SRB: Target Requirements and Gap Analysis Document

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History of modifications

Version	Date	Description of modification	Chapters / Sections
V1.0	26/04/2023	Original version covering all deliverances between start of Phase II until March 2023	All
V1.1	06/10/2023	Document revised following feedback from independent review	All

Related documents

Reference ID	Document
D1	Algorithm Theoretical Basis Document CM SAF Cloud, Albedo, Radiation data record, AVHRR-based, Edition 2.1 (CLARA-A2.1), Surface Radiation, Issue 2.5 Link to CM SAF ATBD document
D2	Product User Manual CM SAF Cloud, Albedo, Radiation data record, AVHRR-based, Edition 2.1 (CLARA-A2.1), Surface Radiation Products, Issue 2.3 Link to CM SAF PUM document
D3	Validation Report, CM SAF Cloud, Albedo, Radiation dataset, AVHRR-based, Edition 2.1 (CLARA-A2.1), Surface Radiation Products, Issue 2.4 Link to CM SAF Validation Report
D4	CM SAF CDOP2 Product Requirement Document, SAF/CM/DWD/PRD, v3.7. Available upon request from Deutscher Wetterdienst (DWD).
D5	Algorithm Theoretical Basis Document CM SAF Cloud, Albedo, Radiation data record, AVHRR-based, Edition 2.1 (CLARA-A2.1), Cloud Products (level-1 to level-3), Issue 2.5 Link to CM SAF ATBD document (cloud products)
D6	[GCOS-107] Systematic Observation Requirements for Satellite-based Products for Climate, 2006 Link to GCOS-107
D7	[GCOS- 200] Global Climate Observing System, Implementation Plan, 2016. World Meteorological Organization, Geneva, Switzerland. Available from https://library.wmo.int/doc_num.php?explnum_id=3417
D8	Hollmann R., Mikalsen A.C. (2020), C3S Service: Input - Inventory for each product - 2020, Copernicus Climate Change Service, Document ref. C3S_D312b_Lot1.3.1.1-2020_Input_Inventory Not yet in CKB
D9	Meirink, J.F. et al (2022) C3S Service: Key Performance Indicators (KPIs), Copernicus Climate Change Service, Document ref. C3S_D312b_Lot1.0.4.8_201903_UpdatedKPIs_v1.0 https://confluence.ecmwf.int/x/AM_BEQ Last accessed on 21/02/2023
D10	Bobryshev O. (DWD) (2021), C3S Surface Radiation Budget CLARA, Service: Product User Guide and Specification (PUGS), Copernicus Climate Change Service, Document ref. C3S_D312b_Lot1.3.5.1-v2.1_202007_PUGS_ECVSurfacRadiationBudget_v1.0 https://confluence.ecmwf.int/x/ZVMiEg Last accessed on 21/04/2023
D11	Algorithm Theoretical Basis Document CM SAF Cloud, Albedo, Radiation data record, AVHRR-based, Edition 2.1 (CLARA-A2.1), Surface Albedo, Issue 2.4 Link to CM SAF ATBD document (surface albedo)
D12	Bobryshev O. (DWD) (2021), C3S Surface Radiation Budget CLARA, Service: Product Quality Assessment Report (PQAR), Copernicus Climate Change Service, Document ref. C3S_D312b_Lot1.2.2.3-v2.1_202010_PQAR_ECVSurfaceRadiationBudget_v1.0 https://confluence.ecmwf.int/x/U1MiEg Last accessed on 21/04/2023

D13	Sentinel-3 SLSTR User Guide, ESA , v.5.1, 16.01.2020. https://climate.esa.int/media/documents/Cloud_Product-User-Guide-PUG_v5.1.pdf Last accessed on 21/04/2023
D14	ESA Cloud CCI Algorithm Theoretical Basis Document, v.6.2, 14.10.2019. Available from: https://climate.esa.int/media/documents/Cloud_Algorithm-Theoretical-Baseline-Document-ATBD_v6.2.pdf Last accessed on 21/04/2023
D15	ESA Cloud CCI Algorithm Theoretical Basis Document: Community Cloud retrieval for Climate (CC4CI), v.6.2, 18.10.2019. Available from: https://climate.esa.int/media/documents/Cloud_Algorithm-Theoretical-Baseline-Document-ATBD-CC4CL_v6.2.pdf Last accessed on 21/04/2023
D16	ESA Cloud CCI Validation Report for MODIS multi-layer clouds, v1.1, 30.04.2018. Available from: https://climate.esa.int/media/documents/Cloud_Validation-Report-CC4CL-MLEV_v1.1.pdf Last accessed on 21/04/2023

Acronyms

Acronym	Definition
(A)ATSR	Term used to refer to the combined ATSR and AATSR dataset
AATSR	Advanced Along-Track Scanning Radiometer
ATBD	Algorithm Theoretical Basis Document
ATSR	Along-Track Scanning Radiometer
AVHRR	Advanced Very High Resolution Radiometer
BC-RMSD	Bias corrected RMSD (equal to cRMSD)
BSRN	Baseline Surface Radiation Network
C3S	Copernicus Climate Change Service
CCI	Climate Change Initiative (ESA)
CCI+	Follow-on project of ESA’s Climate Change Initiative
CDR	Climate Data Record
CDS	Climate Data Store
CEDA	Centre for Environmental Data Analysis (United Kingdom)
CERES	The NASA Clouds and Earth Radiant Energy System sensor
CF	Climate & Forecast conventions
CKB	C3S Knowledge Base
CLARA-A2.1	The CM SAF Cloud, Albedo and surface Radiation dataset from AVHRR data (Edition 2.1)
Cloud_cci	ESA’s Climate Change Initiative on Clouds
Cloud_CCI+	Extension of Cloud_cci project
CM SAF	Satellite Application Facility on Climate Monitoring
cRMSD	Centred (or bias-corrected) RMSD
DM	Daily mean
DSD	Data Set Description
DWD	Deutscher Wetterdienst (Germany’s National Meteorological Service)
ECMWF	European Center for Medium Range Weather Forecasts

ECV	Essential Climate Variable
ERA-5	ECMWF Reanalysis version 5
ERA-Interim	A global atmospheric reanalysis produced by ECMWF
EUMETSAT	European Organization for the Exploitation of Meteorological Satellites
FOV	Field Of View
GAC	Global Area Coverage (AVHRR)
GCOS	Global Climate Observing System
GOES	Geostationary Operational Environmental Satellite (NOAA)
Himawari	Japanese geostationary satellite
ICDR	Interim Climate Data Record
IFS	Integrated Forecasting System (ECMWF)
KPI	Key Performance Indicator
LUT	Lookup Table
Metop	Meteorological Operational Satellite
MM	Monthly mean
NASA	National Aeronautics and Space Administration
NEODC	National Earth Observation Data Centre (United Kingdom)
netCDF	Network Common Data Format
NISE	Near-real-time Ice and Snow Extent
NOAA	National Oceanic and Atmospheric Administration
NSIDC	National Snow and Ice Data Center
NTC	Non-Time Critical
OLCI	Ocean Land Colour Instrument on board Sentinel-3A satellite
ORAC	Optimal Retrieval of Aerosol and Cloud
PQAR	Product Quality Assessment Report
PRD	Product Requirements Document (CM SAF)
PUM	Product User Manual (CM SAF)
RMSD	Root-mean-squared deviation
RTTOV	Radiative Transfer for TOVS
SAL	Surface Albedo
SDL	Surface Downwelling Longwave Radiation
SEVIRI	Spinning Enhanced Visible and Infrared Imager (EUMETSAT)
SIS	Surface Incoming Shortwave Radiation
SLSTR	Sea and Land Surface Temperature Radiometer
SMHI	Swedish Meteorological and Hydrological Institute
SNL	Surface Net Longwave radiation
SNS	Surface Net Shortwave radiation
SOHO	Solar and Heliospheric Observatory
SOL	Surface Outgoing Longwave Radiation
SORCE	Solar Radiation and Climate Experiment
SRB	Surface Radiation Budget

SRS	Surface Reflected Shortwave radiation
Suomi-NPP	Suomi National Polar-orbiting Partnership
TCDR	Thematic Climate Data Record
TOA	Top-Of-Atmosphere
TOVS	Tiros Operational Vertical Sounder
TRGAD	Target Requirements and Gap Analysis Document
WMO	World Meteorological Organisation

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General definitions

Climate data records

Climate data compilations from observations are most often referred to as Climate Data Records (CDRs). However, the data records from satellites may consist of different types of quantities, from original radiances to derived products. Radiance data of climate quality are defined as Fundamental Climate Data records (FCDRs) while data records consisting of satellite-derived geophysical products are defined as Thematic Climate Data Records (TCDRs). In the ideal case the TCDRs should be derived by methods using FCDRs as input. However, if standards for the used radiances have not fulfilled the strict requirements for being classified as FCDRs, these radiances may be denoted Fundamental Data Records (FDRs). Notice that TCDRs can currently be based on either FCDRs or FDRs.

