EUMETSAT Satellite Application Facility on Climate Monitoring

Validation Report

Surface albedo

CLARA Edition 2.1

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Reference	Title	Code
AD 1	EUMETSAT CM SAF CDOP 2 Product Requirements Document (PRD)	SAF/CM/DWD/PRD/3.4
AD 2	Requirements Review RR 2.4 document	SAF/CM/CDOP2/KNMI/RR24, v1.2

Reference Documents

Reference	Title	Code
RD 1	Product User Manual CM SAF Cloud, Albedo, Radiation data record, AVHRR-based, Edition 2 (CLARA-A2) Surface Albedo	SAF/CM/FMI/PUM/GAC/SAL/2.1
RD 2	Algorithm Theoretical Basis Document CM SAF Cloud, Albedo, Radiation data record, AVHRR-based, Edition 2 (CLARA-A2) Surface Albedo	SAF/CM/FMI/ATBD/GAC/SAL/2.3
RD 3	Validation Report CM SAF Cloud, Albedo, Radiation data record, AVHRR-based, Edition 2 (CLARA-A2) Surface Albedo	SAF/CM/FMI/VAL/GAC/SAL/2.1

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1 Executive Summary

This CM SAF report provides information on the validation of the 2016-2019 extension of the CM SAF CLARA-A2 SAL data record derived from Advanced Very High Resolution Radiometer (AVHRR) observations on-board National Oceanic and Atmospheric Administration (NOAA) platforms NOAA7 – NOAA19 and EUMETSAT's Metop-A. Metop-B is not included due to uncertainty about the visible channel calibration stability.

The shortwave surface albedo, the ratio of reflected solar flux to the incoming solar flux, is an important driver of the surface energy budget of the Earth. Variations and trends in surface albedo can influence near-surface air temperatures as well as the melt-freeze cycles of sea ice and snow cover. Accurate determination of surface albedo is particularly important in the Polar regions, where snow and ice dynamics largely govern the surface energy budget.

This report presents an evaluation of the extended data record of Surface Broadband Albedo CM-11221, derived from the AVHRR radiances covering the years 1982-2019 (up to June).

The validation of the CLARA-A2 SAL extended record (Edition 2.1) follows the same procedure as the validation of CLARA-A2 SAL [RD 3]. We evaluate the product accuracy against reference ground observations of surface albedo from the Baseline Surface Radiation Network, augmented with the FMI Sodankylä site observations for high-latitude coverage. The comparability of the large-scale satellite observations against the point-like in situ observations is problematic. To minimize the effect of this, we primarily report the mean performance of individual (GAC-resolution) SAL observations against the in situ measurements (N=149619).

Augmenting information is offered on the performance of the grid cell albedo estimates, but noting that areal representativeness can play a very large role in the observed differences when comparing ~25 by 25 km grid cells against effective point-like in situ measurements. For this reason, the ~5 kilometer GAC retrieval performance is reported as the primary metric for accuracy. For stability, we report the maximum and standard deviations in multidecadal albedo retrievals at grid cell resolution over a quasi-stable target on Earth's surface (area on top of the Greenland Ice Sheet).

The product requirements for CLARA-A2 SAL Edition 2.1 [AD 1] report a target requirement of 10% relative retrieval bias, with 15% threshold accuracy. For stability, the requirements are 15% for target and 20% for threshold. The performance is now comparable to the requirements, with comments regarding performance against intended specifications.

Summarizing the retrieval performance, at GAC resolution the mean relative retrieval bias from all evaluated instantaneous retrievals is -9.8% (N=149619). At grid cell level, the corresponding mean relative retrieval error is -18.5% (-16.1% for 90% of evaluated months), highlighting the representativeness issue in point-to-pixel validation. The results at grid cell level differ from the original CLARA-A2 validation [RD 3] as the set of evaluated sites is different and metrics are now presented as averages of all evaluated months at all sites, thus giving greater weight to sites with longest in situ measurement coverage. We recall, however, that the GAC-resolution retrievals reflect 'true' algorithm performance better, and these retrievals are within target specification for accuracy. The CLARA-A2 SAL products have also been shown to be capable of tracking both the correct level of surface albedo for different land cover types, as well as its seasonal evolution over areas with seasonal snow cover [RD 3]. No apparent change in performance was detected during the extension period (2016-2019) relative to the original CLARA-A2 record.

