EUMETSAT Satellite Application Facility on Climate Monitoring

Product User Manual
CM SAF Cloud, Albedo, Radiation data record, AVHRR-based, Edition 3 (CLARA-A3)
Surface Black-sky, White-sky and Blue-sky Albedo

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	TCDR	ICDR
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White-sky albedo from AVHRR-GAC	CM-11223	CM-6223
Blue-sky albedo from AVHRR-GAC	CM-11224	CM-6224

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Applicable Documents

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Reference Documents

Reference	Title	Code
RD 1	Algorithm Theoretical Basis Document CM SAF Cloud, Albedo, Radiation data record, AVHRR-based, Edition 3 (CLARA-A3) Surface Albedo	SAF/CM/FMI/ATBD/CLARA/SAL/3.3
RD 2	SYSTEMATIC OBSERVATION REQUIREMENTS FOR SATELLITE-BASED DATA PRODUCTS FOR CLIMATE - 2011 Update	GCOS-154
RD 3	Validation Report CM SAF Cloud, Albedo, Radiation data record, AVHRR-based, Edition 3 (CLARA-A3) Surface Albedo	SAF/CM/FMI/VAL/CLARA/SAL/3.1
RD 4	Algorithm Theoretical Basis Document CM SAF Cloud, Albedo, Radiation data record, AVHRR-based, Edition 3 (CLARA-A3) Cloud Products	SAF/CM/DWD/ATBD/CLARA/CLD/3.3

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1 The EUMETSAT SAF on Climate Monitoring (CM SAF)

The importance of climate monitoring with satellites was recognized in 2000 by EUMETSAT Member States when they amended the EUMETSAT Convention to affirm that the EUMETSAT mandate is also to “contribute to the operational monitoring of the climate and the detection of global climatic changes". Following this, EUMETSAT established within its Satellite Application Facility (SAF) network a dedicated centre, the SAF on Climate Monitoring (CM SAF, http://www.cmsaf.eu).

The consortium of CM SAF currently comprises the Deutscher Wetterdienst (DWD) as host institute, and the partners from the Royal Meteorological Institute of Belgium (RMIB), the Finnish Meteorological Institute (FMI), the Royal Meteorological Institute of the Netherlands (KNMI), the Swedish Meteorological and Hydrological Institute (SMHI), the Meteorological Service of Switzerland (MeteoSwiss), and the Meteorological Service of the United Kingdom (UK MetOffice). Since the beginning in 1999, the EUMETSAT Satellite Application Facility on Climate Monitoring (CM SAF) has developed and will continue to develop capabilities for a sustained generation and provision of Climate Data Records (CDR’s) derived from operational meteorological satellites.

In particular the generation of long-term data records is pursued. The ultimate aim is to make the resulting data records suitable for the analysis of climate variability and potentially the detection of climate trends. CM SAF works in close collaboration with the EUMETSAT Central Facility and liaises with other satellite operators to advance the availability, quality and usability of Fundamental Climate Data Records (FCDRs) as defined by the Global Climate Observing System (GCOS). As a major task the CM SAF utilizes FCDRs to produce records of Essential Climate Variables (ECVs) as defined by GCOS. Thematically, the focus of CM SAF is on ECVs associated with the global energy and water cycle.

Another essential task of CM SAF is to produce data records that can serve applications related to the new Global Framework of Climate Services initiated by the WMO World Climate Conference-3 in 2009. CM SAF is supporting climate services at national meteorological and hydrological services (NMHSs) with long-term data records but also with data records produced close to real time that can be used to prepare monthly/annual updates of the state of the climate. Both types of products together allow for a consistent description of mean values, anomalies, variability and potential trends for the chosen ECVs. CM SAF ECV data records also serve the improvement of climate models both at global and regional scale.

As an essential partner in the related international frameworks, 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 record assessments performed by research organisations 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, https://www.cmsaf.eu. Here, detailed information about product ordering, add-on tools, sample programs and documentation is provided.

2 Introduction

The purpose of this document is to provide interested users with information on the features, quality and usage of the third edition of the CM SAF cLoud, Albedo and surface RAdiation dataset from AVHRR data – Surface ALbedo (CLARA-A3 SAL) data record of the CM SAF. The first part of the document introduces the product and its significance. The second part discusses the features and quality of the product in more detail, and the third part describes the end user product format.

Surface albedo is one of the factors governing the Earth's radiation budget, which in turn drives the climate of our planet. (Shortwave) Surface albedo is the dimensionless ratio of the reflected (solar) radiation flux to the incoming (solar) radiation flux. It has been designated as one of the Essential Climate Variables (ECV) of the GCOS, as required by IPCC and UNFCCC (GCOS Secretariat, 2006). Because of surface albedo's significance to the radiation budget, its continuous monitoring is of importance in understanding climate change. Satellites provide the most cost-effective means to achieve global coverage with a relatively short repeat period. All products have been developed and evaluated with respect to requirement goals defined in [AD 1]. The finally achieved product accuracies are described in [RD 3]. Of specific interest here are requirements in [RD 2] as outlined by the Global Climate Observing System (GCOS) community and issued by the United Nations World Meteorological Organisation (WMO) in 2012.

The CLARA-A3 SAL data record spans the period from 1979 to 2020, with the ICDR extension continuing the time series with the same algorithm, although with some limitations in the quality of the input data (see next section). The albedo products, distributed as pentad and monthly means at 0.25 degree resolution (also available at 25 km resolution over polar regions in an equal-area grid), are composed from overpass data from the Advanced Very High Resolution Radiometer (AVHRR) instruments on board the National Oceanic and Atmospheric Administration (NOAA) and METOP satellites. The characteristics of the time series and its usage are described in the following chapters. The purpose of this document is not to be a detailed guide to the workings of the algorithm itself. Although processing flow is described, readers interested in the nuts and bolts of the SAL algorithm are encouraged to read the CLARA-A3 SAL Algorithm Theoretical Baseline Document (ATBD) [RD 1], available on the CM SAF project website.

2.1 Suggested usage and limitations

The CLARA-A3 SAL data record has been validated against a large number of in-situ reference data. Validation criteria have been fulfilled for both vegetated regions and snow/ice-covered areas. Particularly the product bias over snow and ice has been shown to be low on average; therefore we have grounds to recommend using CLARA-A3 SAL for large-scale cryospheric studies especially over the Arctic owing to the availability of sea ice albedo coverage in CLARA-A3 SAL. Due to representativeness issues resulting from the relatively coarse spatiotemporal resolution, large differences against in situ observations were noted in a point-to-pixel comparison over areas with rapid temporal surface albedo variability and/or partial snow/ice coverage in the CLARA grid cell [RD 3].

Care needs to be taken when utilizing CLARA-A3 SAL over regions with a high variability in aerosol concentrations in the atmosphere. In general, users are also strongly recommended to examine the number of observations-datafield within each SAL product, as well as the other statistical QA data provided such as skewness and kurtosis. It should be noted that areas where the monthly and pentad means are composed of only a few valid observations are vulnerable to retrieval errors in atmospheric correction, reflectance anisotropy correction, or cloud masking, especially in regions with high value of mean solar zenith angles. Furthermore, regions with persistently high aerosol loading during any month (AOD>1) will be masked out of the data. This feature is often present over Amazon, eastern Siberia and the metropolitan regions of coastal China.

At present, the ICDR continuation of the CLARA-A3 timeseries is processed without Metop-C owing to uncertainties in the calibration of the visible channels of its AVHRR instrument. Users should be aware of ensuing potential consistency and continuity effects. Please see the Validation Report for further details.

