditions. The required input data is shown on the left side of the diagram, the right part represents the calculation of the surface solar irradiance using the MAGIC clear-sky model. The figure is adopted from Mueller et al. (2009).

2.1.2 SIS Algorithm

The algorithm used here to derive the surface irradiance from the AVHRR GAC data set is based on the application of a look-up-table to derive the atmospheric transmission and the surface incoming solar radiation (Pinker and Laszlo, 1992). The details of the algorithm are already provided in Mueller et al. (2009). 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 (SZA), the cloud coverage, the vertically-integrated water vapour and the aerosol optical depth.

The solar zenith angle 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 AVHRR GAC data set. Also no suitable data set of the aerosol optical depth is readily available from the AVHRR GAC data. For these two parameters, external data sources have to be consulted to calculate the transmissivity and the surface solar incoming radiation. The main information that is used from the satellite data in the estimation of surface irradiance is the information on cloud coverage.

The surface albedo only has a weak impact on the downwelling surface solar radiation, except for high albedo values, e.g., over snow-covered surfaces. However, the contributions of the reflections from clouds and from the surface to the satellite measurements do depend on the surface albedo, in particular under thin cloud and high albedo conditions.

The retrieval algorithm used to derive the surface incoming solar radiation consists of two steps. First, the full spectral information of the satellite instrument is used to derive information on cloud mask for each pixel using the PPS Nowcasting SAF (SAFNWC) software [RD 1]. In case, no cloud is detected (i.e., the satellite pixel is considered 'cloud-free'), the surface solar irradiance is calculated by radiative transfer modelling using information on the integrated water vapour, the aerosol optical depth, and the surface albedo from auxiliary sources without the use of additional satellite observations. In the case the cloud retrieval algorithm detects the presence of a cloud (i.e., the pixel is classified by the SAF NWC software either as 'cloud-contaminated' or as 'fully cloudy'), the pixel is considered 'cloudy' and the atmospheric transmissivity and subsequently the surface solar irradiance is derived using the method described in Section 2.1.2.2.

2.1.2.1 Cloud-free conditions

Under clear-sky cloud-free conditions the surface irradiance is primarily driven by the solar zenith angle and the atmospheric scattering and absorption by gaseous compounds and aerosol particles; for bright surfaces, also the surface albedo has a non-negligible contribution. Only very limited information on the relevant parameters is available in and, hence, could be extracted from the AVHRR satellite measurements. Some information on the aerosol and the surface albedo might be available in the AVHRR measurements under clear-sky conditions and it would be, indeed, very valuable to have access to collocated aerosol and albedo information for the estimation of clear-sky surface irradiance. However, the extraction of these data on the basis of the individual pixels is not easily possible; in particular the separation of the contributions of the aerosol properties and the surface albedo in the satellite signal, which is highly important for the estimation of surface irradiance, is associated with large uncertainties and not expected to substantially improve the estimation of surface irradiance under clear-sky conditions.

Consequently, the calculation of the surface solar irradiance under cloud-free conditions does not use any additional information from satellite, but is based purely on the clear-sky Mesoscale Atmospheric Global Irradiance Code (MAGIC, https://sourceforge.net/projects/gnu-magic/, Mueller et al. (2009)) as presented in Section 2.1.1 for each satellite pixel. The results of the clear-sky surface irradiance model are determined by the auxiliary data as described in the following sections.

2.1.2.1.1 Auxiliary data

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.

2.1.2.1.1.1 Aerosol

For the aerosol information, a modified version of the climatological monthly mean aerosol fields from the GADS/OPAC climatology (Hess et al., 1998) has been used. Based on the study of Mueller et al. (2015) we reduced the maximum AOD values of the original GADS/OPAC climatology to account for the detection of thick aerosol layers by the cloud retrieval algorithm. The aerosol information comprise of column-integrated values for the aerosol optical depth, the single scattering albedo, and the asymmetry factor.

2.1.2.1.1.2 Water vapour and ozone columns, surface albedo

The vertically integrated water vapour (ERA-5 terminology: tcwv, ID: 137) and ozone columns (ERA-5 terminology: tco3, ID: 206) as well as the broadband surface albedo (ERA-5 terminology: fal, ID: 243) are taken from the ERA-5 reanalysis (Hersbach et al., 2020) and interpolated to the satellite pixel using the PPS software system. The surface albedo in ERA-5 is based on a climatological background albedo, modified by contributions from reanalysis-based snow and sea-ice.