A special case of TCDRs are data records produced with short latency (e.g., shortly after the end of a month). These are called Interim Climate Data Records (ICDRs). The word Interim means that the data record has a higher uncertainty than the original TCDR since it has not been possible to use exactly the same input data as for the TCDR due to the short latency. Interim also means that a user may have to wait for the next edition of the TCDR to get a fully consistent and homogenous climate data record that includes data from the period with ICDR data. Normally ICDRs behave very similar to TCDRs but continuous monitoring of their quality is recommended.

Notice that since ICDRs are continuous extensions of the TCDR they are also delivered at subsequent times in separate batches (numbered 1,2,3..etc) where each one covers a certain time period (e.g. a number of months). Thus, when formally describing the full ICDR in the text (i.e., using the name specified in the delivery list), the ICDR version number is given but the batch number is written in generic form using letter x, for example ICDR v1.x. This is just to indicate that the batch number is only describing a temporal increment of the product and not any change of the product.

Uncertainty parameters

The meaning of the terms uncertainty, accuracy and error is often difficult to interpret and may be treated differently in various referred documents. In this document we adopt the following interpretation:

The accuracy, uncertainty or error of an estimated ECV (or, more formally, Thematic Climate Data Record, TCDR) is described by three differently contributing components:

1. The systematic error
2. The random error

3. The time-dependent error

The systematic error is commonly the **mean error** or the **Bias**. For non-Gaussian distributions of the error the **median** or the **mean absolute error** can be a more useful quantity.

The random error is commonly the root-mean-squared deviation **RMSD**. Sometimes the Bias is subtracted yielding the centred root-mean-squared deviation **cRMSD**. Notice that if the Bias is zero the two mentioned quantities are equal and may be interpreted as the standard deviation of the error (often denoted **standard error**).

The time-dependent error is commonly the change in Bias over time (for ECVs or TCDRs over decades). We call this parameter **stability**.

All TCDRs are normally evaluated against target requirements for the systematic, random and time-dependent error.

Testing the quality and consistency of TCDRs and ICDRs

This C3S project also deals with extensions of TCDRs, i.e. products derived from continued processing of the CDRs using the same methods and algorithms as originally used for TCDR production. We denote these CDRs Intermediate Climate Data Records, ICDRs. To evaluate the ICDR compliance with original TCDRs, a different approach in terms of defined requirements is followed. The ICDR is assessed on the basis of the TCDR distribution with respect to a reference validation source. After calculation of this distribution of differences, the ICDR is evaluated against the same reference and a binomial test is applied to verify that 95 % of the difference values lie within the upper and lower bounds of the TCDR difference distribution. The lower and upper bounds of the difference distribution is defined as the 2.5th and 97.5th percentiles of the difference distribution.

For further clarity, a binomial test is a way to test the statistical significance of deviations by referring to a theoretically expected distribution of observations. In this case, we use the theoretically expected distribution of observation differences which is estimated from the difference between TCDR results and corresponding results from a validation source. We now want to test if a corresponding but restricted, i.e., based on a shorter time series of ICDR results, difference distribution is similar in its shape to the original TCDR difference distribution. This can be tested by selecting one upper and one lower percentile in the original distribution (here, the 2.5th and 97.5th percentiles) and check how many samples will fall within or outside this restricted distribution if randomly extracting a number of samples. The resulting distribution of yes and no answers as a function of the number of samples can be described by the binomial distribution (see statistical standard literature for its definition). Consequently, this sample-based difference distribution from the ICDR can then be numerically compared with what could be expected from the reference distribution based on the TCDR. Based on this, one can judge whether the ICDR results are representative or not for the TCDR results. Deviations here would then indicate particular problems for the ICDR products (assuming that the character of reference observations does not change).

More details on the estimation of errors and uncertainty parameters are given in the Report on Updated KPIs (D9).

Product requirements

Depending on the data record producer, different product requirements may be applied and they are used to evaluate validation results. An often-used way to handle this is to define several levels of requirements where each level is linked to specific needs or priorities. A three-level approach like the following is rather common:

Requirement	Description
Threshold requirement	A product should at least fulfil this level to be considered useful at all. Sometimes the term ‘Breakthrough” is used instead.
Target requirement	This is the main quality goal for a product. It should reach this level based on the current knowledge on what is reasonable to achieve.
Optimal requirement	This is a level where a product is considered to perform much better than expected given the current knowledge.

Satellite product levels

Satellite-based products are often described as belonging to the following condensed description of processing levels, each one with different complexity and information content:

Level	Description
Level-0	Raw data coming directly from satellite sensors, often described as sensor counts.
Level-1	Data being enhanced with information on calibration and geolocation. Three sub-levels are often referred to: Level-1a: Data with attached calibration and geolocation information Level-1b: Data with applied calibration and attached geolocation information Level-1c: Data with applied calibration and additional layers of geolocation, satellite viewing and solar angle information
Level-2	Derived geophysical variables at the same resolution and location as L1 source data. An often-used Level-2 variety is the following: Level-2b: Globally resampled images, two per day per satellite, describing both ascending (passing equator from south) and descending (passing equator from north) nodes. Resampling is based on the principle that the value for the pixel with the lowest satellite zenith angle is chosen in case two or several swaths are overlapping.

Level-3	Gridded data with results accumulated over time (e.g., monthly means).

A more comprehensive definition of all processing levels is given here: https://www.earthdata.nasa.gov/engage/open-data-services-and-software/data-information-policy/data-levels.

Radiation terms

Since satellite measurements are primarily about radiation measurements in different parts of the spectrum, some definitions or synonyms need to be explained. Roughly, the spectrum is usually sub-divided into one part where solar radiation dominates and one part where radiation emitted by the Earth and the atmosphere dominates.

The solar part is usually referred to as "**visible (VIS)"** radiation and covers approximately wavelengths smaller than 1 µm. Two sub-regions are often referred to, namely "**ultraviolet (UV)"** for radiation below approximately 0.38 µm, and "**near-infrared (NIR)**" for radiation between 0.78 µm and 1 µm (but sometimes claimed to continue up to 2.8 µm).

The part dominated by emitted radiation from the Earth is often referred to as "**thermal**" radiation. Common synonyms used are "**infrared (IR)"** or "**terrestri al**" radiation. Also here, we have several sub-regions defined. The "**short-wave infrared (SWIR)**" region is approximately defined by wavelengths between 1 µm and 2.5 µm. The "**medium-wave infrared (MWIR)**" region is approximately defined by wavelengths between 2.5 µm and 5 µm. The "**long-wave**" region (often simply referred to as just "**infrared**" to represent the bulk majority of radiation emitted by the Earth) defines radiation from approximately 5 µm up to about 1 mm. Radiation above 1 mm up to 10 cm is denoted "**microwave (MW)**" radiation.

Special terms

The term "**AVHRR-heritage**" is frequently used in the TRGAD documents. By this is meant spectral channels of other sensors than the AVHRR which show a close similarity (or heritage) to the AVHRR channels, i.e., having almost the same spectral characteristics.

A product is said to be "**brokered**" when an existing data record from an external source (i.e., not produced exclusively within this C3S project) is handled. This also means that target requirements for these products are set to their achieved validation results since the product was not developed and validated in the C3S project.

We can get a better idea of how accurate the final product values are by using the method of "**error propagation**". It means that the retrieval method is capable of accounting for errors or uncertainties in the measurements or products used to derive the final product, e.g., radiances, input or ancillary data. In this way, the uncertainty of the final products can be estimated.

Radiation fluxes are sometimes described as being "**balanced**". It comes from the fact that instrument uncertainties for radiation budget measurements are often too high to be capable of providing accurate estimations of the net radiation fluxes at the top of atmosphere. Thus, balancing is a form of bias correction based on investigations of energy balance from other observations and model studies.

Calibration of radiances are sometimes described as based on "**vicarious**" methods. This indicates that there is no on-board mechanism on the satellite that provides the necessary calibration information. Consequently, parameters used in calibration equations have to be estimated retrospectively from historic data by use of additional references (e.g., for visible radiances, often Earth surfaces which are considered to be invariant or stable are used as reference targets).

An "**OPeNDAP**" server is an advanced software solution for remote data retrieval (see https://www.opendap.org/).

"**Triple Collocation (TC)"** is a large-scale validation technique by which error variances and data-truth correlation coefficients of three independent datasets can be estimated without a specific reference observation. For further details, see Stoffelen (1998).