The evaluation scores and their compliance to the target requirements of accuracy and precisions are given below:

Product	**Accuracy requirement** (relative bias)	**Achieved accuracy**
Surface Broadband Albedo (SAL)	**5% optimum** **10% target** **15% threshold**	**-9.8% (GAC resolution)**

Product	**Stability requirement** (max deviation from interannual mean albedo over a stable target, also reporting stdev of monthly mean albedos)	**Achieved accuracy**
Surface Broadband Albedo (SAL)	**2% optimum** **15% target** **20% threshold**	**8.39%**. Standard deviation of monthly mean retrievals: 0.0148

2 The EUMETSAT SAF on Climate Monitoring

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

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

In particular, the generation of long-term data 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 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 (World Climate Research Program). This role provides the CM SAF

with deep contacts to research organizations that form a substantial user group for the CM SAF CDRs,

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

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

3 Introduction

Shortwave surface albedo is defined as the ability of a surface to reflect solar radiation, i.e. it is the ratio of the reflected shortwave solar flux to the incoming one. The albedo of natural surfaces varies from ~5-6% (water, concrete) up to 90% (fresh, small-grained snow). Determination of the Earth's surface energy budget is dependent on our ability to accurately and robustly monitor global surface albedo. Thus, climate change studies require information about surface albedo and its changes. Thus has been acknowledged by GCOS in through naming surface albedo as an Essential Climate Variable (ECV). The directional-hemispherical reflectance, or black-sky albedo, is one way to estimate the surface albedo. Because the non-reflected solar radiation is absorbed and converted to heat energy, surface albedo and its variations also play a part in determining near-surface air temperatures.

In the polar and boreal regions, seasonal snow cover and changes in polar sea ice cover cause considerable changes in surface albedo (and vice versa through feedback effects). Changes in polar surface albedo have global effects (Hudson et al., 2011), and changes in surface albedo of the Arctic sea ice are closely tied to its mass budget (Holland et al., 2010). Therefore, monitoring polar, and especially Arctic, surface albedo is of highest importance.

This document is divided as follows; first we shall introduce the (extended) CLARA-A2 SAL product, validation strategy, and the validation reference data records. More details on the CLARA-A2 SAL product generation procedure and applied algorithms are available in the CLARA-A2 SAL Product User Manual [RD 1] and the Algorithm Theoretical Basis Document [RD 2]. Then we shall present the validation results per reference data source with a brief discussion. After all the results have been shown, we shall then discuss the data record stability and quality as a whole, and conclude with the main findings of the validation study.

4 The SAL products and validation strategy

The CLARA SAL is a shortwave black-sky surface albedo product, defined for the waveband of 250-2500 nm. Broadly speaking, the product generation process is as follows (details in ATBD [RD 2]):

- Inputs are the AVHRR CH1, CH2, solar/satellite geometry, cloud mask, geolocation, and land cover data from the Polar Platform System (PPS).
- AVHRR reflectances are corrected for radiometric and geolocation accuracy in terrain with steep topography (Manninen et al., 2011). The derived albedo therefore represents the surface material without Sun shadowing considerations.
- The atmospheric effects in the observed reflectance are removed with the SMAC algorithm (Rahman and Dedieu, 1994)
- 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). Snow BRDF effects are averaged temporally, no observed -level correction is applied.
- The spectral albedos are processed to shortwave broadband albedos via a narrow-to-broadband (NTB) conversion (Liang, 2000). The conversion is both instrument and pixel land cover specific. The land cover information comes from 4 different land use classification data records: USGS, GLC2000, GLOBCOVER2005 and GLOBCOVER2009. Open water albedo is derived from a LUT by Jin et al. (2004). The open water albedo depends on SZA and surface roughness, which is derived from wind speed, and is normalized to 60 degrees everywhere. Snow ice NTB is carried out following Xiong et al. (2002)