2.1.2.2 Cloudy Condition

Under cloudy conditions (i.e., the pixel is classified as ‘cloud-contaminated’ or ‘fully clouded’ by the PPS Nowcasting SAF (SAFNWC) software) a different approach is taken to derive the surface solar radiation. The identification of a cloudy pixel is based on the probabilistic cloud mask (Karlsson et al., 2020) using a threshold of 50 %. For pixels over snow- and sea ice-covered surfaces the threshold of the probabilistic cloud mask to detect cloudy conditions was set to 90 %, to the reduce the likelihood of detection of thin clouds with low impact on surface irradiance under these conditions.

Figure 2-2 presents the diagram of the retrieval of the surface solar incoming radiation under cloudy conditions, which follows the ideas of Pinker and Laszlo (1992). 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 (i.e, aerosol optical depth, single scattering albedo, asymmetry factor). In addition to this auxiliary input data, also satellite data is used to derive the surface radiation under cloudy conditions.

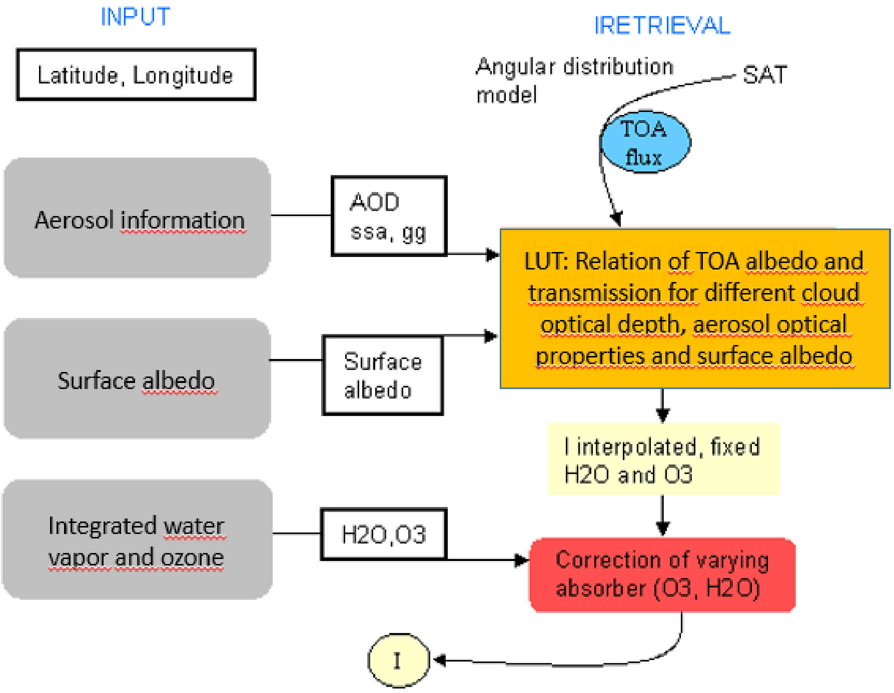

Figure 2-2: Diagram of the calculation of the surface solar incoming radiation under cloudy conditions. The required input data is shown on the left side of the diagram, the right part represents the calculation of the surface solar irradiance using the look-up tables for the TOA albedo. The figure is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

2.1.2.2.1 Broad-band ToA albedo

To limit the size of the look-up–table under cloudy conditions the retrieval algorithm requires the derived top-of-the-atmosphere broadband albedo in the shortwave spectral region as input parameter (see Figure 2-2). However, this quantity is not measured directly by the AVHRR instrument, but has to be inferred from radiance measurements in the two available visible channels.

Here, we are using the top-of-the-atmosphere broadband albedo retrieved within the CLARA-A3 processing [RD 2]. This method uses scene-type dependent regression coefficients derived from simultaneous AVHRR-CERES observations to convert the narrow-band measurements to the broadband radiances (Akkermans and Clerbaux, 2020) and provides shortwave broadband albedo data for each AVHRR pixel [RD 2].

2.1.2.2.2 Look-up tables

The broadband top-of-the-atmosphere albedo from the satellite data is used in a look-up-table approach to derive the atmospheric transmissivity and, subsequently, the surface solar radiation. The look-up-tables have been generated using the RTM model libRadtran (Mayer and Kylling, 2005). All details on the generation of the look-up-table (incl. figures documenting the relation between TOA albedo and atmospheric transmissivity) are provided in Mueller et al., 2009; here, a general overview with the main relevant aspects is provided.