Note: For the period onwards from 2015, the AOD estimates are based on a climatology, and thus may not track anomalies similarly to the original record. Also, the AVHRR radiances for the ICDR have not gone through the same level of intercalibration as the original record. Wind speed data in the ICDR re-uses the 2020 estimates from the TCDR.

2.2 Changes relative to the predecessor data record CLARA-A2 SAL

Though the core of the retrieval algorithm remains the same as in the predecessor record(s), there are numerous updates and expansions in this data record as follows:

1. In addition to the black-sky surface albedo estimate (SAL), estimates for white- and blue-sky albedo (WAL and BAL) are now provided.
2. Atmospheric correction now treats desert regions separately from other continental areas.
3. Scope of provided data has been substantially expanded to better enable uncertainty characterization and QA flagging for users with varying needs. For each provided variable, the A3 edition contains mean, median, standard deviation, skewness, and kurtosis. For snow/ice WAL and BAL, only mean is available.
4. Separate estimates are now provided for snow-free, snow-covered, and combined (_all) surface albedos in SAL. For WAL and BAL, snow-free and combined data fields are available, with snow/ice albedo present only in the "_mean" data field, derived from SAL.
5. New AVHRR-carrying satellites expand the spatiotemporal coverage; the CLARA-A3 record features observations from TIROS-N in 1979 to the METOP series of satellites, with all morning satellites now included.
6. Cloud detection and masking is now based on probabilistic methods in the Polar Platform System (PPS) software. SAL uses a fixed threshold of 20% cloud probability to screen and discard cloud-contaminated observations.
7. For internal consistency, all albedo estimates are now not normalized to any Sun Zenith Angle (SZA). Mean SZA data is provided per grid cell for users wishing to normalize

the albedo estimates. White-sky albedo estimates are independent of SZA by definition.

8. Data source for atmospheric composition (ozone, surface pressure, water vapour columnar content) is now changed to ERA5 atmospheric reanalysis for the TCDR, and its continuation data record ERA5T for ICDR.

3 CLARA Edition 3 Surface Albedo (CLARA-A3 SAL)

3.1 Product Definition

In CLARA-A3, estimates exist for three physical quantities describing surface reflectivity; the black-, white-, and blue-sky surface albedos. These quantities are mathematically defined as (Schaepman-Strub et al., 2006):

black-sky surface albedo (directional-hemispherical reflectance):

$$\alpha_{BLACK}(\theta_s, \varphi_s) = \int_0^{2\pi} \int_0^{\pi/2} f_r(\theta_s, \varphi_s; \theta_r, \varphi_r)\, cos(\theta_r)\, sin(\theta_r)\, d\theta_r d\varphi_r \quad (1)$$

Where f_r is the bidirectional surface reflectance from solar zenith/azimuth direction (θ_s, φ_s) to the reflection direction (θ_r, φ_r). The black-sky surface albedo (**SAL**) is the integral of radiation reflected from a single incident direction towards all viewing directions in the zenithal and azimuthal planes. The spectral dependency of albedo is omitted here; a full (black-sky) broadband albedo would be obtained by integrating the spectral directional-hemispherical reflectance over the waveband under investigation. CLARA-A3 SAL is a broadband albedo product, defined with a wavelength range of 0.25 - 2.5 µm for AVHRR.

white-sky surface albedo (bihemispherical reflectance under diffuse illumination):

$$\alpha_{WHITE} = \frac{1}{\pi} \int_0^{2\pi} \int_0^{\pi/2} \rho(\theta_s, \varphi'_s; 2\pi)\, cos(\theta_s)\, sin(\theta_s)\, d\theta_s d\varphi_s \quad (2)$$

The white-sky surface albedo is defined under conditions of fully diffuse (isotropic) illumination of the surface. It therefore does not vary by solar geometry. In CLARA, we call the white-sky albedo estimates by the acronym **WAL**. We again omit spectral considerations here, and note that both white- and black-sky albedos represent theoretical opposite ends of the surface reflectance's response to the directionality of the incoming solar flux. The observable surface albedo under natural (ambient) conditions is the blue-sky surface albedo.

blue-sky surface albedo (bihemispherical reflectance under ambient illumination):

It has been shown that the surface albedo under natural illumination conditions (i.e. varying combination of direct and diffuse illumination) may be estimated as a weighted mean of the black- and white-sky albedo (e.g. Lewis and Barnsley, 1994; Lucht et al., 2000; Román et al., 2010). The primary limit to this simplification is that Sun Zenith Angles must be sufficiently small; a general applicability limit of 70 degrees is often quoted (Román et al., 2010). As the albedo processing here carries a cut-off SZA of 70 degrees for all satellite observations, we consider the boundary condition honored and we derive the blue-sky albedo (**BAL**) simply as

$$\alpha_{BLUE} = f_{DIR}\, \alpha_{BLACK} + (1 - f_{DIR})\, \alpha_{WHITE}$$

where f_{DIR} is the fraction of direct illumination in the grid cell during the period in question. Note that all cloudy- and clear-sky satellite observations taken when SZA < 70 degrees are considered when calculating f_{DIR} during processing, in order to form an estimate for α_{BLUE} valid for the (daylight) sky conditions of the whole period.

3.2 Products and availability

The CLARA-A3 surface albedo products are available as pentad (five-day) and monthly means in a global equally spaced lat/lon grid at 0.25 degree spatial resolution. Temporal coverage of the TCDR is 1979-2020, with the ICDR continuing the time series forward. Area coverage is shown in Figure 1. The global product is delivered in geographic projection, using WGS-84 ellipsoid, with product limits -179.875 -> 179.875 degrees of longitudes and 89.875->-89.875 degrees latitude (720 columns, 1440 rows, with coordinates indicating the pixel centre). A subset of the data spanning either the Arctic or Antarctic region in 25 km resolution EASE-2 grid is also delivered. Please contact the CM SAF User Help Desk for details.

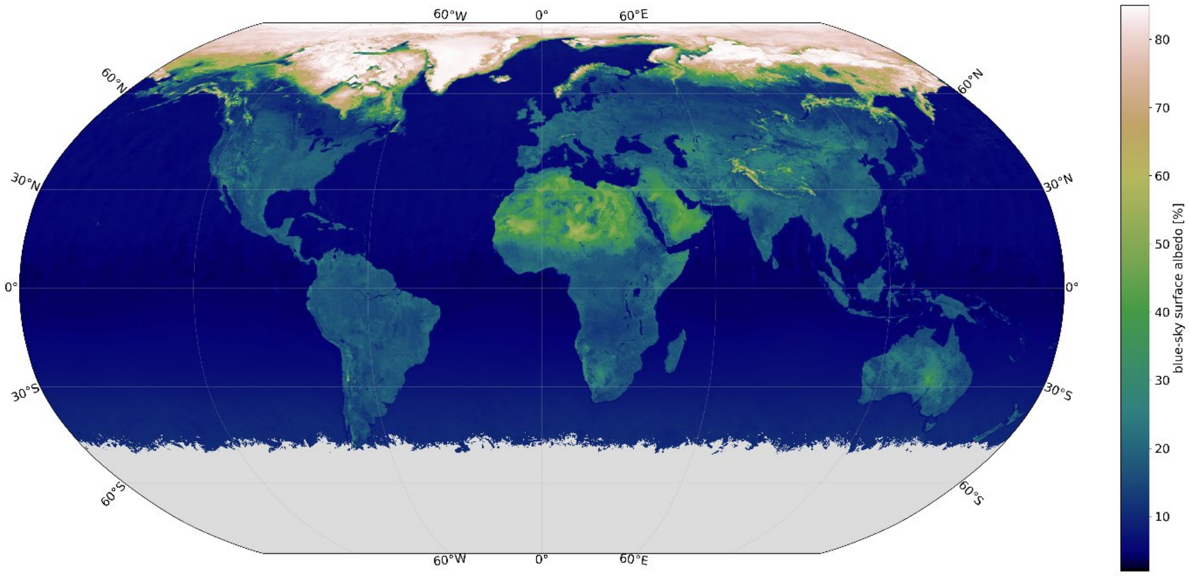

Figure 3-1: CLARA-A3 BAL (blue-sky albedo) monthly mean for May 2015.