The observed products are then re-projected on a 0.05 degree global WGS84 latitude-longitude grid. Later, the products are temporally and spatially averaged to 5-day (pentad) and monthly means on a 0.25 degree global WGS84 latitude-longitude grid. This reprojection procedure is also re-applied to generate the means on Arctic and Antarctic products with a resolution of 25 kilometres.

For the CLARA-A2 extension, the daily AOD data record used for the atmospheric correction is not dynamic but a climatology (2005-2014) of the AOD used in the original CLARA-A2 SAL processing. This change was implemented due to the non-availability of timely and robust OMI and TOMS data for the extension period at the time of processing. The climatology is expected to capture the most relevant seasonal and geographical variation in atmospheric aerosol loading for the relatively short 2016-2019 period.

An example of the CLARA-A2.1 SAL end products is shown in Figure 1. The Antarctic region is in its midwinter period, thus there is no satellite data available due to poor solar illumination.

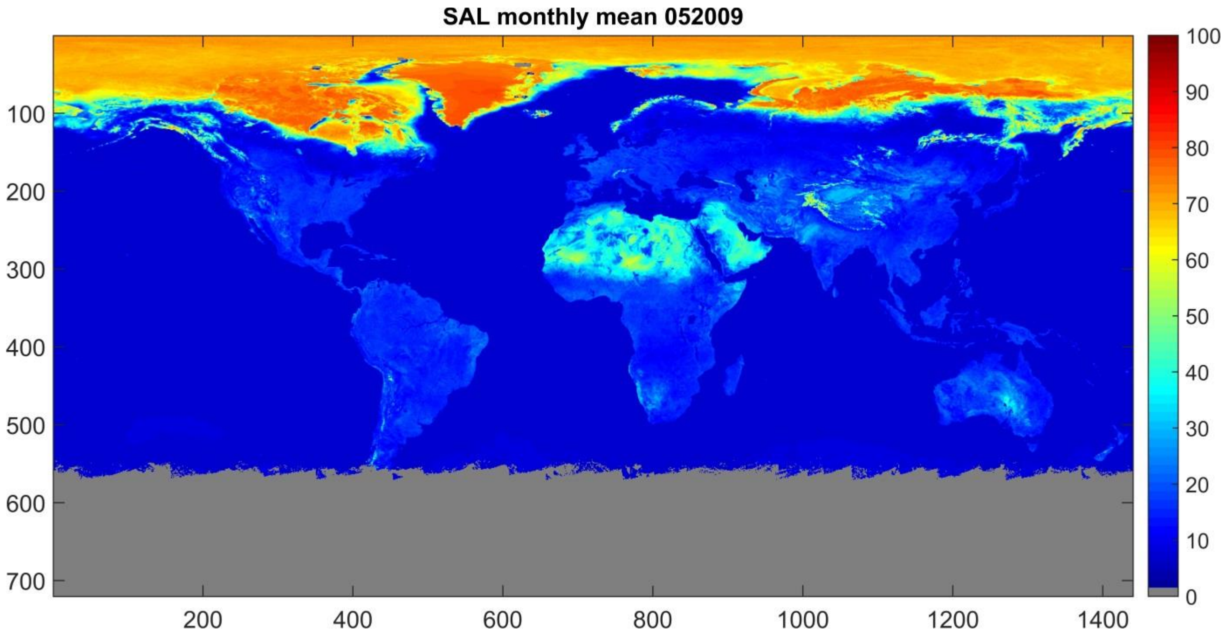

Figure 1: CLARA-A2.1 SAL monthly mean from May 2009.