Scope of the document

This document provides relevant information on requirements and gaps for a total of three Surface Radiation Budget (SRB) products. Two of these SRB products are based on AVHRR data and one product is based on (A)ATSR and SLSTR data. The first AVHRR-based data record is the CLARA-A2.1 data record (CLARA-A2: CM SAF CLoud, Albedo and Radiation data record – AVHRR based, Edition 2.1) and the second is the CLARA-A2.1 extra data products and their respective ICDR extensions. The third product, the (A)ATSR-based data record, is produced in the ESA CLOUD-CCI project and it is extended with SLSTR based products generated specifically for C3S.

The document is divided into three parts. Part 1 describes the products the present document refers to. Part 2 provides the target requirements for the products. Part 3 provides a past, present, and future gap analysis for the products and covers both gaps in the data availability and scientific gaps that could be addressed by further research activities (outside C3S).

Executive summary

The Surface Radiation Budget products consist of several components which altogether can be combined to give the total net radiation at the surface. If the latter shows a positive result, it means that the surface gains energy, which leads to a warming, while a negative result leads to a cooling. Further, surface radiation can be separated into contributions from different parts of the spectrum. Commonly, a separation into the visible part of the spectrum and the infrared part of the spectrum is applied. This separation defines largely the part where solar radiation dominates (visible) from the part where thermal radiation emitted by the Earth and the atmosphere dominate (infrared). In each of these parts, a net radiation can be calculated which in the end can be combined to give the total net radiation at the surface. A further breakdown of radiation for the two radiation parts of the spectrum is commonly made to isolate incoming radiation to the surface from outgoing radiation from the surface. If combining these two components we get the net radiation at the surface for each particular radiation region.

To summarize, this gives in total the following seven surface radiation products:

1. Incoming solar radiation at the surface
2. Outgoing solar radiation at the surface

3. Net solar radiation at the surface
4. Incoming thermal radiation at the surface
5. Outgoing thermal radiation at the surface
6. Net thermal radiation at the surface
7. Net total radiation at the surface

Notice that solar radiation is often referred to as “shortwave” or “visible” and that “thermal” is also often referred to as “longwave” or “infrared”.

This document describes the Surface Radiation Budget products together with their target requirements and future perspectives. They include three data records:

1. The CLARA-A2.1 data record (CLARA-A2: CM SAF CLoud, Albedo and Radiation data record – AVHRR based, Edition 2.1),
2. The CLARA-A2.1 extra data products and their respective Interim Climate Data Record (ICDR) extensions
3. The ESA (A)ATSR-based v3.0 data record and its Sea and Land Surface Temperature Radiometer (SLSTR)based ICDR extension.

The first two CLARA-A2.1 data records must be combined to cover all seven radiation components above while the third dataset provides all seven radiation components.

The CLARA-A2.1 TCDR comprises 37 years (January 1982-December 2018) of satellite-based climate data records and the subsequent ICDR production covers data from January 2019 to June 2022. The target requirements (expressed as mean absolute error) for the AVHRR-based monthly mean products (from CLARA-A2.1 and extra data products) are set to 10 Wm^{-2}. However, the incoming solar radiation product is also provided as daily means and has a target accuracy of 20 W m^{-2}. Stability requirements are set to 2 $Wm^{-2}dec^{-1}$ for solar radiation products and to 3 $Wm^{-2}dec^{-1}$ for thermal radiation products. Many features of the CLARA-A2.1 extra data products are similar to the ones of CLARA-A2.1. Target requirements for extra data products are therefore same as for CLARA-2.1, 10 Wm^{-2}.

For the ESA Cloud_cci data record, the target requirements are defined by GCOS, and are defined as a mean absolute error of 1 Wm^{-2} for the monthly, global mean surface radiation budget in both shortwave and longwave. Stability requirements are 0.2 $Wm^{-2}dec^{-1}$ for both short- and longwave.

The data record of the (A)ATSR sensors r runs from 2017-2020 at time of writing, with data for 2021 to be delivered shortly, with six-monthly extensions to delivered thereafter. The SLSTR-based ICDR data record runs from Jan 2017 to Jun 2022 from Sentinel-3A and with additional Sentinel-3B data beginning in Oct 2018. . Options for filling the four-year gap between the end of the AATSR data record and the beginning of the SLSTR record are also provided. A key advantage of the (A)ATSR and SLSTR data (compared to AVHRR) is that the data are highly stable, both in terms of satellite orbital parameters and instrument calibration, at the cost of temporal coverage and instrument swath width.

An extensive description of past, current and future availability of data from the Advanced Very High Resolution Radiometer (AVHRR) and the (A)ATSR + SLSTR data records is given in the Gap Analysis part of this document. In addition, future prospects of utilizing AVHRR-heritage spectral channel data from new imaging sensors on new satellites are described.

It is concluded that the AVHRR-based observations series, based on one morning and one afternoon orbit constellation, can be prolonged to reach at least 60-year duration if adding AVHRR-heritage information. However, for this to become realized, efforts are needed to harmonize and homogenize observations between true AVHRR data and AVHRR-heritage data. This concerns both calibration aspects and spatial resolution aspects. Further developments of surface radiation products are required in particular over bright surfaces, i.e., deserts and polar snow- and ice-covered areas. Work is also needed for a better characterization of conditions with high solar zenith angles and for improved estimates of fluxes under cloudy conditions. A future continuation of active observations from space is judged as crucial for further development of retrieval methods based on AVHRR-heritage data.

Regarding the future availability of SLSTR data, the goal of the Copernicus Sentinel satellite program (jointly funded by ESA and EU) is to provide high-quality and sustained measurements for climate and environmental monitoring. Consequently, a measurement prolongation beyond the current Sentinel-3A and Sentinal-3B satellites is planned for with two more satellites (Sentinel 3C and Sentinel 3D).

1. Product description

A detailed description of the surface radiation thematic climate data records (TCDRs) follows below. They basically provide the following general set of surface radiation products which together give a complete picture of the surface radiation budget:

1. Incoming solar radiation at the surface
2. Outgoing solar radiation at the surface
3. Net solar radiation at the surface
4. Incoming thermal radiation at the surface
5. Outgoing thermal radiation at the surface
6. Net thermal radiation at the surface
7. Net total radiation at the surface

Notice that each TCDR might use different notations or acronyms for each individual radiation product in this list.

The following TCDRs make use of data from three different sensors:

1. The Advanced Very High Resolution Radiometer (AVHRR)
2. The Advanced Along Track Scanning Radiometer (AATSR)
3. The Sea and Land Surface Temperature Radiometer (SLSTR)

1.1 AVHRR-based Surface Radiation Products

1.1.1 Licensing overview for the AVHRR-based Surface Radiation Budget Products

The AVHRR-based Surface Radiation Budget Products available via the C3S are a combination of both brokered products and those produced within the C3S project itself. The brokered products are from the EUMETSAT Satellite Application Facility on Climate Monitoring (CM SAF). Table 1-1 provides a comprehensive overview of all current datasets and licence owners. This separation into two datasets is necessary to keep the origin of the data, e.g. licence affiliations: "*EUMETSAT's CM SAF*" and *"Copernicus"*, clear for individual products.

The individual product names in Table 1-1 are the Surface Incoming Shortwave radiation (SIS, representing general product 1 in the list above), the Surface Downwelling Longwave radiation (SDL, product 4 in the list), the Outgoing Longwave Radiation (OLR, product 5 in the list), the Surface Reflected Shortwave Radiation (SRS, product 2 in the list) and Net Fluxes represent the shortwave, longwave and total net radiation at the surface (i.e., products 3, 6 and 7 in the list).

For the purposes of providing a complete picture of the surface radiation conditions, we will combine two data records: Surface Radiation Budget AVHRR CLARA (1) TCDR v2.0+ ICDR v2.x (known as the brokered CLARA-A2.1 TCDR) and the Surface Radiation Budget AVHRR (2) TCDR v2.0 + ICDR v2.x (known as CLARA-A2.1-extra data products). The two data records are combined into one group called the "CLARA product family".

Table 11: Licence overview of the CLARA product family Surface Radiation Products, including products SIS, SDL, SOL, SRS and Net Fluxes. Products marked in blue are taken from the CLARA-A2.1 TCDR and the remaining products are Extra Data Products produced in the C3S project.

Period	**CDR Type**	**CLARA Product Family**			
		CLARA-A2.1		Extra Data Products	
		SIS	**SDL, SOL** Longwave fluxes	**SRS**	**Net Fluxes**
1982 – 2018	TCDR	CM SAF	CM SAF	C3S	C3S
01/2019 – 06/2022	ICDR	CM SAF	C3S	C3S	C3S

The extra data products are not included in the CLARA-A2.1 dataset and are calculated specifically within the C3S project as complimentary data for enabling the description of the full surface radiation budget. Notice also that the SDL and SOL products for the ICDR could not be provided by CM SAF because of computer environment limitations in producing all products in the ICDR version of CLARA-A2.1. Once again, we repeat that combining all variables in the "CLARA product family" group logically combines all variables which are needed for the full description of the Energy Budget at the surface.