3.3 CLARA-A3 SAL algorithm (level 2)

AVHRR channels 1 and 2 (0.58-0.68 µm and 0.725-1 µm) are used for the SAL product generation as radiance sources. The overall processing flow is shown in Figure 3-2. The necessary preprocessing of the satellite data for use with SAL is done by the PPS software package. Details on PPS processing are available from the CLARA-A3 ATBD for Cloud Products [RD 4]. The package converts observed satellite radiances to TOA reflectances for SAL and performs the critical cloud detection operation. Geolocation and Sun-satellite geometry data are also provided.

The aerosol optical depth (AOD) information used in the atmospheric correction is derived from aerosol index data measured by Total Ozone mapping (TOMS) and Ozone monitoring instruments (OMI). The wind speed data required for the ocean surface albedo determination is compiled from Scanning Multi-channel Microwave Radiometer (SMMR), Special Sensor Microwave Imager (SSM/I), Special Sensor Microwave Imager Sounder (SSMIS) and anemometer based wind speed data. Other auxiliary data, such as the water vapour content in the atmosphere or surface pressure, are based on the ERA5 reanalysis. Land use information is based archetypes derived from 5 different land use classifications: USGS 1993, GLC2000, GLOBCOVER 2005, and GLOBCOVER 2009, and ESA CCI (2015). These land use datasets are also used for land/sea –masking.

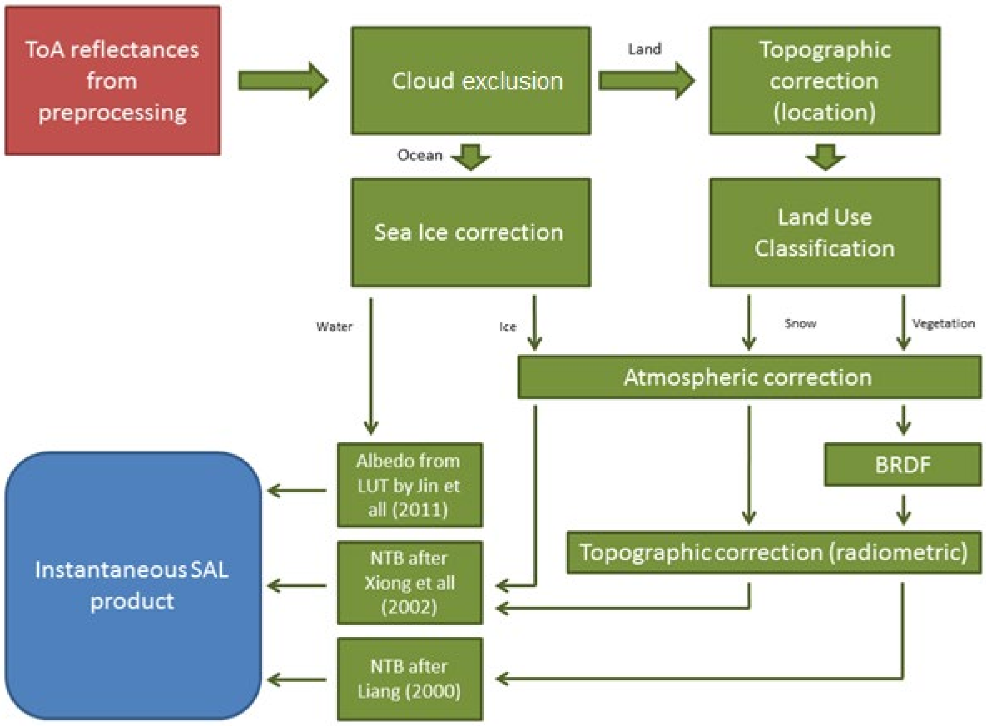

Figure 3-2: The process flow of the CLARA-A3 SAL product computation (level 2).

The product processing proceeds as follows (for details the reader is referred to the SAL ATBD [RD 1]):

- The ToA AVHRR reflectances are provided by the Polar Platform System (PPS) processing software, as discussed above.
- The classification of snow covered pixels in Arctic and Antarctic sea areas provided by PPS are verified by using Ocean and Sea Ice Satellite Application Facility (OSI SAF) sea ice concentration data.
- The open water albedo is determined on the basis of the Sun zenith angle and the surface wind data using the algorithm by Jin et al. (2004 and 2011).
- Topography correction for geolocation and radiometry is applied for areas (pixels) with slopes exceeding 5 degrees. See [RD 1] for details.
  - Motivation: improvement of retrieval accuracy of albedo over mountainous regions.
- The pixels that are classified as cloud free (i.e. cloud probability less than 20%) and not covered by snow are given a land use information using land use classification data.
- The surface reflectances are expanded into hemispherical spectral albedos by applying a BRDF algorithm based on the work of Roujean et al. (1992) and Wu et al. (1995). The BRDF algorithm is applied to both 0.6 and 0.8 µm channel separately.
- Snow albedo algorithm utilizes empirical sampling of pentad/monthly BRDF. The observed overpasses are kept as directional-directional reflectances, temporal

averaging forms desired hemispherical-directional reflectances (black-sky albedo). Details in [RD 1].

  - Motivation: No robust, universal snow BRDF models available for anisotropy correction. Testing and validation have proven that sufficient sampling of the viewing hemisphere is achieved over most snow-covered regions of the Earth.
  - The narrow-to-broadband conversion equation adapts to wet and dry snow/ice cases.

- SMAC atmospheric correction applied for all observed reflectances.
  - A dynamic value of AOD is used to land surfaces excluding ice sheets, where a static value of 0.05 is used. The ozone and water vapour content of the atmosphere are derived from ERA5 reanalysis data. **The climatology of 2005-2014 is used for the period after 2014 for AOD.**
  - NOAA-18 SMAC coefficients are applied for all satellites, since the AVHRR radiances are intercalibrated across the AVHRR-GAC FDR.
- The fraction of direct irradiance is derived from SMAC for clear-sky cases; for cloudy cases (cloud probability >20%), it is estimated using the cloud probability as a proxy for clearness index. See the ATBD for details.
- The spectral albedos are processed to a shortwave broadband albedo via a narrow-to-broadband (NTB) conversion. The conversion is pixel land cover specific. The land cover information comes from 5 different land use classification data records: USGS, GLC2000, GLOBCOVER2005, GLOBCOVER2009, and ESA CCI (2015).
  - For water pixels, the BB albedo is taken from a LUT after Jin et al. (2011).
  - For snow pixels, the observed BB directional reflectance is computed from the channel-specific spectral directional reflectances (see above) by an NTBC algorithm by Xiong et al. (2002).
  - For other types of land cover, the NTBC conversion takes place based on an algorithm by Liang (2000).
- The observations are not normalized to any Sun Zenith Angle. SZA data is carried forward to level 3 aggregation to be provided to users in order to enable later normalization if so desired.
- Over non-snow land surfaces, white-sky albedo estimates are derived from the black-sky estimates following Yang et al. (2008).