4.1 Validation method

The validation of the CLARA SAL was made against in situ reference surface albedos, calculated from 1 minute measurements of global and reflected shortwave radiation. For the reference data to be comparable to the shortwave black-sky SAL product, an angle correction was made to the in situ surface albedo values for vegetated surfaces. The in situ surface albedo was also limited to include only realistic (between 0 and 1) values to exclude erroneous radiation measurements. Only measurements from times when the SZA was below 70° were included in the validation, due to the higher uncertainty of satellite based measurements made at high SZA.

The validation was made between the in situ value and the nearest SAL pixel value (at GAC and grid cell level), for both monthly and pentad SAL. In order for the validation to be as representative as possible, only in situ measurements from the SAL retrieval times were used. This was ensured by calculating 15 minute averages of the in situ surface albedo around the SAL retrieval times. These retrieval time averages were further averaged over the pentad and monthly product times.

Mean relative errors and RMSE were calculated for the SAL pentad and monthly products, using the corresponding in situ reference surface albedo. Instantaneous errors were calculated between the SAL at retrieval times and the corresponding in situ 15 minute average.

5 Validation data records

5.1 BSRN

The reference data used needs to be quality-controlled and have a sufficient data length to provide a meaningful comparison against the CLARA SAL time series. These criteria lead us to choose the Baseline Surface Radiation Network (BSRN) as the primary reference data source. The BSRN stations listed in Table 2 were used as reference. The choice of stations was done by the above-mentioned criteria and also for practical reasons; only a fraction of the BSRN stations worldwide record the reflected shortwave radiation necessary to calculate the surface albedo.

Table 1: BSRN stations used in validation

Station code	Name	Latitude (N)	Longitude (E)	Elevation	Time period
BOU	Boulder	40.0500	-105.0070	1577.0	1992-2015
DRA	Desert Rock	36.6260	-116.0180	1007.0	1998-2019
E13	Southern Great Plains	36.6050	-97.4850	318.0	1994-2018
FPE	Fort Peck	48.3167	-105.1000	634.0	1995-2019
GVN	Georg von Neumayer	-70.6500	-8.2500	42.0	1992-2019
PSU	Rock Springs	40.7200	-77.9333	376.0	1998-2019
TOR	Toravere	58.2540	26.4620	70.0	1999-2019
SYO	Syowa	-69.0050	39.5890	18.0	1998-2019
SDK	Sodankylä	67.381	26.629	179	2001-2014
SPO	South Pole	-89.9830	-24.7990	2800.0	1992-2017

Different BSRN sites exhibit different timeliness in the delivery of their measurements to the BSRN database. Therefore, the evaluation record lengths used here vary by evaluation site.

6 Evaluation of SAL against in situ observations

6.1 Overall results

We first display the overall retrieval evaluation statistics and some explanatory visualizations. For the site-specific results over the extension period 2016-2019, we highlight three sites; Syowa, Georg von Neumayer, and Southern Great Plains with a more detailed analysis. Respective in-depth analyses over other BSRN sites, sites on the Greenland Ice Sheet, and a comparison against MODIS albedo data (MCD43) are available for the interested reader in the CLARA-A2 SAL Validation Report [RD 3].

The monthly mean relative retrieval error per site is illustrated in Figure 2.