As mentioned above, the longwave fluxes (SDL, SOL) are not currently produced by the CM SAF for inclusion in the ICDR. To ensure the dataset integrity and continuity, they are calculated within the C3S for inclusion in the ICDR using algorithms developed by CM SAF. As such, the longwave fluxes change their licence affiliation, namely they are provided within the C3S project for the ICDR part (2019-2020) and are brokered from EUMETSAT's CM SAF for the TCDR part (1982 to 2018).

1.1.2 CLARA-product family

The CLARA-A2.1 TCDR comprises 37 years (January 1982 - December 2018) of satellite-based climate data records derived from the measurements of the Advanced Very High Resolution Radiometer (AVHRR) onboard the polar orbiting NOAA and METOP satellites. The subsequent ICDR production covers data from January 2019 to June 2022. Table 1-2 provides an overview of successive AVHRR sensors onboard dedicated platforms that are included in the generation of the CLARA-A2.1 dataset. The brokered CLARA-A2.1 TCDR and the subsequent ICDR are provided on a regular global latitude-longitude grid with a spatial resolution of 0.25° x 0.25°.

Table 12: Different AVHRR versions and the lifetime of AVHRR on different platforms. The middle row for AVHRR/3 describes the satellites operated by NOAA and the bottom row the satellites operated by EUMETSAT.

<table>
<tr><th>Sensor</th><th>Number of channels</th><th colspan="12">Platform/Lifetime</th></tr>
<tr><td>AVHRR/2</td><td>5</td><td></td><td></td><td></td><td colspan="5">NOAA-7,9,11,12,14</td><td colspan="2">1982-2002</td><td></td><td></td></tr>
<tr><td>AVHRR/3</td><td>6</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="2">NOAA-15,16,17,18,19</td><td colspan="2">1998-onward</td></tr>
<tr><td>AVHRR/3</td><td>6</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="2"></td><td colspan="2">MetOp-A, B, C</td><td>2006-onward</td></tr>
</table>

The retrieval of the shortwave surface radiation parameters is based on an estimation of the atmospheric transmission and the associated reflected irradiance at the surface. The retrieval of the longwave surface radiation parameters is based on the cloud information from a combination of CLARA-A2.1 cloud products, reanalysis data and topographic information.

All products are provided as monthly means, and SIS as both monthly and daily means. Table 1-3 shows the association between product names and Climate and Forecast Convention (CF) Standard names used in the Climate Data Store (CDS). The CF convention is an effort to create an international standard regarding the naming of geophysical products (see https://cfconventions.org/). Product names are included in the netCDF files as "long_names", and CF names as "standard_names". The table also indicates the links to the general surface radiation terms given in the beginning of Section 1.

Table 13: Association table of original CLARA product names and CF Standard names used in the CDS (Climate Data Store). In the first column, product acronyms are given in parenthesis together with corresponding positions in the list of general radiation components provided in the beginning of Section 1.

CLARA Long Names	**CF Standard names**
Surface Incoming Shortwave Radiation (SIS, 1)	Surface downwelling shortwave flux
Surface Downwelling Longwave Radiation (SDL, 4)	Surface downwelling longwave flux
Surface Outgoing Longwave Radiation (SOL, 5)	Surface upwelling longwave flux
Surface Reflected Shortwave (SRS, 2)	Surface upwelling shortwave flux

Surface Net Shortwave Radiation (SNS, 3)	Surface net downward shortwave flux
Surface Net Longwave Radiation (SNL, 6)	Surface net downward longwave flux
Surface Radiation Budget (SRB, 7)	Surface net downward radiative flux

AVHRR Global Area Coverage (AVHRR GAC) data is the fundamental climate data record (FCDR) used for generation of the seven Surface Radiation Budget datasets, that are presented in the following sub-sections. The detailed description of the algorithm used to generate AVHRR GAC is given in CM SAF ATBD Cloud Products [D5], Section 4.3. Further information on the specific input and auxiliary data can be found in the Algorithm Theoretical Basis Document (ATBD) for this dataset [D1].

More specific descriptions of all surface radiation products for the CLARA family follows in the next sub-sections.

1.1.2.1 Surface Incoming Shortwave Radiation (SIS)

The set of input and auxiliary data used to generate SIS are given in CM SAF ATBD [D1], Section 2.1.1.x. A flow-chart that summarizes all processing steps is given in CM SAF ATBD [D1], Figures 2-1 and 2-2.

Under the conditions of snow-covered surface and in regions with varying surface albedo, the surface incoming shortwave radiation dataset performs poorly in comparison to the reference datasets. Grid points in such areas are masked out. Thus, no data is available for large parts of the polar regions. Another aspect of the algorithm to derive the monthly averages is that it requires a minimum of 20 observations per month. In the period 1982–1991, when only afternoon satellites with AVHRR instruments were operational, some parts of the globe did not have the required number of observations per months, resulting in gaps in the spatial coverage. Moreover, in the case of instrument errors or satellite transitions, the period from 1982 to 2003 is influenced by measurement gaps of one or more AVHRR instruments, resulting in a reduced accuracy estimation of daily and monthly radiation fluxes.

A full list of the known limitations and their implications for SIS are described in CM SAF ATBD [D1] Chapter 2.1.1.4. In summary, these are:

- Limitation due to the temporal resolution of surface albedo
- Uncertainty under cloudy conditions, especially with thin clouds
- Uncertainties in the cloud-detection algorithm
- Application of monthly climatological aerosol information instead of the real time data

1.1.2.2 Surface Downwelling Longwave Radiation (SDL)

The algorithm used to generate the SDL dataset is described in CM SAF ATBD [D1] Section 2.2.1.

The known limitations and their implications for SDL are described in CM SAF ATBD [D1] Section 2.2.1.3. These are:

- Underestimation of inter-annual cloud cover variability due to linear regression
- Limited topographic correction by using constant values (i.e., -2.8 Wm^{-2} per 100 m elevation).

1.1.2.3 Surface Outgoing Longwave Radiation (SOL)

The algorithm used to generate the SOL dataset is described in CM SAF ATBD [D1] Section 2.2.2.

The known limitations and their implications for SOL are described in CM SAF ATBD [D1] Section 2.2.2.1. These are:

- Assumption of dry-adiabatic temperature gradient for topographic correction
- Predefined emissivity depending on land type classes ignoring soil moisture

1.1.2.4 Surface Reflected Shortwave Radiation (SRS)

The SRS product is generated from the Surface Incoming Shortwave radiation (SIS) from the Surface Radiation Budget brokered from EUMETSAT's CM SAF CLARA-A2.1 [D10] and the Surface Albedo (SAL) from the CLARA-A2.1 dataset (monthly means).

The set of input and auxiliary data used to generate the SIS is given in CM SAF ATBD Surface Radiation Products [D1], Section 2.1.1. The set of input and auxiliary data used to generate the SAL is given in CM SAF ATBD Surface Albedo [D11], Section 5.1.

1.1.2.5 Surface Net Shortwave Radiation (SNS)

The SNS product is also generated from the SIS and the SAL monthly means.

The set of input and auxiliary data used to generate the SIS is given in CM SAF ATBD Surface Radiation Products [D1], Section 2.1.1. The set of the input and auxiliary data used to generate the SAL is given in CM SAF ATBD Surface Albedo [D11], Section 5.1.

1.1.2.6 Surface Net Longwave Radiation (SNL)

The SNL product is generated from the Surface Downwelling Longwave radiation (SDL) and the Surface Outgoing Longwave radiation (SOL) brokered from EUMETSAT's CM SAF CLARA-A2.1 [D10].

The set of input and auxiliary data used to generate the SDL is given in CM SAF ATBD Surface Radiation Products [D1], Section 2.2.1. The set of input and auxiliary data used to generate the SOL is given in CM SAF ATBD Surface Radiation Products [D1], Section 2.2.2.

1.1.2.7 Surface Radiation Budget (SRB)

The SRB product is composed as the sum of SNL and SNS.

1.2 The Surface Radiation Budget TCDR CCI_AATSR v3.0 + ICDR CCI_SLSTR v3.1.1-v4.0

This section describes the surface radiation products of the TCDR CCI_AATSR v3.0 data record, which we will refer to as Cloud_cci v3, and its extension with the same retrieval scheme applied to the Sea and Land Surface Radiometer (SLSTR), which is produced specifically for C3S.

The Cloud_cci v3 data record is based on Along-Track Scanning Radiometer 2 (ATSR-2) and Advanced Along-Track Scanning Radiometer (AATSR) observations onboard the ESA 2nd European Research Satellite (ERS-2) and ENVISAT satellites. Together, the data record provided by these two instruments is often abbreviated to (A)ATSR. The SLSTR instrument, which is the successor to (A)ATSR, is on board the Copernicus Sentinel-3 platform [D 13].