In addition to the clear-sky approach, under cloudy conditions, also cloud information has to be taken into account when generating the look-up-tables. A standard cloud parameterisation has been used (Hu and Stamnes, 1993) with varying cloud optical depth and a constant effective droplet radius of 10 µm. The use of a constant effective radius of cloud droplets and neglecting of ice clouds in the generation and the application of the look-up-tables under cloudy conditions constitutes a fundamental assumption, which might impact and possibly degrade the results of the satellite retrieval. The quality of the final data set and, in particular, the fulfilment of the requirements, is expected to be not substantially impacted.

To retrieve the relationship between the atmospheric transmissivity and the top-of-the-atmosphere albedo from the look-up-tables, the information on the aerosol optical properties and the surface albedo is taken from the auxiliary data (see Section 2.1.2.1.1). Based on the measured top-of-the-atmosphere albedo, the corresponding atmospheric transmissivity is extracted from the look-up-tables. As for the clear-sky case, the look-up tables for the cloudy case have been generated for fixed values of vertically-integrated water vapour and ozone. The required correction of the atmospheric transmissivity due to the contribution of these two atmospheric absorbers are applied subsequently (see Mueller et al. (2009)). The look-up-tables are estimated for 6 values of the solar zenith angle between 0° and 80°; for solar zenith angles larger than 80° (i.e, at low sun), no atmospheric transmissivity and subsequently, no surface irradiance is estimated.

Based on the retrieved atmospheric transmissivity, the surface solar irradiance is calculated using Equation 2-1 for each satellite pixel.

2.1.2.3 Calculation of gridded daily averages

The CM SAF CLARA SIS data set generated from the AVHRR satellite measurements is generated and provided on a regular lon-lat grid with a grid point spacing of 0.25° as daily and monthly means. To generate this data from the irregular-sampled satellite observations, the information from the satellite retrieval (clear-sky and cloudy-sky solar surface radiation) for each pixel is remapped to a regular lon-lat grid with a spatial resolution of 0.05° using the nearest-neighbour remapping. This resolution is comparable to the spatial resolution of the AVHRR instrument, so no spatial or temporal averaging is performed in this step.

In the next step, the daily mean is calculated for each 0.05° grid point following the method by Möser and Raschke (1984):

Equation 2-2

$$I_{dm} = I_{clr,dm} * \frac{\sum I_i}{\sum I_i^{clr}}$$

where 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. All satellite observations from the specific day and grid are considered in the summation, incl. those from different satellites. This method to calculate the daily means of the surface radiation substantially reduces the error introduced due to the limited number of observations per pixel per day Möser and Raschke (1984).

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. Monthly information about the tropospheric aerosol optical depth and their physical properties are taken from model-based estimates (Fiedler et al, 2019 a, b). These estimates are based on assumptions about the pre-industrial natural aerosol and emission inventories (Fiedler et al., 2019a) as well as on emission scenarios (Fielder et al., 2019b). For the generation of CLARA-A3, the monthly climatology MACv2 of natural aerosol data has been used (Fiedler et al., 2019a); the anthropogenic aerosol is prescribed by MACv2-SP (1979 – 2014) and by the scenario SSP2-45 (2015 bis 2025) (Fiedler et al., 2019a, b). These aerosol scenario are also part of the Scenario Model Intercomparison Project (ScenarioMIP) of CMIP6. Due to the remaining uncertainty of the long-term variability and trend of the monthly aerosol data, the aerosol data have been used to generate a multi-year monthly climatology, which has been used to estimate the daily clear-sky surface solar irradiance. Hence, the clear-sky surface irradiance does not include any year-to-year aerosol variability nor any long term aerosol trend.

The spatial distribution of the climatological aerosol optical depth are shown in Figure 2-3.

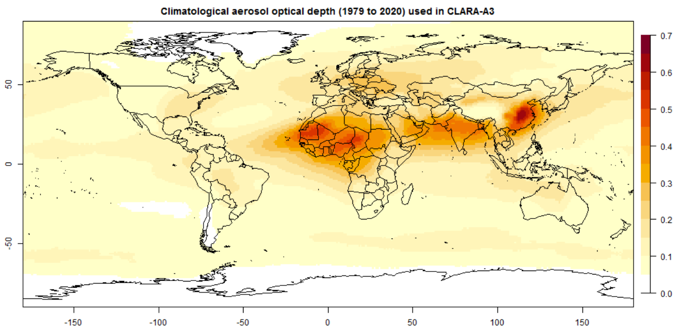

Figure 2-3: (Left) Spatial distribution of the climatoligical aerosol optical depth (Right) TThe AOD data are based on Fiedler et al., 2019 a,b.