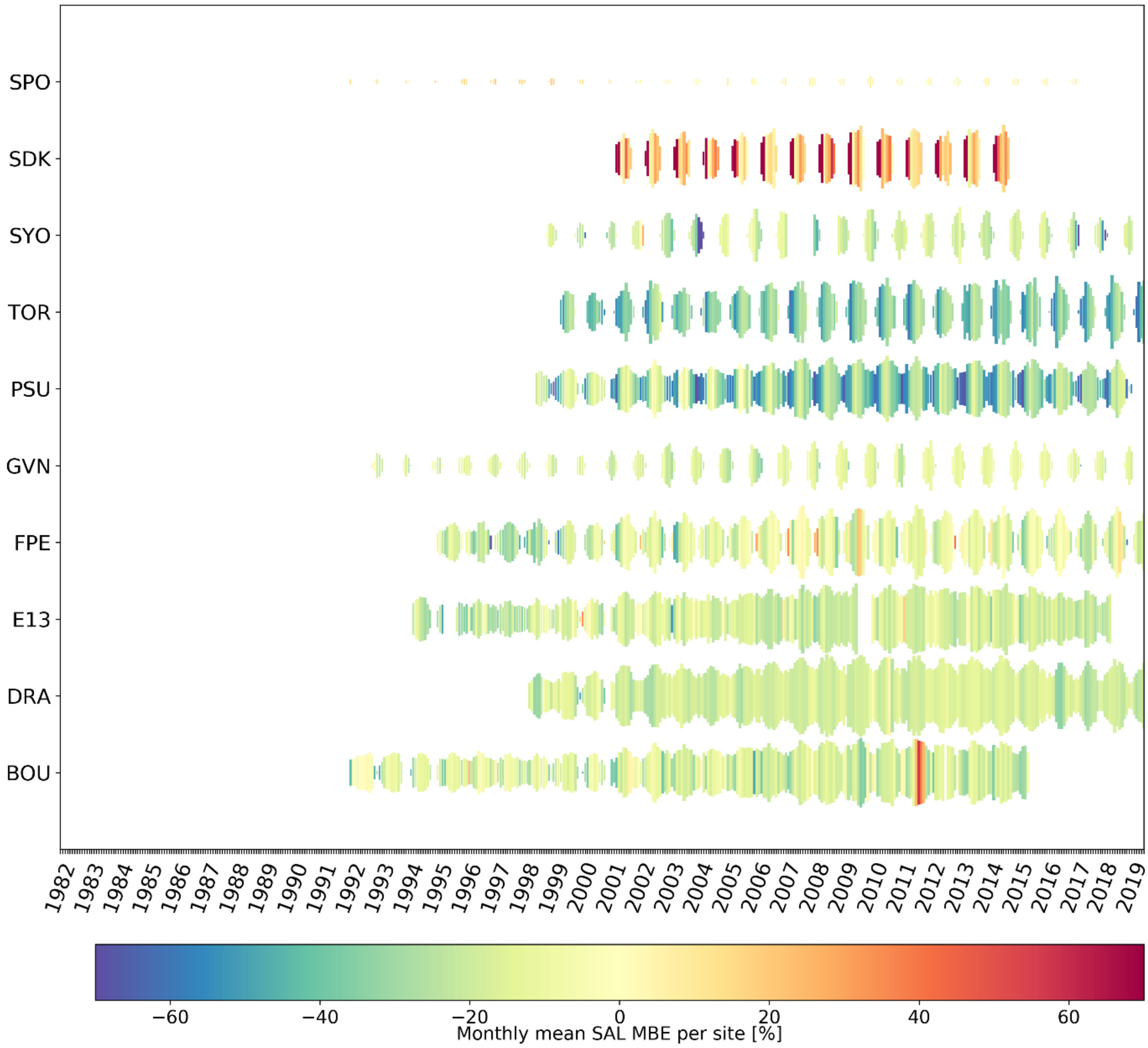

Figure 2: Monthly mean CLARA-A2.1 SAL relative retrieval error (MBE) per evaluation site across the dataset coverage. Sizes of coloured boxes reflect the amount of valid SAL retrievals at GAC resolution over the site during each period.

Of the evaluated sites, FMI-Sodankylä (SDK) tends to overestimate during spring because of different views on the seasonal snow cover between grid cell resolution SAL and the in situ measurement. Of the vegetated BSRN sites, Toravere and Rock Springs (TOR and PSU) show some tendency for underestimation, for other sites no major bias is evident. Year-to-year stability in retrieval performance is good and no significant change is apparent in the extension period relative to original. Pentad performance is highly similar to the monthly means shown here, with a mean retrieval bias of -18.2%. Of course, owing to the shorter sampling period, the pentad means exhibit more noise than monthly means, implying that the retrieval error for any specific pentad may be considerably higher or lower than the all-site average reported here.