3.3.1 AOD time series

Since CLARA-A2, the previously constant AOD value (0.1) has been replaced with a new dynamic AOD time series constructed for the time frame 1982-2014 (Jääskeläinen et al., 2017). Because no AOD data record at wavelength 550 nm (needed by SMAC) is available for the whole time range, the needed AOD is calculated from the TOMS and OMI Aerosol Index (AI) data, which cover almost the whole time range. The AOD time series has been constructed by studying the relation between AI and AOD (derived from OMI) in the years 2005-2008, during which period there is both AI and AOD at 550 nm (calculated from the OMI-AOD values at the UV wavelength range) available. The information on SZAis included in the conversion to increase accuracy.

OMI-AI can have both negative and positive values (non-absorbing or absorbing), but only the latter ones are used. For the regression function $AOD = \alpha \cdot AI \cdot cos(SZA) + \beta$ calculation the AI and AOD data are screened for clouds (using MODIS-AOD), and deseasonalized. Since SMAC cannot be reliably applied to AOD values higher than unity, the regression is made only for AI and SZA values which correspond to the AOD values below 1.

While constructing the AOD time series, to achieve a larger global coverage, the AI data is not screened as much as for the regression. Even though the AI values can be measured for cloudy conditions, the screening for clouds was not implemented in the time series construction. This is because the cloudy pixels are excluded from the SAL calculation by the cloud mask. The AOD time series data is gathered into global daily maps. The possible gaps in these maps are filled by using weighted mean to the whole map. The AOD time series is not applied for sea ice, ice sheets or water. For these areas the constant value of 0.05 is used. **Note: The original data record was extended by calculating a climatology of the original data record for years 2005-2014.**

3.4 CLARA-A3 SAL algorithm (level 3)

During this last stage of processing, the data from the satellite overpass swathes (i.e. level 2) are aggregated onto the final grids (global and polar), the WAL/BAL estimates are derived, and snow/non-snow observations are combined. Figure 3-3 illustrates the process flow.

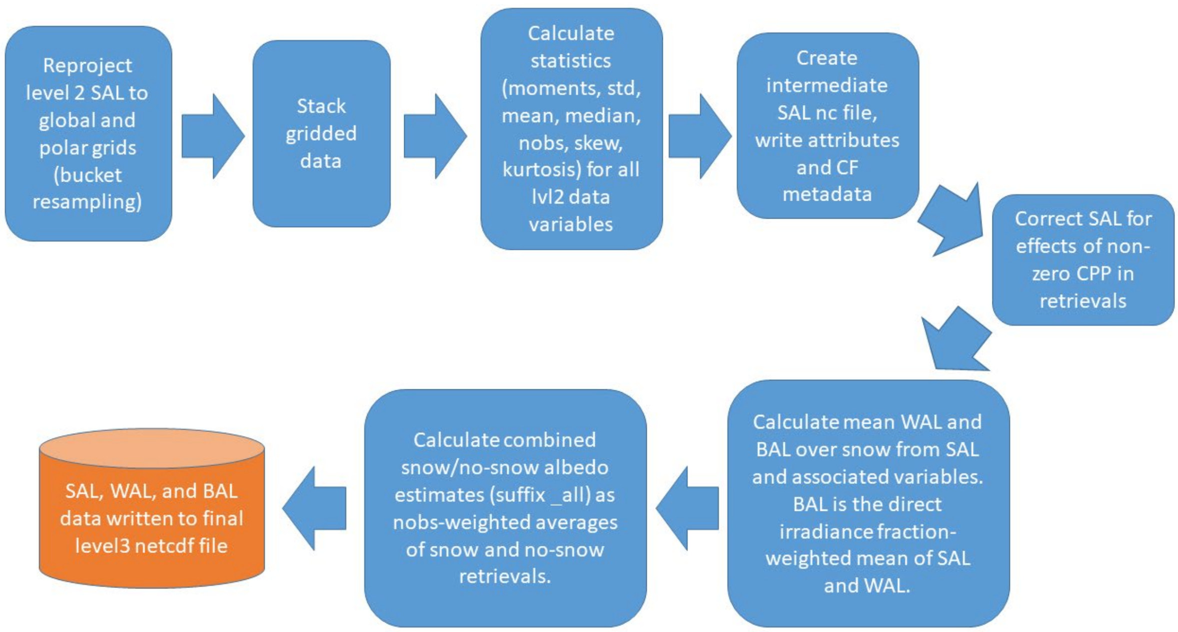

Figure 3-3: Overview of CLARA-A3 SAL level 3 processing

For a detailed description of the processing, please see the ATBD [RD 1]. The key features here are as follows:

- Swath observations are gathered onto the final grids using drop-in-bucket resampling.

- Statistical quantities (moments, std, mean, median, skewness, kurtosis) are calculated and provided in the end product files.
- Potential impacts of cloud contamination (i.e. non-zero cloud probabilities) are accounted for though observation weighing by cloud probability and a correction for cases where the period-mean cloud probability is larger than zero. See the ATBD for details.
- Over snow and ice, the mean WAL estimate is calculated based on an empirically observed relationship between in situ-measured black- and white-sky albedo (Manninen et al., 2019). Snow cover in forests and open areas is treated separately. Note that for WAL and BAL over snow, only the mean estimate contains the data; all other statistical descriptors are set to NaN.
- Over sea ice, mean WAL is constrained to not exceed SAL by more than 10% (relative).
- BAL is calculated as the direct irradiance fraction-weighted mean of SAL and WAL. Note that all observations (clear-sky and cloudy-sky) taken during SZA<70 degrees are used to infer the mean direct irradiance fraction during the estimation period, so that the blue-sky albedo estimate matches the prevailing illumination conditions of the period.
- For grid cells where both non-snow and snow observations exist (e.g. seasonal snow cover margins), the combined albedo estimates ("_all") are formed as the weighted mean of snowy and non-snow albedo estimates. The observation counts are provided for QA purposes in the end products as well.

3.5 Validation

The CLARA-A3 SAL TCDR has been validated prior to release against ground truth data from the Baseline Surface Radiation Network (BSRN), the PROMICE in situ measurement network in Greenland, and the Tara and SHEBA campaigns from the Arctic Ocean's sea ice [RD 3].

The accuracy of the albedo estimates is evaluated using three metrics: bias (mean retrieval error through time), precision (bias-corrected rmse, i.e. scatter of retrieval errors), and stability (decadal trend in bias). The targets for these metrics are <15% bias (<25% for WAL/BAL as newly introduced estimates), <0.1 precision, and <10% stability (<15% for WAL/BAL) [AD 1]. Table 3-1 provides an overview of fulfilment of these targets across the components of validation and performance metrics. All three albedo estimates share the listed performance, therefore only a single table is provided here.

As we can see, targeted performance is achieved in all aspects save one – precision against PROMICE network observations. Over the Greenland ice sheet margins where the majority of PROMICE sites are located, the ice sheet surface undergoes dramatic changes every summer, transitioning from stable and comprehensive winter snow cover to a dynamically changing mix of wet snow, bare ice, and melt ponds and channels, with light-absorbing impurities further adding to the complexity. Against this backdrop, the CLARA grid cell scale retrievals naturally struggle to track station observations, resulting in large scatter in retrieval bias. Examples of this effect are discussed below.