Data on the vertically-integrated water vapour and ozone as well as on the surface albedo are taken from ERA-5, consistent with the estimation of the clear-sky irradiance during the satellite retrieval (Section 2.1.2.1.1.2). The daily mean clear-sky surface irradiance is calculated as the average of 24 hourly surface irradiance calculations.

The daily mean surface radiation on the 0.25°-grid is obtained by averaging the corresponding 25 high-resolution (i.e, 0.05°) grid boxes. To limit the uncertainty of the calculation of the daily averages due to limited number of observations, all daily mean values of the surface solar irradiance that are based on less than 20 observations on the 0.25°-grid are set to missing value. No limit is set on the number of available satellites and/or satellite overpasses when estimating the daily average surface irradiance. This implies that the daily average might be calculated from only one satellite overpass, assuming 20 or more valid satellite pixels are available in the 0.25° grid box. In this case, only the spatial variability of the daily means are considered when averaging. The accuracy of the gridded daily mean is expected to be substantially reduced under these conditions, in particular in regions with a pronounced diurnal cycle of cloud coverage, which can only be partly observed by a single satellite.

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. The remaining grid boxes are considered missing data.

The determination of the exact number of the required pixels in each grid box to derive a meaningful daily average and the number of valid daily means to derive a meaningful monthly average needs further investigations. Based on the validation with surface observations (see validation report for CLARA-A2.1 [RD 3]) the assumed values (20 observations to derive a daily average, 20 daily averages to derive a monthly average) are shown to ensure a quality of the surface irradiance data set in line with the accuracy requirements. It can be expected that these numbers differ depending on season and region. Projects to further evaluate the impact of the number of observations to derive daily and monthly averages from polar-orbiting satellite observations are under way, but have not yet been finalized to be included in the generation of the CLARA SIS data set.

2.1.2.4 Known Limitations and their Implications

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

- The algorithm requires broadband solar fluxes at the top-of-the-atmosphere to retrieve the atmospheric transmissivity and subsequently the surface solar radiation under cloudy conditions. The conversion of the satellite-observed radiances at two wavelengths into broadband solar fluxes requires assumptions on the spectral responses of the satellite channels and the bidirectional reflectance distribution function (BRDF), which can introduce some uncertainty into the satellite retrieval under cloudy conditions.
- The algorithm depends on the ability of the cloud-detection software to detect clouds. Misclassification of pixels by the cloud-detection algorithm enhances the uncertainty of the retrieved surface solar radiation.
- The look-up-tables used for the estimation of the surface irradiance under cloudy conditions are based on purely on water clouds (no ice clouds) with an effective droplet radius of 10 µm (no variability in effective cloud radius). Both aspect result in some uncertainty of the estimated surface irradiance.
- The application of monthly aerosol information derived from model simulations limits the accuracy of the data set, especially in regions with high interannual and sub-monthly aerosol variability, e.g., desert regions.
- No threshold requirement is set on the number of available satellite overpasses for the estimation of daily averages of surface irradiance. With few satellites available (e.g., in the early years of the data record) this can result in reduced data accuracy and spurious temporal changes, in particular in regions with a pronounced diurnal cycle of cloud coverage.

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

2.2 Longwave Surface Radiation

This section describes the algorithm to derive the surface downwelling longwave radiation product (SDL) of the CM SAF CLARA-A3 data set.

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 passive satellite data, e.g, the AVHRR GAC 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, satellite signals alone do not contain sufficient relevant information to retrieve the surface longwave downwelling radiation within good accuracy.

To overcome this fundamental limitation, data from the ERA-5 data set (Hersbach et al., 2020) is used to generate the CM SAF CLARA surface downwelling longwave radiation data set. The ERA-5 data set is generated at the spectral TL639 horizontal resolution, corresponding to approximately 31 km spacing on a reduced Gaussian grid (Hersbach et al., 2020), i.e. with a horizontal resolution similar to the CLARA-A3 data record. The ERA-5 data are derived from ECMWF on a 0.25° x 0.25° spatial grid and remapped to the CM SAF CLARA-A3 grid. To improve the internal consistency within the CM SAF CLARA-A3 data records the monthly mean cloud fraction from the CM SAF CLARA-A3 CFC data set are used to adjust the original ERA-5 data set.