The performance of the GAC-resolution retrievals is illustrated as aggregated over all sites and as a function of the Sun Zenith Angle (SZA) of the time of observation in Figure 3

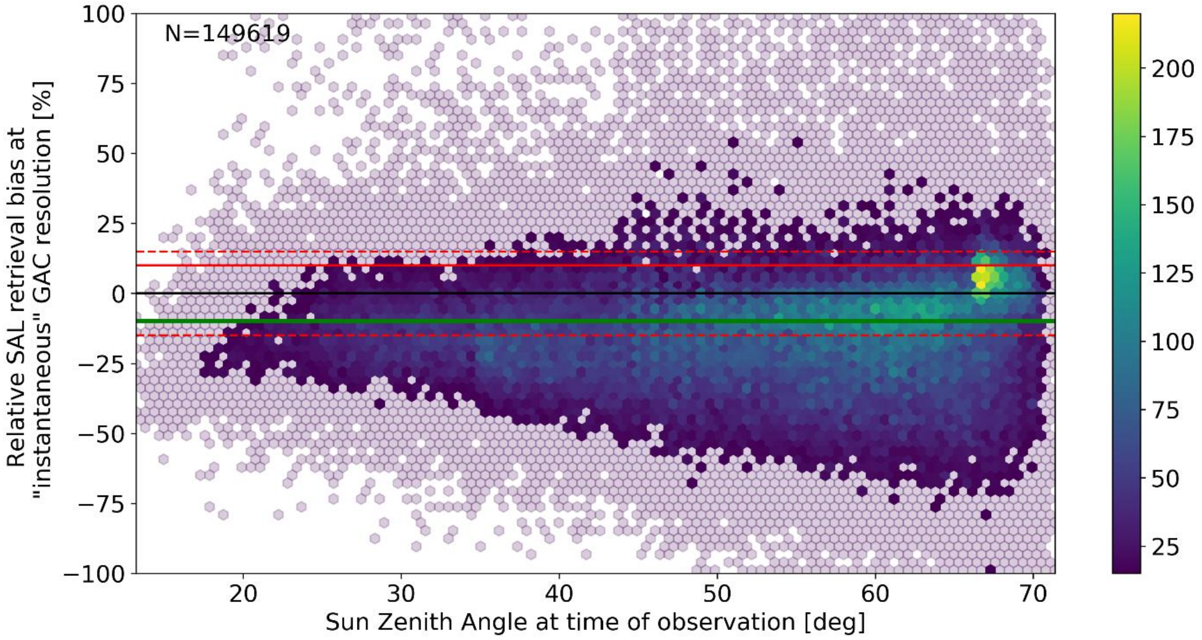

Figure 3: GAC-resolution relative retrieval error aggregated over all sites and full dataset coverage, as a function of Sun Zenith Angle (SZA) at time of observation. Red solid (dashed) lines indicate printed (intended) accuracy target requirement of 10% (15%). Green horizontal line indicates achieved mean relative retrieval error (bias) for GAC-resolution CLARA-A2 SAL Edition 2.1. Colouring truncated to highlight major portion of sample population.

As expected, retrieval errors increase with SZA. The cause is twofold; firstly, atmospheric path lengths increase with increasing SZA, presenting additional challenges for the atmospheric correction in SAL. Bidirectional reflectance effects (BRDF) also increase with oblique incoming radiation angles. And secondly, over Arctic or Antarctic sites SZAs tend to be larger, combining the aforementioned issues with ones such as different views (between AVHRR-GAC and in situ) into snow cover extent and properties.