Table 3-1: Fulfillment of target performance requirements for CLARA-A3 SAL/WAL/BAL

Reference	Bias target fulfilled?	Precision target fulfilled?	Stability target fulfilled?
BSRN	Yes	Yes	Yes
PROMICE	Yes	Partially	Yes
SHEBA & Tara	Yes	N/A	N/A

As examples of the achieved accuracy against BSRN observations, we show validation results from Southern Great Plains (SGP) site against the blue-sky albedo estimate BAL in Figure 3-4. As is apparent from the bottom panel, relative retrieval errors are annually quite stable between 1994 and 2018 where in situ data is available. The spatiotemporally aggregated end products as well as the retrievals from individual overpasses have similarly low bias, although the range in retrieval errors is naturally larger in the individual overpasses. The relatively homogeneous land cover surrounding the Great Plains site makes for an uncomplicated point-to-pixel comparison, reflected in the very similar behaviour at the grid cell scale (0.25 degrees) versus overpass scale (5-10 km satellite footprint).

On the validation against PROMICE observations, we highlight two contrasting examples. The KAN-U site is located on the western side of the ice sheet at 1840 m elevation. The validation results there for blue-sky albedo (Figure 3-5) show very good agreement across the evaluation period, with the modest annual surface melt effects generally well tracked. In contrast, if we examine the KPC_L site, located near the ice sheet's northeastern edge (elevation 380 m), the validation results show a wide range of retrieval errors at the monthly mean scale (Figure 3-6). While early summer retrievals are similar to observed albedos, discrepancies grow large as the surface melt gets underway. Notably, minimum BAL estimates for each summer are stable from year to year, suggesting that the grid cell contains a large area of either highly impure ice or lost seasonal snow/ice cover, which is not seen by the point-like in situ measurement, whose minima vary substantially from year to year. This behaviour indicates that the albedo estimates near ice sheet edges should be treated with due caution.

Finally, Figure 3-7 illustrates the validation results against albedo observations at the drifting ice camp of the SHEBA expedition on the Arctic Ocean. Here the temporal resolution is pentads instead of monthly means. After the onset of summer melt, the measured surface albedo declines steadily as melt ponds form and expand and the dry snow cover on ice is lost. The CLARA estimates track this evolution well, with notable disagreements only apparent in August when worsening solar illumination combines with persistent cloud cover to diminish the available satellite observations (blue bars in top panel). The performance seen here is consistent with the predecessor CLARA-A1 record (Riihelä et al., 2013), although here the comparison is against the blue-sky albedo estimate BAL, which is physically more consistent with the measured in situ surface albedo.

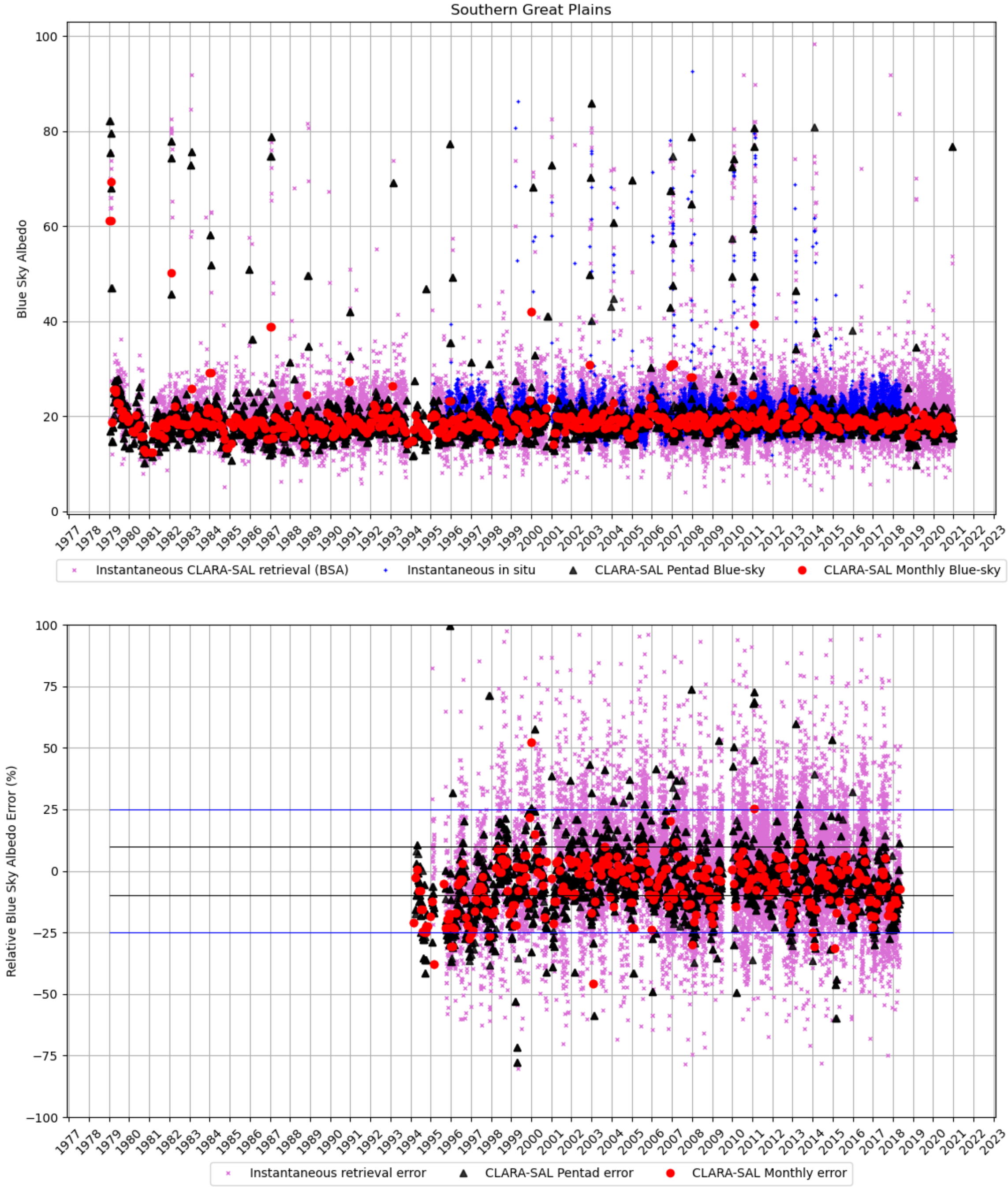

Figure 3-4: CLARA-A3 BAL validation over Southern Great Plains BSRN site. (Top) Retrieved CLARA-A3 monthly mean BAL (red circles), pentad mean BAL (black triangles), GAC-resolution (overpass) BAL (magenta x), in situ measured albedo (blue +). (Bottom) Relative retrieval error (bias) of the pentad, monthly mean and instantaneous satellite estimates, markers consistent with the top panel.