2.2.1 SDL Algorithm

The CM SAF algorithm to derive the surface downwelling longwave (SDL) radiation from the AVHRR GAC data set is based on the monthly mean surface downwelling longwave radiation data from the ERA-5 data set. The CM SAF CLARA cloud fraction (CFC) data set is used to improve the consistency between the CLARA-A3 SDL data record and the other parameters of the CLARA-A3 data set by adjusting the ERA-5 SDL data for grid boxes, in which the cloud fraction from CLARA-A3 and ERA-5 deviate.

2.2.1.1 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-5 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:

Equation 2-3

$$CCF = \frac{\Delta SDL}{CFC_{ERA}} = \frac{SDL_{allsky} - SDL_{clr}}{CFC_{ERA}}$$

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-5 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 of the calendar year resulting in a CCF data set for each month of the calendar year based on the 42 years of ERA-5 data from 1979 to 2020. Figure 2-4 shows the correlations and the corresponding linear regression lines for five grid points along the dateline for July.

The cloud correction factor is derived from the linear regression for grid boxes with a correlation coefficient between *ΔSDL* and *CFC* above 0.75. For the remaining grid boxes the correlation is considered too low for an adjustment and, hence, CCF is set to zero. Figure 2-5 shows the temporally averaged cloud correction factor derived from 42 year of data taken from the ERA-5 data set.

In general, about 80 % of the surface downwelling longwave radiation originate from the lowest 500 m of the atmosphere (Schmetz, 1989). In particular under tropical conditions (high humidity) the contribution of clouds on the downwelling longwave radiation is limited to the atmospheric window, i.e, spectral regions with low water vapor absorption, and decreases with higher moisture since the transparency of the window decreases due to water vapor continuum absorption (see Schmetz, 1989). The effect explains the low values of the cloud correction factor in the tropical regions (Figure 2-5), where the differences of the monthly means of the clear-sky and the all-sky surface downwelling longwave radiation are 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. Low clouds have the largest impact on the surface downwelling longwave radiation; improved detection of low clouds from satellite observations or improved description of low clouds in reanalysis data sets would help to reduce the uncertainties in the SDL.

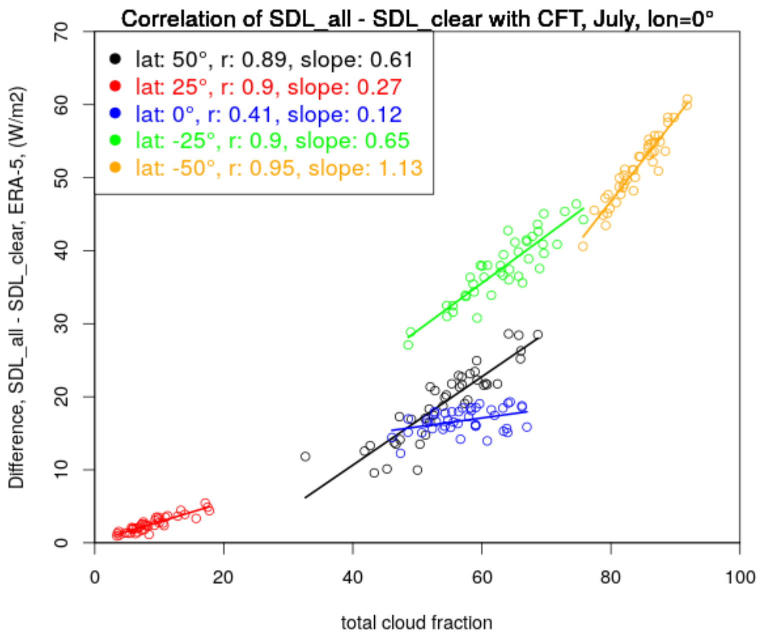

Figure 2-4: Correlation of the difference between the monthly all-sky and clear sky suface downwelling longwave radiation with the monthly total cloud fraction based on 42 years of ERA-5 data for five grid points along the dateline (longitude = 0 °E) for July. The slope of the linear regression corresponds to the cloud correction factor (CCF).