The mean relative errors for the three spatiotemporal scales (instantaneous GAC, pentad grid, and monthly mean grid) for each site are summarized in Table 2

Table 2: Site-specific mean retrieval errors for the full CLARA period. Large relative error at Sodankylä is caused partly by the different views into seasonal snow, and partly by the low albedo of boreal forest (10% error from albedo of 0.1 is just 0.01, thus small absolute errors lead to large relative errors).

Site	GAC mean relative retrieval error [%]	Pentad mean relative retrieval error [%]	Monthly mean relative retrieval error [%]
BOU	-4.7	-13.0	-16.0
DRA	-19.5	-17.6	-18.0
E13	-15.0	-15.4	-17.8
FPE	-13.3	-12.4	-14.3
GVN	-8.8	-13.8	-14.1
PSU	-22.5	-30.9	-34.9
TOR	-27.9	-34.6	-37.0
SYO	-9.9	-20.0	-21.2
SDK	+33.3	+45.1	+44.1
SPO	+6.9	+6.8	+6.9

6.1.1 Syowa (SYO) station, Antarctica

The extension period validation against in situ reference measurements at BSRN Syowa station, Antarctica, are illustrated in Figure 4. The results indicate stable retrieval performance over austral summer of 2016 (Jan-Mar), but substantial differences between in situ measurement and SAL over the latter parts of austral summers of 2017 and 2018. These differences are traceable to representativeness issues over the site during these periods.

Specifically, examination of high-resolution Landsat-8 imagery revealed that sea ice conditions around East Ongul Island varied considerably between 2016 and 2017-2018. Figure 5 illustrates this variation, explaining why 2016 results are in line with expected performance (intact sea ice around the island implies good areal representativeness of point-like in situ measurement over snow), whereas the open water around the island in 2017 and 2018 will inevitably produce large differences between the 25 x 25 km SAL grid cell mean albedo and the point-like albedo measurement at Syowa station.

This reasoning is further supported by the much better agreement between the instantaneous SAL retrievals over Syowa, recorded at GAC resolution during the algorithm calculations, and the in situ measurement. The performance of these higher-resolution retrievals is arguably a better benchmark for SAL algorithm accuracy because of this high degree of spatial heterogeneity in local surface conditions relative to the in situ measurement point, even though we note that also the GAC resolution retrievals begin to degrade once the immediate waters around the island become free of ice. Considering the apparent transition from ice cover to open water, though, it might instead be argued that the increasing difference between the grid-scale SAL retrievals and the small-footprint in situ measurements is actually a positive sign for the data record performance, as stability in retrieved albedo under these conditions would have implied substantial problems in either cloud detection or atmospheric corrections over the site.

The validation metrics at Syowa are presented in Table 3. The in situ record for 2019 is rather short and prevents evaluation of retrieval performance at the seasonal scale.

Table 3: Monthly mean validation metrics at Syowa station for the extension period

	MBE	RMSE	N
Instantaneous	-12.13%	0.162	590
Monthly mean	-33.90%	0.300	16
DJF	-40.97%	0.337	9
MAM	-51.10%	0.414	2
JJA	-	-	-
SON	-14.30%	0.126	5

Table 4: Pentad mean validation metrics at Syowa station for the extension period

	MBE	RMSE	N
Pentad mean	-33.04%	0.294	79
DJF	-39.81%	0.334	53
MAM	-50.81%	0.436	2
JJA	-	-	-
SON	-16.63%	0.150	24