The SLSTR instrument was designed as the operational successor to the (A)ATSR instruments, using the same measurement principles and techniques, improving them based on the experience gained with the (A)ATSRs, and continuing the 17-year data record provided by ATSR-2 and AATSR (21 years if ATSR-1 is included). Unfortunately, the development time of the Copernicus Sentinel satellites and the demise of ENVISAT in 2012, broke the continuity of this dataset, with an almost five-year gap between the end of the AATSR record and the availability of SLSTR. Despite this, SLSTR products can be considered an ICDR extension of the (A)ATSR TCDR, for the following reasons:

1. The (A)ATSR and SLSTR instruments were conceived with the goal of creating long-term data records for climate monitoring. Consistency and stability are at the core of their design.
2. The instruments are very similar – SLSTR provides a wider swath, some additional channels, increases the spatial resolution of the shortwave channels and alters the viewing geometry compared to (A)ATSR. But the differences in the instrument and orbital characteristics between AATSR and SLSTR are comparable to those between ATSR-2 and AATSR.
3. There are two SLSTR instruments, one onboard Sentinel-3A and -3B respectively. If data from both platforms are included in producing level-3 products, SLSTR provides almost global coverage twice daily (from both the daytime and night time overpasses). The v4.0 SLSTR data is just such a product, while v3.1.1 provides data from each instrument separately.

Observations are available on a 1x1 km grid, which closely matches the true instrument spatial resolution globally and the final CDR is compiled in a regular global grid with 0.5° latitude-longitude resolution for monthly averages. The covered time period of the Cloud_cci data record ranges from June 1995 to April 2012. SLSTR products from Sentinel-3A begin in January 2017, with Sentinel-3B products beginning in October 2018. At the time of writing SLSTR data from both platforms is available up to June 2022, with data for 2022 to be published shortly.

Cloud_cci products were based on the third reprocessing of the AATSR-multimission archive (denoted collection 3), which included vicarious calibration of the shortwave channels over the entire data record to correct for long-term calibration drift (Smith, 2012). SLSTR products are based on collection 3 of the non-time critical (NTC) SLSTR level 1 archive. NTC products are products delivered with a latency of 1 month or longer.

The Cloud_cci v3 data record was produced using the Community Cloud for Climate (CC4Cl) processing chain, which is based on the Optimal Retrieval of Aerosol and Cloud (ORAC) retrieval scheme, both of which are described in detail in [D14, D15] and by Sus et al. (2018) and McGarragh et al. (2018).

In addition to being based on (A)ATSR radiances, the Cloud_cci CC4Cl processing chain makes use of the following auxiliary datasets:

- USGS Digital Elevation Map (USGS, 1996)
- ERA-Interim surface and atmospheric profile temperatures and pressure (Dee et al., 2011)
- ERA-Interim profiles of moisture content and Ozone concentrations (Dee et al., 2011)
- ERA-Interim snow depth and albedo (Dee et al., 2011)
- National Snow and Ice Data Center (NSIDC) Near-real-time Ice and Snow Extent (NISE) sea ice concentration (Brodzik and Stewart, 2016).
- ERA-Interim 10 m u and v wind components (Dee et al., 2011).
- MODIS-based land surface bidirectional reflectance distribution function (BRDF) data (MCD43C1 Collection 6, (Schaaf and Wang, 2015).
- Land surface emissivity from the Cooperative Institute for Meteorological Satellite Studies (CIMSS) “Baseline Fit” database.
- Solar and Heliospheric Observatory (SOHO) and Solar Radiation and Climate Experiment (SORCE) incoming total solar irradiance.

For Level-1 data outside the temporal coverage of the above auxiliary datasets (for example, ATSR-2 data prior to the 1999 launch of MODIS products), climatologies based on the above auxiliary datasets are used. In the case of the SLSTR ICDR, ERA-5 data is used rather than ERA-Interim (for details, see [D14]).

The seven surface radiation parameters provided to C3S from the Cloud_cci v3 dataset and SLSTR are the same as those provided by the AVHRR products described in section 1.1.2 and they have similar limitations.

2. User Requirements

This section describes the requirements which have been set to be achieved by the described products. Requirements can be set at different levels (as explained in the section with General definitions) but here we will focus on what is called the Target Requirements. These requirements define the main goals for data producers which have to be fulfilled by their products. Requirements are specified by the use of various accuracy parameters which are also listed in the section with General definitions. Observe that for brokered products the target requirements are set to the achieved validation results since these products are not developed and tested within the C3S project.

Concerning products to be used in climate monitoring, requirements for what should be achievable through Earth Observation systems are generally defined by the World Meteorological Organisation (WMO) Global Climate Observation System (GCOS) expert panel. However, these requirements are generally oriented towards the capability and resolution of climate models with a rather course spatial resolution while many products listed here are focusing more on the monitoring of local and regional scale conditions. Also, they are often not attainable using existing or historical observing systems. Thus, GCOS requirements are not always identical to the requirements listed here since also other user groups than the climate modelling community have contributed in setting the requirements. However, the relation to GCOS requirements are discussed below for each individual product. Notice also that the GCOS requirements are not specified for all products described in this document.

2.1 CLARA product family

2.1.1 Summary of target requirements (Key Performance Indicators – KPIs)

This report covers the following products from CLARA family: the SIS, the SDL, the SOL, the SRS, the SNS, the SNL and the SRB. The predefined requirements for the SIS, the SOL and the SDL are given in CM SAF Product Requirement Document (PRD) [D4], Annex A. The same requirements are applied for the remaining (or extra products) ensuring that the net radiation requirement is the same as for the three mentioned products (i.e., no radiation component is allowed to have a larger absolute error than the net radiation products). The validation of the three core surface radiation datasets was conducted against surface measurements from the Baseline Surface Radiation Network (BSRN) (Ohmura et al., 1998).

There are three accuracy categories in the CM SAF PRD document ([D4], Section 5): threshold, target and optimal accuracies (see General definitions for a detailed description). They are defined keeping in mind different target users: operational climate monitoring, global and regional climate modelling and global and regional climate studies.

The CLARA-A2.1 surface radiation products are brokered from the CM SAF project, and consequently cannot be altered in this C3S project Therefore, the current target requirements on the key performance of the data set, measured within C3S by the so-called Key Performance Indicators (KPIs), are defined as the requirements achieved (with original requirements described in D3 and D4) in previous CLARA-A2.1 validation activities in CM SAF. These values are listed in Table 2-1.

Table 21: Key Performance Indicators (KPIs) or target requirements for surface radiation products.

Variable	KPI: accuracy Wm^{-2} (mean absolute error) Fulfilled by CLARA-A2.1 CDR	KPI: decadal stability, $Wm^{-2}decade^{-1}$ Fulfilled by CLARA-A2.1 CDR
SIS Monthly mean (MM)	9.5 Wm^{-2}	2 $Wm^{-2}decade^{-1}$
SIS Daily mean (DM)	18.6 Wm^{-2}	2 $Wm^{-2}decade^{-1}$
SDL MM	8.1 Wm^{-2}	3 $Wm^{-2}decade^{-1}$
SOL MM	13.8 Wm^{-2}	3 $Wm^{-2}decade^{-1}$
SRS MM	7.8 Wm^{-2}	3 $Wm^{-2}decade^{-1}$
SNS MM	13.0 Wm^{-2}	3 $Wm^{-2}decade^{-1}$
SNL MM	21.9 Wm^{-2}	3 $Wm^{-2}decade^{-1}$
SRB MM	34.9 Wm^{-2}	3 $Wm^{-2}decade^{-1}$

At the time (~2010) when requirements for the CLARA-A2 data record were defined, as described in [D4], there was no guidance available for surface radiation products in the available GCOS-107 document [D6]. Instead, requirements had to be set based on a dialogue with experts and potential users (e. g., in association with CM SAF User Workshops).

For the evaluation of the ICDR, corresponding products from the ground-based BSRN measurements are used as reference. The distribution of the global differences between BSRN products and the CLARA-A2.1 TCDR has been compiled and the corresponding 2.5 and 97.5 percentile differences are given in Table 2-2. These percentiles are used to check, by means of a binomial test at 5 % significance level, whether the corresponding ICDR differences are consistent with the TCDR differences or not. Further details on these tests are found in the Report on Updated KPIs (D9).

Table 22: Key Performance Indicators (KPIs) for the surface radiation budget ICDR products.