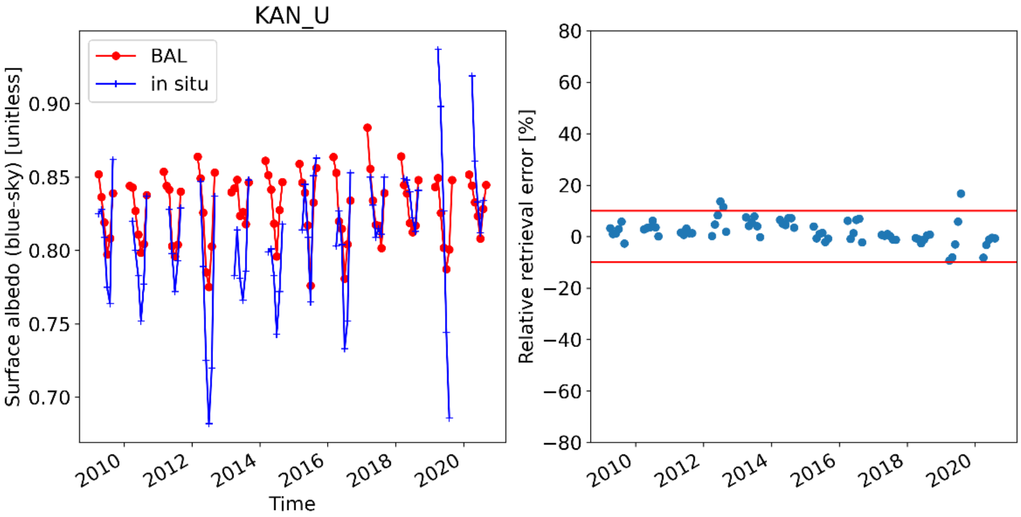

Figure 3-5: Left, retrieved (red) and measured (blue) surface albedo at KAN_U PROMICE site during the evaluation period 2009-2020. Right, relative retrieval error [%] of the satellite-based estimate. Red horizontal lines indicate +/10%.

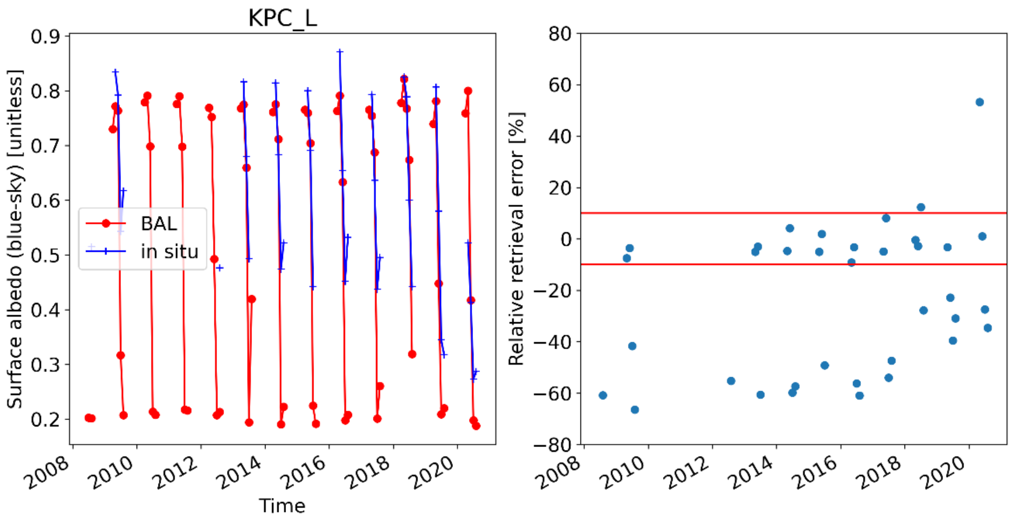

Figure 3-6: As Figure 3-5, but for the KPC_L site.

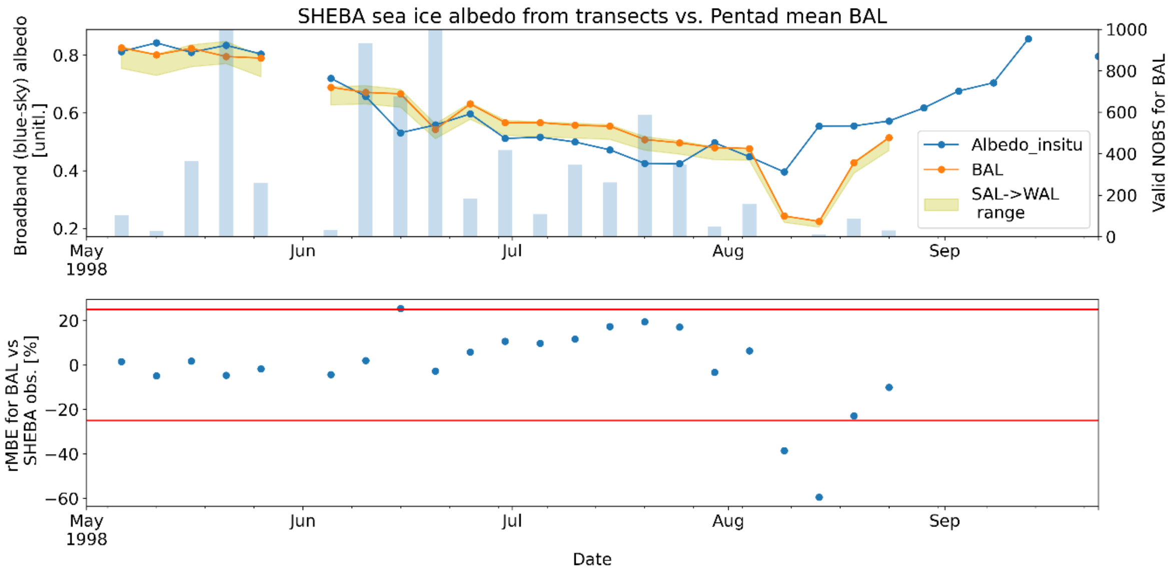

Figure 3-7: Top: In situ albedo from SHEBA transect measurements (blue, 5 day average) versus CLARA-A3 albedo pentad mean products – BAL in orange line & markers, with the variability range between SAL and WAL shown with a beige envelope. Faint blue overlaid bar chart indicates the amount of valid GAC-resolution SAL retrievals at the ice camp's grid cell during the Arctic summer 1998. Below: Relative bias (rMBE) of CLARA-A3 BAL vs. SHEBA in situ measurements. Red lines indicate the 25% relative error levels.

3.6 Limitations

The following is a list of known issues and limitations in the CLARA-A3 surface albedo estimates.

- Mean WAL for snow/ice surfaces is estimated with an empirical relationship based on SAL parameters. This means that no other quantities such as median, std, skewness or kurtosis are available over snow/ice in WAL. Therefore, only the field *white_sky_albedo_all_mean* contains information over snow/ice surfaces. Subsequently, this also holds for BAL. Note that misclassified snow/ice conditions may still result in large albedo estimates being present in e.g. the median blue-sky albedo. However, as these are a result of application of the non-snow SAL/WAL algorithm to what is typically a very small set of misclassified (snowy) satellite observations, these data should not be relied upon.

- Certain individual grid cells appear to have retrievals beyond the SZA cutoff latitude due to malformed satellite geolocation information. Occurs sporadically and only during the early part of the record (1980s and early 1990s). Identifiable through examination of the *sun_zenith_angle_mean* data field.

- The current atmospheric correction is a compromise between the need to avoid introducing artificial retrieval errors into product and a desire to correctly account for the atmospheric physics affecting the surface albedo retrieval. We use atmospheric reanalysis data to account for the second-order atmospheric variables that affect surface albedo retrievals, namely columnar water vapour and surface pressure. The most important atmospheric variable affecting the surface albedo retrievals is the aerosol optical depth (AOD) in the atmosphere. Variations in AOD are both regional and global; their effect in space-observed surface reflectances is substantial. Yet an accurate derivation of AOD from satellite observations to support surface albedo retrievals requires assumptions on the albedo of the underlying surface. Through making these assumptions, the product contains an internal correlation between the AOD and the albedo of the terrain underneath, which is an undesired combination. To avoid this, we have produced a dynamic AOD timeseries from Aerosol Index (AI) data for the purpose of atmospheric correction of satellite based surface products. However, for the last years (2015->) of the record, the AOD is a climatology from the latest full decade.