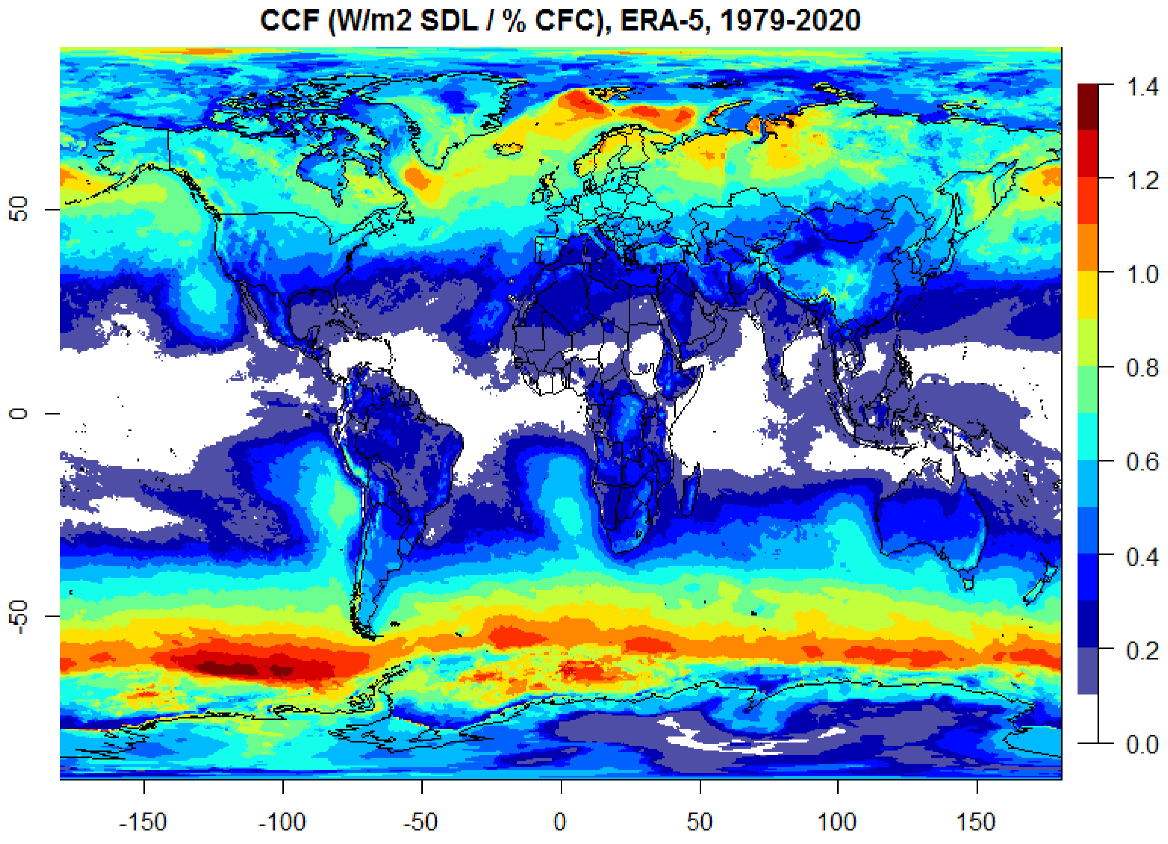

Figure 2-5: Temporal average of the cloud correction factor derived from the ERA-5 data set.

2.2.1.2 Calculation of SDL

The surface downwelling longwave radiation from the CLARA-A3 data set is calculated from the monthly mean of the surface downwelling longwave radiation derived from ERA-5 and the cloud correction term, i.e., the *CCF* multiplied with the difference of the cloud cover derived from ERA-5 and CLARA-A3 data sets:

$$SDL_{CLARA} = SDL_{ERA} + \Delta CFC * CCF = SDL_{ERA} + (CFC_{CLARA} - CFC_{ERA}) * \frac{\Delta SDL}{\Delta CFC}$$

here SDL_{ERA} denotes the monthly mean clear-sky surface downwelling longwave radiation from ERA-5 and CFC_{CLARA} is the cloud fraction from the CM SAF CLARA data set. By the application of the cloud correction factor using the difference between the cloud fraction derived from ERA-5 and CLARA the consistency of the CLARA SDL data set with the other CLARA data records is improved. To prevent unrealistic low values of CLARA SDL, in particular under polar conditions where satellite-based cloud detection remains challenging, the adjustment of the SDL from ERA-5 is limited to ± 10% of the ERA-5 SDL.