Variable	KPI: lower percentile (2.5 %), Wm^{-2}	KPI: higher percentile (97.5 %), Wm^{-2}
SIS Monthly mean	5.27	14.66
SIS Daily mean	8.21	41.36
SDL Monthly mean	5.11	11.63
SOL Monthly mean	8.12	25.84

2.1.2 Discussion of requirements with respect to GCOS and other requirements

The product requirements listed in the CM SAF Product Requirement Document [D4] for the CLARA-A2.1 data record were generally defined in accordance with the GCOS report GCOS-107 [D6]. However, since this version of the GCOS document did not yet include requirements for the Surface Radiation ECV, some CM SAF-specific requirements had to be defined and used as explained above in section 2.1.1. A comparison between original GCOS requirements and achieved CLARA-A2 results is given in Table 2-3.

Table 23: GCOS-200 requirements for surface radiation products compared to CLARA-A2.1 requirement.

Requirements	GCOS (Target)	CLARA-A2.1 TCDR + ICDR v2.x
Spatial resolution	100 km	25 km

Temporal resolution	Monthly (resolving diurnal cycle)	Monthly
Accuracy:		
SIS MM	1 Wm^{-2}	9.5 Wm^{-2}
SIS DM	1 Wm^{-2}	18.6 Wm^{-2}
SDL MM	1 Wm^{-2}	8.1 Wm^{-2}
SOL MM	1 Wm^{-2}	13.8 Wm^{-2}
SRS MM	1 Wm^{-2}	7.8 Wm^{-2}
SNS MM	1 Wm^{-2}	13.0 Wm^{-2}
SNL MM	1 Wm^{-2}	21.9 Wm^{-2}
SRB MM	1 Wm^{-2}	34.9 Wm^{-2}

New GCOS requirements for the ECV Surface Radiation Budget are summarized in GCOS-200 [D7] and include requirements for the horizontal resolution, temporal resolution, accuracy and stability. However, these requirements are only valid for the net fluxes (i.e., SNS and SNL) and not for all individual radiation budget components (see Table 2-4 below). However, one could claim that individual radiation budget components should consequently be constrained in the same way as net fluxes.

All products in the brokered CLARA-A2.1 dataset fulfil the new GCOS requirements regarding the horizontal and temporal resolution. However, the SNS and SNL products do not fulfil the new requirements on accuracy and stability which are very stringent compared with previously used requirements for the CLARA data record. Nevertheless, achieved accuracy and stability results allow consistent quantification of mean values, anomalies, variability and the Earth energy budget in general. Existing uncertainties in the methodology of comparison with area-to-point measurements (i.e. satellite-area to point-ground-based reference networks) are important reasons for not fulfilling the new requirements (as discussed by Schwarz et al., 2017).

2.1.3 Data format and content issues

Information on the file format is provided in the CM SAF Product User Manual (PUM) [D2] Section 4. The CLARA A-2.1 surface radiation products are defined using standard data formats (netCDF4) and map projections (regular latitude/longitude). Meta data and naming definitions follow the Climate & Forecast (CF) conventions (https://cfconventions.org).

Based on the recommendations formulated within C3S_312b Lot1, the license field was added to all the netCDF-files that are brokered and produced. The goal is to provide a clear identification of the data record producer.

2.2 The Surface Radiation Budget TCDR CCI_AATSR v3.0 + ICDR CCI_SLSTR v3.1.1+v4.0

2.2.1 Summary of target requirements

The GCOS expert panel defines and lays down targets for the observation of ECVs (Table 2-4).

The Cloud_cci product, and the SLSTR extension, achieve or exceed the frequency and resolution requirements, with the exception of resolving the diurnal cycle, which is not possible with a single low-Earth-orbit platform. The GCOS accuracy target of 1 Wm-2 is not met by the Cloud_cci/SLSTR products, however it should be noted that GCOS requirements are targets for what should be achievable through Earth observation and are often not attainable using existing or historical observing systems. GCOS only defines targets for the net-radiation fluxes, but as these are simple sums of the up- and down-welling fluxes, they provide target constraints for the entire suite of surface radiation parameters provided by the Cloud_cci products.

Table 24: Target requirements for surface radiation budget defined by GCOS-200 ([D7], Table 23, page 279].

GCOS quantity	Corresponding Cloud_cci variable	GCOS targets
Surface ERB longwave	Surface net longwave radiation (SNL)	• Frequency: Monthly (resolving diurnal cycle) • Resolution: 100 km • Measurement uncertainty: 1 Wm^{-2} on global mean • Stability: 0.2 $Wm^{-2}dec^{-1}$
Surface ERB shortwave	Surface net solar radiation (SNS)	• Frequency: Monthly (resolving diurnal cycle) • Resolution: 100 km • Measurement uncertainty: 1 Wm^{-2} on global mean • Stability: 0.2 $Wm^{-2}dec^{-1}$

2.2.2 Key Performance Indicators - KPIs

Similar to the CLARA-A2.1 products, the Cloud_cci (A)ATSR products are brokered products (but in this case from the ESA CCI programme) and cannot be altered within the scope of C3S_312b_Lot1 and C3S2_312a_Lot1. Table 2-5 shows the target requirements based on earlier validation results. The performance of the ESA-CLOUD-CCI product was assessed against ground-based radiation measurements of downwelling flux from the Baseline Surface Radiation Network (BSRN) for surface incoming shortwave radiation (SIS) and surface downwelling longwave radiation (SDL), while the other parameters were compared to values derived from the CERES SRB CDR. Stability figures were only calculated for SIS and SDL comparisons, where ground-truth data is available.

Table 25: Key performance indicators (KPIs) or target requirements (i.e. fulfilled requirements by the ESA-CLOUD-CCI project) for surface radiation products from ESA_CCI_AATSR TCDR v3.0.

Variable	KPI: accuracy (Bias) Fulfilled by ESA-CLOUD-CCI	KPI: decadal stability Fulfilled by ESA-CLOUD-CCI
SIS	8.2 W/m^2	0.97 W/m^2/decade
SDL	12 W/m^2	2.76 W/m^2/decade
SRS	4.6 W/m^2	-
SNS	13 W/m^2	-
SOL	11 W/m^2	-
SNL	23 W/m^2	-
SRB	36 W/m^2	-

The Cloud_cci (A)ATSR data record forms the basis for the calculation of KPIs for the SLSTR based ICDR. The KPIs for the SRB products are based on comparison against the NASA Clouds and the Earth's Radiant Energy System (CERES) instruments (Wielicki et al., 1996). These comparisons are represented as the 2.5 and 97.5 percentiles of the distribution of differences between (A)ATSR or SLSTR monthly-mean values and the corresponding CERES values (corrected for the mean seasonal cycle). These values, calculated from the 12-year (A)ATSR CDR are summarized in Table 2-6.

It should be noted that CERES surface radiation values are a product of a similar level of processing, based on knowledge or assumptions of the atmospheric state, as those produced from the CC4Cl retrieval scheme. Thus, CERES should not be considered as a more accurate estimate of SRB than the Cloud_cci CDR. However, significant effort has gone into ensuring the stability and consistency of the CERES products, making them suitable for monitoring the relative performance of the Cloud_cci products and their extension with SLSTR.

Table 26: Key performance indicators (KPIs) for the Cloud_cci SRB record, applied to the SLSTR ICDR data.

Variable	KPI: lower percentile (2.5 %), Wm^{-2}	KPI: higher percentile (97.5 %), Wm^{-2}
SIS Monthly mean	-1.3	2.12
SRS Monthly mean	-0.45	0.36
SDL Monthly mean	1.95	2.23
SOL Monthly mean	-4.04	3.68

2.2.3 Discussion of requirements with respect to GCOS and other requirements

A discussion on these requirements has already been provided in section 2.2.1 (related to Table 2-4).

2.2.4 Data format and content issues

The Cloud_cci v3 cloud property products are defined using standard data formats (netCDF) and map projections (regular latitude/longitude grids). Meta data definitions follow the Climate & Forecast conventions (http://cfconventions.org/).

3. Gap Analysis

3.1 Description of past, current and future satellite coverage

3.1.1 CLARA product family

The surface radiation and cloud products belong to the CLARA-A2.1 datasets. These two datasets make use of the same instruments, installed on the same satellites. A full presentation of the AVHRR sensor and relevant satellites can be found in the C3S2_D3.1.1-2021-CLD, Section 3.1.1 Cloud properties TCDR AVHRR CLARA v2.0 + ICDR v2.x [D8].