- Albedo retrievals are not attempted when AOD exceeds 1.0 as the SMAC algorithm uncertainties increase rapidly after this point. Therefore, some seasonal data gaps may appear over the Amazon and certain regions in East Asia, where continuously high aerosol loading conditions are possible.

- Errors in the land use classification data are another source of retrieval error that should be considered. The LUC data is not continuously updated, therefore some man-made or natural changes in land may not be correctly identified in processing, which is dependent on LUC data to choose a proper surface albedo subroutine. Their effect and source is also very difficult to localize in time or space, but are more likely to occur the longer the time from the observations used in the land use classification.

- Malformed surface albedo estimates were detected during February-March 1997 from NOAA12 and NOAA14 observations. To correct this, all NOAA12 observations and a small subset of NOAA14 observations were excluded from the processing of CLARA-A3 SAL products for these months.

- Due to uncertainty in the (v2017) vicarious calibration of visible channels, Metop-C is presently excluded from the ICDR extension of CLARA-A3. Re-introduction into processing is foreseen once a sufficiently robust calibration is available. Impact on TCDR-ICDR differences is small on large scales, but notable over some regions. Further details are available in the Validation Report [RD 3].

3.7 Outlook

With the advent of the CLARA-A3 TCDR and the ICDR which continues it, the full AVHRR instrument family data record is now contained within, from TIROS-N to the METOP series. In the future, the expected retirement of the AVHRR imager imposes a need to prepare for the integration of suitable spaceborne optical imagers to continue the time series in future CLARA editions. Towards this goal, it is foreseen that the Visible Infrared Radiometer Suite (VIIRS) imager on board Suomi-NPP and NOAA-20 satellites shall be the primary successor to AVHRR. Going further, the future METOP-Second Generation (SG) satellites carrying the Metimage and 3MI optical sensors will eventually replace the data from the current METOP satellite constellation. Future efforts shall be made towards ensuring a smooth transition from AVHRR to these instruments to preserve the consistency and continuation of the CLARA record.

Other future development directions include assessing the potential for improvements in the atmospheric correction code and the land cover data needed to select appropriate processing paths for SAL. It is further expected that machine learning-based improvements to the AOD timeseries will further improve retrieval quality and consistency for surface albedo in forthcoming CLARA editions.

3.8 ICDR

To continue the CLARA-A3 TCDR coverage (1979-2020) forward in time, an Interim Climate Data Record is delivered in the same data format using the same algorithms as for the full TCDR. The extension in time allows for continuous analysis up to (nearly) the present day. However, the following changes in the ICDR versus the full TCDR should be noted:

- As the data source for atmospheric composition (pressure, ozone and water vapour content), the ERA5 reanalysis has been switched to the continuously updated ERA5T.
- AOD and ocean wind speeds are based on climatologies (multiyear for AOD, re-use of 2020 for winds)
- Ocean sea ice data source changed to the operationally available OSI-401b data record.
- The AVHRR radiances have not gone through the level of rigorous intercalibration that has been applied to the TCDR input; the ICDR data stream is from NOAA CLASS (for details, please refer to the PUM on Cloud Products in CLARA-A3). As a result, perfect consistency in estimated surface albedo should not be expected.

To ensure consistency between TCDR and ICDR, a period of six months (07-12 / 2020) was produced in parallel with both TCDR and ICDR inputs. For the surface albedo estimates, differences up to 2-4% (absolute) were noted over ice sheets, most likely due to differences in AVHRR radiances. Sporadic larger differences were apparent over grid cells where the sea ice identification differed or where high aerosol loadings where present; however, on the global scale the mean difference between ICDR and TCDR albedo estimate never exceeded 1% (absolute).

Beware that possible changes in the ICDR input data streams and a decay with time of calibration corrections can lead to reduced quality in the CM SAF ICDR products, with partly distinct regional imprints and exceeding the effective ICDR Service Specifications. Please use the data and associated plots with care and check the Service Messages and the Annual Validation Reports (AQARep) of the ICDR (https://www.cmsaf.eu). Also note the present exclusion of Metop-C from processing, as discussed in section 3.6.

4 Data Description

CM SAF's climate monitoring CLARA products are provided as NetCDF (Network Common Data Format) files (http://www.unidata.ucar.edu/software/netcdf/). The data files are created following NetCDF Climate and Forecast (CF) Metadata Convention version 1.7 (http://cf-pcmdi.llnl.gov/) and NetCDF Attribute Convention for Data record Discovery version 1.3.

For data processing and conversion to various graphical packages input format, CM SAF recommends the usage of the climate data operators (CDO), available under GNU Public License (GPL) from MPI-M (https://code.mpimet.mpg.de/projects/cdo/).

4.1 Data file contents

A common NetCDF file consists of dimensions, variables, and attributes. These components can be used together to capture the meaning of data and relations among data. All CLARA SAL product files are built following the same design principles.

Each global grid data file contains the following coordinate variables (as datatype double):

- *time* start of averaging/composite time period [days counted from 1970-01-01]
- *time_bnds* two-dimensional array defining the averaging/composite time period [days counted from 1970-01-01]
- *lat* geographical latitude of pixel centre [degree_north]
- *lat_bnds* two-dimensional array defining boundaries of latitude grid cells
- *lon* geographical longitude of pixel centre [degree_east]
- *lon_bnds* two-dimensional array defining boundaries of longitude grid cells

Each data file contains 66 data variables. The data are grouped by the following parameter families (datatype float):

Table 4-1: CLARA-A3 SAL parameter families in a NetCDF file

Parameter family	Coordinates	Description
black_sky_albedo_all	Time, lat, lon	Black-sky albedo, combined snow/ice and non-snow observations
black_sky_albedo	Time, lat, lon	Black-sky albedo, non-snow/ice observations only

Parameter family	Coordinates	Description
blue_sky_albedo_all	Time, lat, lon	Blue-sky albedo, combined snow/ice and non-snow observations
blue_sky_albedo	Time, lat, lon	Blue-sky albedo, non-snow/ice observations only
cloud_probability	Time, lat, lon	Cloud probability for non-snow/ice observations accepted into SAL retrieval
cloud_probability_snow	Time, lat, lon	Cloud probability for snow/ice observations accepted into SAL retrieval
dir_irradiance_fraction	Time, lat, lon	Estimated fraction of direct irradiance for all cloudy and clear overpasses during daylight conditions
sun_azimuth_angle	Time, lat, lon	Sun Azimuth Angle of satellite observations (relative to north)
sun_zenith_angle	Time, lat, lon	Sun Zenith Angle of satellite observations (relative to north)
white_sky_albedo_all	Time, lat, lon	White-sky albedo, combined snow/ice and non-snow observations
white_sky_albedo	Time, lat, lon	White-sky albedo, non-snow/ice observations only

For all parameter families, the following separate data fields exist (accessed as parameter family + data field, e.g. black_sky_albedo_all_median):

- **_kurtosis : Kurtosis of data**
- **_mean : Mean of data**
- **_median : Median of data**
- **_skew : Skewness of data**
- **_std : Standard deviation of data**

In addition, the following data fields are available for QA:

- nobs_nosnow : Amount of valid non-snow/ice GAC-resolution observations for SAL processing
- nobs_nosnow : Amount of valid snow/ice GAC-resolution observations for SAL processing
- nobs_total : Amount of valid combined snow/ice and non-snow/ice GAC-resolution observations for SAL processing
- record_status : Scalar value indicating status of processing for the file. Value of zero indicates successful SAL processing.