2.2.1.3 Known limitations

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

- The CM SAF CLARA-A3 SDL data record strongly depends on and is highly correlated with the ERA-5 surface downwelling longwave radiation, incl. the long-term trend of the data set The CLARA-A3 SDL data record, hence, is not suited for an independent evaluation of reanalysis- and/or model-derived surface longwave radiation data records.
- The cloud correction factor (CCF) is determined on a monthly basis by linear regression using ERA-5 data between 1979 and 2020. By using linear regression to determine CCF, Equation 2-3 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 CLARA SDL data set.

These limitation and its impact will be further investigate and possibly addressed in future versions of the CM SAF CLARA SDL data set.

2.3 Surface Net Shortwave Radiation

The surface net shortwave radiation is the net radiaton in the solar spectrum at the Earth's surface. Here, the daily surface net shortwave radiation, SNS, is estimated from the CLARA-A3 daily surface irradiance, SIS, and the CLARA-A3 pentad-mean blue-sky surface albedo, BAL:

$$SNS = SIS * (1. - BAL)$$

The monthly mean CLARA-A3 SNS data are derived as averages of the daily mean SNS values requiring a minimum of 20 valid daily mean SNS data.

2.3.1 Known limitations

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

The CM SAF CLARA-A3 SNS data record contains a significant number of grid boxes with missing data, in particular for the early time period of the data record. An estimation of the surface net shortwave radiation had not been possible for those grid boxes due to the reduced availability of satellite data. This circumstance needs to be considered when estimating spatial (e.g., global) averages. Surface Net Longwave Radiation

2.4 Surface Net longwave Radiation

The surface net longwave radiation is the net radiaton in the thermal spectrum at the Earth's surface. As mentioned in Section 2.2 insufficient information is available in the satellite measurements to estimate with adequate accuracy the surface longwave radiation from satellite observations. As a consequence the CLARA-A3 retrieval scheme to estimate net longwave surface radiation uses substantial and relevant information from ERA-5.

The monthly surface net longwave radiation, SNL, is derived as the sum of the monthly surface downwelling longwave (SDL) and surface outgoing longwave (SOL) radiation. The CM SAF CLARA-A3 SDL data are used; the monthly SOL data are derived from the monthly net surface longwave and the surface downwelling longwave radiation provided, both provided as part of ERA-5.

2.4.1 Known limitations

Here is a list of known limitations of the CLARA-A3 SNL data set:

- The CM SAF CLARA-A3 SNL data record strongly depends on and is highly correlated with the ERA-5 surface longwave radiation. The CLARA-A3 SNL data record, hence, is not suited for an independent evaluation of reanalysis- and/or model-derived surface longwave radiation data records.

2.5 Surface Radiation Budget

The surface radiation budget (SRB) is the total net radiation budget at the Earth's surface. It can be separated into the shortwave (solar) and the longwave (thermal) parts. The shortwave part is determined by the solar irradiance and the surface albedo, the net longwave surface radiation budget is determined by the downwelling and the upwelling longwave radiation, the latter being driven by the surface temperature and the emissivity.

Within the CLARA-A3 retrieval scheme the monthly surface radiation budget is estimated as the sum of the monthly surface net shortwave and the monthly surface net longwave radiation.

2.5.1 Known limitations

Here is a list of known limitations of the CLARA-A3 SRB data set:

- The CM SAF CLARA-A3 SRB data record strongly depends on and is highly correlated with the ERA-5 surface downwelling longwave radiation. The CLARA-A3 SRB data record, hence, is not suited for an independent evaluation of reanalysis- and/or model-derived surface longwave radiation data records.
- The CM SAF CLARA-A3 SRB data record contains a significant number of grid boxes with missing data, in particular for the early time period of the data record. An estimation

of the surface net shortwave radiation had not been possible for those grid boxes due to the reduced availability of satellite data. This circumstance needs to be considered when estimating spatial (e.g., global) averages.

2.6 ICDR specific adaptions

The retrieval algorithm used for the generation of the CLARA-A3 surface radiation ICDR data record is identical to the algorithm used for the generation the CLARA-A3 CDR surface radiation data. The main difference between these two processing environments is the use of a different data source for the meteorological input data. Due to the unavailabilitty of the final ERA5 data (used for the CDR proceessing) at the time of the CLARA-ICDR processing the ERA5 initial release data, i.e., ERA5T, is used. These data are generated at ECMWF with the same IFS model setup as the final ERA5 data, but might differ slightly from the final ERA5 data record due to additional quality checks that are not possible for the initial release data.