Known data gaps

Monthly dataset:

- February 1985

Daily dataset:

- 1982-05-29–1982-05-31
- 1982-09-25–1982-09-26
- 1983-07-27–1983-08-02
- 1983-08-06
- 1983-09-21–1983-09-26
- 1984-01-14–1984-01-15
- 1984-07-23
- 1984-12-06
- 1985-02-03–1985-02-24
- 1986-03-15

3.1.2 (A)ATSR-based Surface Radiation Products and its SLSTR-based ICDR extension

The Cloud_cci v3 is based on radiances provided by the ATSR series of sensors. These instruments flew on sun-synchronous polar orbiting satellites with daytime equatorial crossing times in the mid-morning; 10:30 Local Time on Descending Node (LTDN) for ATSR-2 and 10:00 LTDN for ENVISAT, with both satellites sharing the same ground track. There were 14.3 orbits per day, meaning 28 equatorial overpasses per-day, with measurements covering a total of 18% of equatorial circumference of the Earth (with equally spaced 512 km swaths). The observation frequency increased at higher latitudes (with a maximum of 14 observations per day at the poles) due to increasing overlaps between the satellite swaths. Both sensors provided the same seven channels (and used the same conical dual-viewing geometry), but not all channels were provided at all times, or at full digitization rate, from ATSR-2, due to limitations of the data bandwidth provided by the ERS-2 platform. Over ocean regions, ATRS visible channels were often only provided in a 256 pixel “narrow-swath” mode. The channels provided by both instruments were centred at 0.55, 0.67, 0.87, 1.6, 3.7, 10.8, 12.0 m and the filter band passes were very similar between instruments. Despite the low-data rate modes of ATSR-2, the combination of the very similar instrument specifications, very close orbital parameters and the lack of any significant orbital drift in the ERS-2 and ENVISAT satellites mean that ATSR-2 and AATSR provide a highly consistent data record, especially when compared to that provided by the AVHRR record used by the CLARA-A2 TCDR (although AVHRR provides a much longer data record).

The TCDR from Cloud_cci v3 begins with the launch of ERS-2 in mid-1995 and continued until the failure of ENVISAT in April 2012. Due to instrument problems, there is a six-month data gap in the ATSR-2 record from January to June 1996.

There is an overlap of 1 year of data between the two platforms, between mid-2002 (when ENVISAT was launched) and mid-2003 (when the onboard data storage on ERS-2 failed). There is additional ATSR-2 data available up-to 2009, but this is not global as data could only be collected when the satellite was within line-of-sight with a ground receiving station, and has not been included in the TCDR. There is some scope to push the coverage of the ATSR cloud record back to 1991, by using the ATSR-1 instrument (onboard ERS-1), which also flew in a similar orbit to its successors. However, ATSR-1 lacked the shortwave channels (apart from the 1.6 m) channel, which would reduce the information available to daylight retrievals and would represent a significant inhomogeneity in the TCDR.

The extension of the ATSR TCDR (i.e., the SLSTR ICDR) makes use of SLSTR sensors onboard the Sentinel-3 platforms. SLSTR represents a significant upgrade over (A)ATSR, providing a wider swath, two satellites within interleaved orbit swaths, additional channels and the data available security of an operational system. The Sentinel-3s have a very similar orbit to ENVISAT and the ERS satellites, with a sun-synchronous orbit with an LTDN of 10:00, and 14.3 orbits per-day. However, there is slightly longer than a 4-year gap between the end of the (A)ATSR record and the first SLSTR data. There are several options available to fill this gap, as ORAC can be applied to most radiometers with similar channels to those provided by ATSR. Indeed, cloud CDRs of ORAC applied to both MODIS and AVHRR already exist, having been produced in the Cloud_cci program, but have not been brokered to the CDS.

We suggest that addressing the (A)ATSR/SLSTR data gap, by linking the two datasets with a third source of data which overlaps with each should be a priority for Copernicus, and would likely be readily achievable given the necessary support. There are several datasets which provide similar measurements to the (A)ATSR/SLSTR SRB dataset (including the other C3S products discussed in this report) and which overlap both (A)ATSR and SLSTR temporally. Such data could be used to assess the consistency of the (A)ATSR TCDRs and SLSTR ICDRs, but this remains to be done for the SRB dataset.

It should also be noted that ORAC could be applied to the VIIRS and MetImage instruments described above, which could complement the SLSTR ICDR.

Regarding the future availability of SLSTR data, a measurement prolongation beyond the current Sentinel-3A and Sentinal-3B satellites is planned with two more satellites (Sentinel 3C and Sentinel 3D, which are scheduled for launch in 2024 and 2028, respectively).

3.2 Development of processing algorithms

The surface radiation and cloud products belong to the CLARA-A2.1 TCDR and use the same satellite sensors from the AVHRR-family. Thus, the pre-processing methods are the same for these two datasets, thereby ensuring the quality checks and corrections of the radiances and a homogeneity of the input data series. A full description of these issues can be found in the C3S2_D3.1.1-2021-CLD, Section 3.2.1 Cloud properties TCDR AVHRR CLARA v2.0 + ICDR v2.x [D8]. Specific issues and research needs of the surface radiation datasets are described later in this document (Section 3.5).

3.2.1 CLARA product family

The Surface Downwelling Longwave and Surface Outgoing Longwave Radiation products use the ERA-Interim data to define the surface downwelling longwave fluxes and the surface temperature (needed to calculate the Outgoing Longwave Radiation), respectively. When ERA-Interim was discontinued in 2019, operational analyses from the ECMWF Integrated Forecasting System (IFS) model was used as replacement.

3.2.2 (A)ATSR-based Surface Radiation Products and their SLSTR-based ICDR extension

As with the CLARA CDRs, the stability and quality of the input data is the key parameter which influences the reliability of the Cloud_cci v3 CDRs. The (A) ATSR TCDR is based on version 3 of the "AATSR multimission archive" maintained by Center for Environmental Data Analysis (CEDA) and the UK National Earth Observation Data Centre (NEODC). This record incorporates the latest calibration corrections (including long-term drift corrections from vicarious calibration) and represents the most consistent and accurate record of radiances from the (A)ATSR record. A future update to this record would make a reprocessing of the Cloud_cci TCDR possible.

In the case of the SLSTR ICDR, the status of the level 1 radiances is considerably less stable. Data from early in the SLSTR record has considerably worse calibration and geolocation than more recent data. When a fully reprocessed version of the data record becomes available in the future, regeneration of the cloud ICDR would be possible.

EUMETSAT has provided updated calibration corrections to SLSTR shortwave channels, communicated through the Sentinel-3 Scientific Validation Team (S3VT), which have been applied retrospectively. However, there is not yet any information on the stability of the SLSTR calibration over time and there remain issues with the colocation of SLSTR channels in early versions of the level 1 products.

3.2.2.1 Adaptions of the ORAC scheme to better exploit SLSTR

As mentioned above, SLSTR provides some additional channels over the earlier AATSR instruments. Of particular note is the new 1.3 m channel, which, due to its location in a water-vapour absorption feature, is particularly sensitive to the presence of high-altitude clouds. Utilizing this channel in the retrieval scheme itself is unlikely to be beneficial, as accurate knowledge of the water vapour profile is needed to accurately model the radiances. However, the use of this channel in prior cloud-detection and characterization has been studied under the Cloud_cci+ project and an assessment of its impact on the quality of ORAC cloud retrievals is underway.

3.2.2.2 Forward model improvements

Further improvements to the forward modelling of clouds for the ORAC retrieval scheme are also underway. In particular:

- The SLSTR ICDR makes use of ERA-5, rather than the ERA-Interim used for the TCDR.
- The spectral dependence of cloud scattering and absorption will be modelled across the bandpass of the instrument channels (rather than at the channel centre as previously).
- At present cloud is modelled as an infinitesimally thin layer within an atmosphere modelled by RTTOV. The modelling of cloud geometric thickness effects will also be investigated in the upcoming Cloud_cci+ project.
- The use of new ice cloud optical properties will also be investigated, as these become available.
- Improvements in the propagation of uncertainty from L2 products to gridded L3 products is also under investigation.

3.3 Methods for estimating uncertainties

3.3.1 CLARA product family

The current CLARA-A2.1 products are not associated with any uncertainty estimates. Thus, uncertainty information is only available as results achieved by associated validation activities ([D3]).

3.3.2 (A)ATSR-based Surface Radiation Products and their SLSTR-based ICDR extension

The ORAC retrieval scheme provides propagated uncertainties on the retrieved cloud parameters, but these are not propagated through the broadband flux calculations at present. Thus, no uncertainty estimates are provided in the Cloud_cci SRB products, aside from the standard deviation of the level-2 pixels included in each monthly-mean grid box. Thus, as with CLARA-A2.1 products, uncertainty information is only available through validation activities.

3.4 Opportunities to improve quality and fitness-for-purpose of the CDRs

3.4.1 CLARA product family

The upcoming new edition of the CLARA dataset, CLARA-A3 (to be released in 2023), will cover an extended period from 1979 to 2020. Adding these years to the currently brokered dataset is of great value for climate studies. CLARA-A3 will also provide improved cloud detection and a revised AVHRR calibration. This will lead to an improved quality of surface radiation products for the entire time period covered.

3.4.2 (A)ATSR-based Surface Radiation Products and their SLSTR-based ICDR extension

Most potential improvements to ORAC radiative flux products stem from improvements to the underlying cloud retrieval scheme, which are discussed below.