The products are available as monthly means and pentad means. Table 4-1 describes the global product, but the data is also available in equal area polar projection for both Arctic and Antarctic areas. In the polar products the lat/lon variable and all data are provided as 1x320x320 (time, lat, lon) for the Antarctic and 1x360x360 (time, lat, lon) for the Arctic. The polar subset data also contain data variables *x* and *y,* which contain the map projection coordinates (1D) for the polar EASE-2 grid. Also, the polar subsets do not contain the bounding data fields for latitude and longitude, as the grid is not regularly spaced.

The data files also contain an array of global attributes for data documentation and improved usability purposes. These attributes are contained in each CLARA-A3 SAL product, and are listed in Table 4-2.

Table 4-2: CLARA-A3 SAL product attributes

Name	Description
title	CM SAF CLARA-A3 surface albedo data
summary	short description of the data
ID	DOI assigned to this data record
product version	3.0
creator_name	institution where the data was produced
creator_email	email contact information for the creator of the data
creator_url	URL contact information for the creator of the data
institution	The institution holding the rights to the data
project	project under which the data record was produced
references	references that describe the data or methods used to produce it
keywords_vocabulary	GCMD Science Keywords, Version 8.6
keywords	the keywords of the standard described in ‘keywords_vocabulary’ relevant to the data record
Conventions	conventions followed,
standard_name_vocabulary	Standard Name Table (v51, 16 May 2018)
date_created	The date, when the level 3 file was created
geospatial_lat_units	latitude attributes unit [degree_north]
geospatial_lat_min	latitude bounding box minimum
geospatial_lat_max	latitude bounding box maximum
geospatial_lon_units	longitude attributes unit [degree_east]
geospatial_lon_min	longitude bounding box minimum
geospatial_lon_max	longitude bounding box maximum
geospatial_lat_resolution	latitude grid resolution
geospatial_lon_resolution	longitude grid resolution
time_coverage_start	temporal coverage start of the data [ISO8601 date]
time_coverage_end	temporal coverage end of the data [ISO8601 date]

time_coverage_duration	temporal coverage duration of the data [ISO8601 duration]
time_coverage_resolution	temporal coverage resolution of the data [ISO8601 duration]
platform_vocabulary	GCMD Platforms, Version 8.6
platform	Earth Observation Satellites > METOP,Earth Observation Satellites > NOAA POES (Polar Orbiting Environmental Satellites)
instrument_vocabulary	GCMD Instruments, Version 8.6
instrument	AVHRR>Advanced Very High Resolution Radiometer
variable_id	Names of the principal data variables in the file (combined albedo estimates)
license	Licensing and copyright statement for the data
source	Principal data sources used during processing of the data
lineage	Identification of processing software versions and lineage
coordinates	Bounding coordinates of data variables

In addition to the global attributes, each variable also has attached attributes. The variable-specific attributes are listed with explanations in Table 4-3.

Table 4-3: Attributes assigned to variables

Name	Description
long_name	long descriptive name
standard_name	standard name that references a description of a variable's content in the CF standard name table
units	physical unit [udunits standards]
valid_min	smallest valid value of a variable
valid_max	largest valid value of a variable
scale_factor	The data are to be multiplied by this factor after it is read.
add_offset	This number is to be added to the data after it is read. If scale_factor is present, the data are first scaled before the offset is added.
_FillValue	This number represent missing or undefined data. Missing values are to be filtered before scaling.
missing	same as _FillValue

calendar	definition of calendar used
bounds	This attribute is only used for the time, lat, and lon variable and defines the ranges over which the product is defined. Lat/lon bounds not present in polar subset data.

4.2 ICDR specific adaptions

The data format for the ICDR products is identical to TCDR. The following changes in input data should be acknowledged when assessing product applicability:

- As the data source for atmospheric composition (pressure, ozone and water vapour content), the ERA5 reanalysis has been switched to the continuously updated ERA5T.
- AOD and ocean wind speeds are based on climatologies (multiyear for AOD, re-use of 2020 for winds)
- Ocean sea ice data source changed to the operationally available OSI-401b data record.
- The AVHRR radiances have not gone through the level of rigorous intercalibration that has been applied to the TCDR input; the ICDR data stream is from NOAA CLASS (for details, please refer to the PUM on Cloud Products in CLARA-A3). As a result, perfect consistency in estimated surface albedo should not be expected.
- Metop-C is presently excluded from ICDR processing.

5 Data ordering via the Web User Interface (WUI)

User services are provided through the CM SAF homepage https://www.cmsaf.eu. The user service includes information and documentation about the CM SAF and the CM SAF products, information on how to contact the user help desk and allows to search the product catalogue and to order products.

On the main webpage, a detailed description how to use the web interface for product search and ordering is given. We refer the user to this description since it is the central and most up to date documentation. However, some of the key features and services are briefly described in the following sections.

Copyright note:

5.1 Product ordering process

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

5.2 Contact User Help Desk staff

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

5.3 Feedback/User Problem Report

Users of CM SAF products and services are encouraged to provide feedback on the CM SAF product and services to the CM SAF team. Users can either contact the User Help Desk (see chapter 5.2) or use the “User Problem Report” page. A link to the “User Problem Report” is available either from the CM SAF main page (https://www.cmsaf.eu) or the Web User Interface main page.

5.4 Service Messages / log of changes

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

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7 Abbreviations

AOD	Aerosol Optical Depth
AVHRR	Advanced Very High Resolution Radiometer
BAL	Blue-sky surface ALbedo product
BB	Broadband
BRDF	Bidirectional Reflectance Distribution Function
BSRN	Baseline Surface Radiation Network
CCI	Climate Change Initiative (ESA)
CLARA	CM SAF cLoud, Albedo and surface RAdiation dataset from AVHRR data
CM SAF	Satellite Application Facility on Climate Monitoring
DEM	Digital Elevation Model
DWD	Deutscher Wetterdienst
ECMWF	European Center for Medium-Range Weather Forecasts
ECV	Essential Climate Variable
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
EPS	Enhanced Polar System
ESA	European Space Agency
FDR	Fundamental Data Record
FMI	Finnish Meteorological Institute
GC-Net	Greenland Climate Network
GCOS	Global Climate Observing System
ICDR	Interim Climate Data Record
IPCC	Intergovernmental Panel on Climate Change
KNMI	Koninklijk Nederlands Meteorologisch Instituut (Royal Netherlands Meteorological Institute)
LUC	Land Use Classification
LUT	Look-Up Table
MODIS	Moderate Resolution Imaging Spectroradiometer

NOAA	National Oceanic and Atmospheric Administration
NTB (C)	Narrow-to-Broadband (Conversion)
NWC-SAF	Nowcasting Satellite Application Facility
NWP	Numerical Weather Prediction
OSI-SAF	Ocean and Sea Ice Satellite Application Facility
PNG	Portable Network Graphics
PPS	Polar Platform System
PROMICE	Programme for Monitoring of the Greenland Ice Sheet
RMIB	Royal Meteorological Institute of Belgium
SAF	Satellite Application Facility
SAL	Surface ALbedo product, black-sky
SEVIRI	Spinning Enhanced Visible and Infra-Red Imager
SGP	Southern Great Plains (a BSRN site in the United States)
SMAC	Simplified method for the atmospheric correction of satellite measurements in the solar spectrum
SMHI	Swedish Meteorological and Hydrological Institute
SZA	Sun Zenith Angle
TCDR	Thematic Climate Data Record
TOA	Top of Atmosphere
UNFCCC	United Nations Framework Convention on Climate Change
USGS	United States Geological Survey
VZA	Viewing Zenith Angle
WAL	White-sky surface ALbedo product