The following data are affected: water vapour (SIS), ozone (SIS), surface albedo (SIS), monthly cloud fraction (SDL, SNL, SRB), monthly surface downwelling longwave radiation (SDL, SNL, SRB), monthly surface net longwave radiation (SNL, SRB). The impact of using these data is expected to be small.

Additional differences between the surface radiation data in the CLARA-CDR and –ICDR are related to changes in the satellite-based input data, namely the cloud mask, the reflected solar flux at the top of the atmosphere, and the surface albedo.

Regarding the satellite-based input data, the production of the ICDR data records will start with the calibration coefficients derived in 2017 (v2017); due to the large calibration uncertainty of the AVHRR data from the Metop-C satellite these data are currently not used for the generation of the CLARA-A3 ICDR data records. When new and updated calibration coefficient will become available (expected in late 2023) the inclusion of AVHRR data from Metop-C in the subsequent ICDR production will be considered. Changes in the accuracy and stability of the CLARA-A3 ICDR are likely to be associated with these changes in the satellite observing system.

3 References

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4 Glossary

AOD	Aerosol Optical Depth
ATBD	Algorithm Theoretical Baseline Document
ATOV	Advanced TIROS Operational Vertical Sounder
AVHRR	Advanced Very High Resolution Receiver
BAL	blue-sky surface albedo
BRDF	Bidirectional Reflectance Distribution Function
CCF	Cloud Correction Factor
CDR	Climate Data Record
CERES	Clouds and the Earth's Radiant Energy System
CFC	Fractional Cloud Cover
CLARA-A	CM SAF cloud, Albedo and Radiation products, AVHRR based
CMIP	Coupled Model Intercomparison Project
CM SAF	Satellite Application Facility on Climate Monitoring
CNRS	Centre National de la Recherché Scientifique
DRR	Delivery Readiness Review
DWD	Deutscher Wetterdienst (German MetService)
ECMWF	European Centre for Medium Range Forecast
ECV	Essential Climate Variable
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
ERA	ECMWF Re-analysis
ERA-5	ECMWF Re-analysis, fifth generation
FCDR	Fundamental Climate Data Record
FMI	Finnish Meteorological Institute
GAC	Global Area Coverage (NOAA)
GADS	Global Aerosol Data Set
GCOS	Global Climate Observing System

GFCS	Global Framework for Climate Services WMO
GISS	Goddard Institute of Space Studies
ICDR	Interim Climate Data Record
KNMI	Royal Netherlands Meteorological Institute
LUT	Look-up Tables
MAC	Multisensor Advanced Climatology
MAGIC	Mesoscale Atmospheric Global Irradiance Code
MeteoSwiss	National Weather Service of Switzerland
MLB	Modified Lambert-Beer function
NASA	National Aeronautics and Space Administration
NMHS	National Meteorological and Hydrological Service
NWCSAF	SAF in Support to Nowcasting and Very Short Range Forecasting
OPAC	Optical Properties of Aerosols and Clouds
PCR	Products Consolidation Reviews
PPS	Polar Platform System
PRD	Product Requirement Document
PUM	Product User Manual
RAD	Radiation
RMIB	Royal Meteorological Institute of Belgium
RTM	Radiative Transfer Model
SAF	Satellite Application Facility
ScenarioMIP	Scenario Model Intercomparison Project
SCOPE CM	Sustained Coordinated Processing of Environmental satellite data for Climate Monitoring
SAL	Surface Albedo
SDL	Surface Downward Long-Wave Radiation
SFC	Surface
SIS	Surface Incoming Shortwave Radiation

SLF	Surface Longwave Fluxes
SMHI	Swedish Meteorological and Hydrological Institute
SNL	Surface Net Long-Wave Radiation
SNS	Surface Net Short-Wave Radiation
SOL	Surface Outgoing Long-Wave radiation
SOLIS	Solar Irradiance Scheme
SRB	Surface Radiation Budget
SSA	Single Scattering Albedo
SSI	Surface Solar Irradiance
SZA	Solar Zenith Angle
TOA	Top of the Atmosphere
TCDR	Thematic Climate Data record
UK	United Kingdom
METOFFICE	Meteorological Office
WCRP	WMO World Climate Research Programme
WMO	World Meteorological Organization