The planned development of the ORAC retrieval scheme, as applied to (A)ATSR and SLSTR, has already been described in section 3.2.2. ORAC is under active development, both through the ESA CCI+ program and through national UK funding (in particular, under the National Centre for Earth Observation). New improvements of the scheme, where applicable, will be fed through to the production of improved CDR products from SLSTR.

It is also worth noting that the ORAC scheme is not specifically designed for application to (A)ATSR or SLSTR. CDRs have already been produced using the scheme for the AVHRR and MODIS instruments, under previous iterations of the CCI program. The scheme has also been applied to geo-stationary sensors (Spinning Enhanced Visible and Infrared Imager - SEVIRI, GOES Advanced Baseline Imager – ABI and Himawari Advanced Himawari Imager - AHI), and improved application of the scheme to SEVIRI in particular (making use of the water-vapor sounding channels provided by the instrument) is being undertaken in CCI+.

The code includes the ability to utilize sounding channels (CO_2 slicing and water-vapor absorption), as well as a multi-layer cloud retrieval mode ([D16]), which greatly improve on the shortcomings of the existing "heritage channel" (AVHRR-like) CDRs produced in CCI, and retrieves the properties of dual-layer cloud scenes. Thus, the scheme provides the scope for the production of cutting-edge CDRs from a wide range of instruments, all with a consistent retrieval approach.

3.5 Scientific Research needs

3.5.1 CLARA product family

3.5.1.1 Surface Incoming Shortwave Radiation (SIS)

The known issue is poor performance of SIS compared with reference datasets in regions with highly-reflecting surfaces. For this reason, studies in relation to snow detection are needed. Additional studies with respect to satellite observations under twilight/dawn conditions could improve the data quality of prior satellite generations.

It should be noted that these and other issues will be tackled and improved in the next revision/version of the CLARA family dataset CLARA-A3.

Furthermore, retrieval of the SIS under the cloudy conditions requires the broadband shortwave flux estimate. In the current version, this conversion is done using two satellite channels. Further investigations are needed on the effect of such a conversion on the retrieved SIS values. The topic has been discussed further by Akkermans et al. (2020).

3.5.1.2 Surface Outgoing Longwave Radiation (SOL)

The topographic correction of the SOL from ERA-Interim is based on the assumption that the surface temperatures are modified with the dry-adiabatic temperature gradient as a function of elevation. This assumption needs to be verified. However, one solution would be to use re-analysis data with better resolution. This will be done in the next CLARA-A3 edition.

Another issue for all satellite measurements is the estimate of the surface emissivity. It is desirable to have routinely updated emissivity estimates. Such data is available and continuously updated from MODIS products and they are likely to be achieved also from new sensors in the future. Thus, this problem can be addressed for more recent datasets but the problem remains for products covering the period before MODIS (i.e., before 2000).

3.5.2 (A)ATSR-based Surface Radiation Products and their SLSTR-based ICDR extension

The requirements for the further improvements of the (A)ATSR and SLSTR CDRs are identical to those for the AVHRR CLARA CDRs.

3.6 Opportunities from exploiting the Sentinels and any other relevant satellite

3.6.1 CLARA product family

Surface Radiation Budget products are brokered without changes. In the current version no information from the Sentinel satellites is used. However, the Surface Radiation Budget ESA SLSTR ICDR v3.x dataset is directly benefiting from the SLSTR instrument installed on the Sentinel-3 series satellites. This instrument has almost identical channels as AVHRR and also some unique channels. This gives a possibility for its use for inter-comparison.

3.6.2 (A)ATSR based Surface Radiation Products and their SLSTR-based ICDR extension

The ESA SLSTR v3.x ICDR directly exploits data from the Sentinel-3 platform. There have been examples shown of utilizing Sentinel-3 OLCI-like measurements (mainly using MERIS on ENVISAT) for cloud retrieval in conjunction with (A)ATSR or SLSTR (Carbajal Henken et al. 2014), but difficulties in cross-calibration and co-registration of the different instruments have meant these products have not shown improved performance over the (A)ATSR /SLSTR only algorithms. The availability of a well co-located and calibrated joint SLSTR-OLCI L1 product, could resurrect this approach to further improving cloud products derived from Sentinel-3 (and the preceding ENVISAT).

As discussed in section 3.1.2, the ORAC retrieval scheme can be, and has been, applied to a wide range of satellite visible-IR imaging radiometers. A particular instrument, of direct relevance to the Sentinel satellite program is the Flexible Combined Imager (FCI) to fly on Meteosat Third Generation /Sentinel-4. This instrument is essentially a replacement for the SEVIRI sensors on MSG, with capabilities similar to those provided by Himawari-AHI and GOES-ABI imagers (which ORAC has already been applied to).

References

Akkermans, Tom, and Clerbaux, N., 2020 : Narrowband-to-broadband conversions for top-of-atmosphere reflectance from the Advanced Very High Resolution Radiometer (AVHRR). Remote Sensing 12, no. 2 (2020): 305.

Brodzik, M. J. and J. S. Stewart. 2016: Near-Real-Time SSM/I-SSMIS EASE-Grid Daily Global Ice Concentration and Snow Extent, Version 5. Boulder, Colorado USA. NASA National Snow and Ice Data Center Distributed Active Archive Center. doi: https://doi.org/10.5067/3KB2JPLFPK3R.

Carbajal Henken, C.K., R. Lindstrot, R. Preusker and J. Fischer, 2014: FAME-C: cloud property retrieval using synergistic AATSR and MERIS observations. Atmos. Meas. Tech., 7, 3873–3890, doi:10.5194/amt-7-3873-2014.

Dee et al. (35 named authors), 2011: The ERA-Interim reanalysis: configuration and performance of the data assimilation system, Quart. J. Royal Met. Soc., 137 (656), 553 - 597. Online version: http://onlinelibrary.wiley.com/doi/10.1002/qj.828/abstract.

McGarragh, G.R.; Poulsen, C.A.; Thomas, G.E.; Povey, A.C.; Sus, O.; Stapelberg, S.; Schlundt, C.; Proud, S.; Christensen, M.W.; Stengel, M.; et al., 2018: The Community Cloud retrieval for CLimate (CC4CL). Part II: The optimal estimation approach. Atmos. Meas. Tech., 11, 3397–3431.

Ohmura, A., et al. (1998), Baseline Surface Radiation Network (BSRN/WCRP): New precision radiometry for climate research, *Bulletin of the American Meteorological Society*, 79(10), 2115-2136.

Schaaf, C. and Wang, Z., 2015: MCD43C1 MODIS/Terra+Aqua BRDF/AlbedoModel Parameters Daily L3 Global 0.05Deg CMG V006, NASA EOSDIS Land Processes DAAC, https://doi.org/10.5067/MODIS/MCD43C1.006.

Schwarz, M., Folini, D., Hakuba, M. Z., & Wild, M., 2017 : Spatial representativeness of surface-measured variations of downward solar radiation. Journal of Geophysical Research: Atmospheres, 122, 13,319– 13,337. https://doi.org/10.1002/2017JD027261

Smith D. 2012: ENVISAT AATSR Instrument Performance – End of Mission Report. Report, accessed 02-Mar-2020: https://atsrsensors.org/pdf/ENVISAT%20AATSR%20Instrument%20Performance%20-%20End%20of%20Mission%20Report%20%20-%20Issue%201.0.pdf

Stoffelen, A., 1998: Towards the true near-surface wind speed: Error modeling and calibration using triple collocation. J. Geophys. Res. 103C3, 7755-7766.

Sus, O.; Stengel, M.; Stapelberg, S.; McGarragh, G.; Poulsen, C.; Povey, A.C.; Schlundt, C.; Thomas, G.; Christensen, M.; Proud, S.; et al., 2018: The Community Cloud retrieval for Climate (CC4CL). Part I: A framework applied to multiple satellite imaging sensors. Atmos. Meas. Tech., 11, 3373–3396.

USGS, 1996: Global 30 arc seconds topography database, GTOPO30, (http://edcdaac.usgs.gov/gtopo30/)

Wielicki, B. A., Barkstrom, B. R., Harrison, E. F., Lee III, R. B., Smith, G. L., & Cooper, J. E.: Clouds and the Earth's Radiant Energy System (CERES): An earth observing system experiment. Bulletin of the American Meteorological Society, 77(5), 853-868, 1996.

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Related articles

- SEC Version 5.0: System Quality Assurance Document (SQAD)
- SEC Version 5.0: Product Quality Assessment Report (PQAR)
- SEC Version 5.0: Product User Guide and Specification (PUGS)
- IV data version 1.5: Product Quality Assurance Document (PQAD)
- IV data version 1.5: System Quality Assurance Document (SQAD)