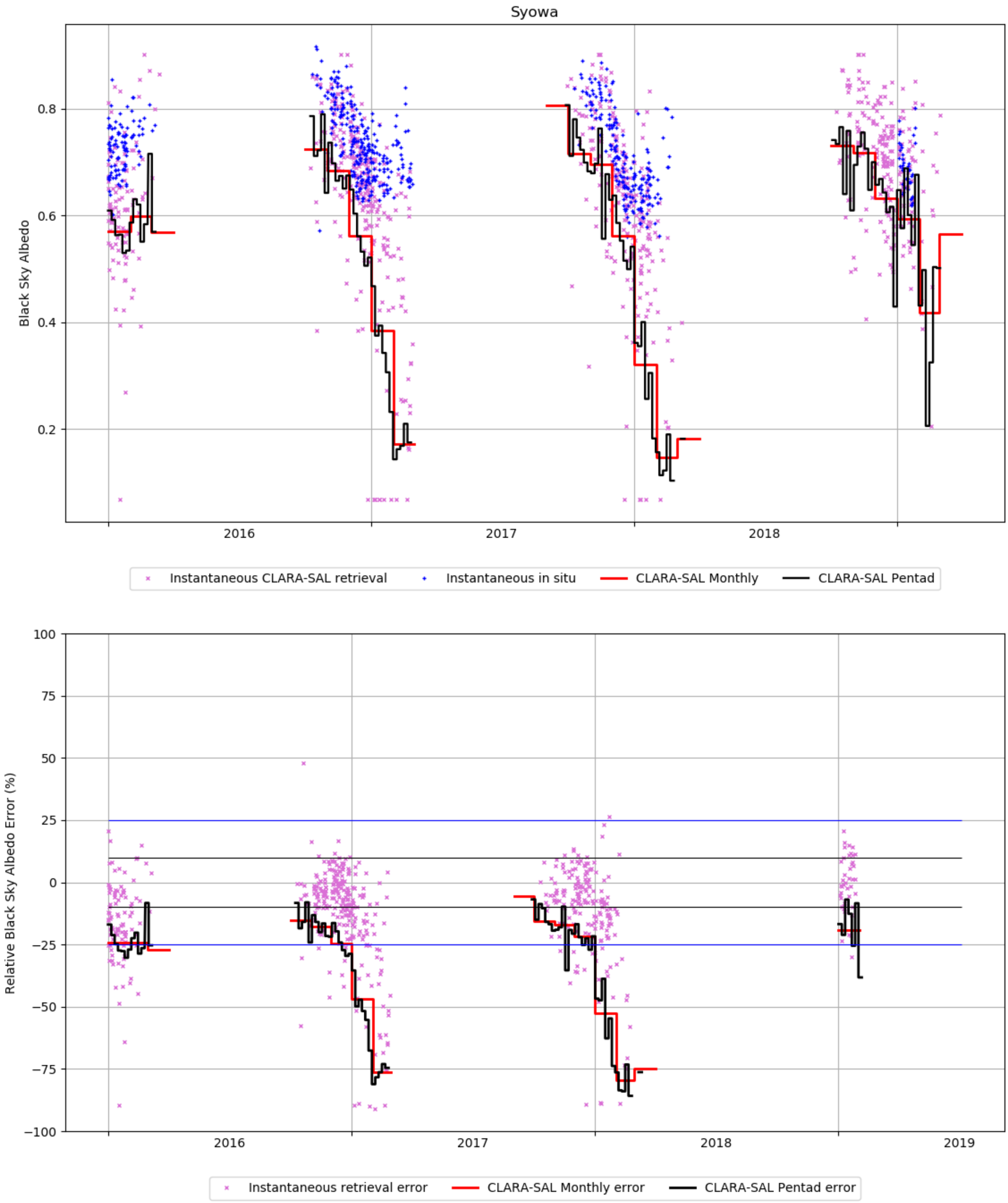

Figure 4: Top: time series representation of SAL monthly means (red stairstep), pentad means (black stairstep), spatiotemporally collocated 15-minute means of BSRN measurements at clear-sky AVHRR overpass times (blue), and the instantaneous SAL retrievals at GAC resolution (purple) at Syowa station. Bottom: Time series representation of differences between retrieved SAL albedos and corresponding sets of BSRN measurements. Colour as in top subplot. Black and blue horizontal lines indicate 10% and 25% (target) relative retrieval errors, respectively. See text for a discussion on result representativeness.

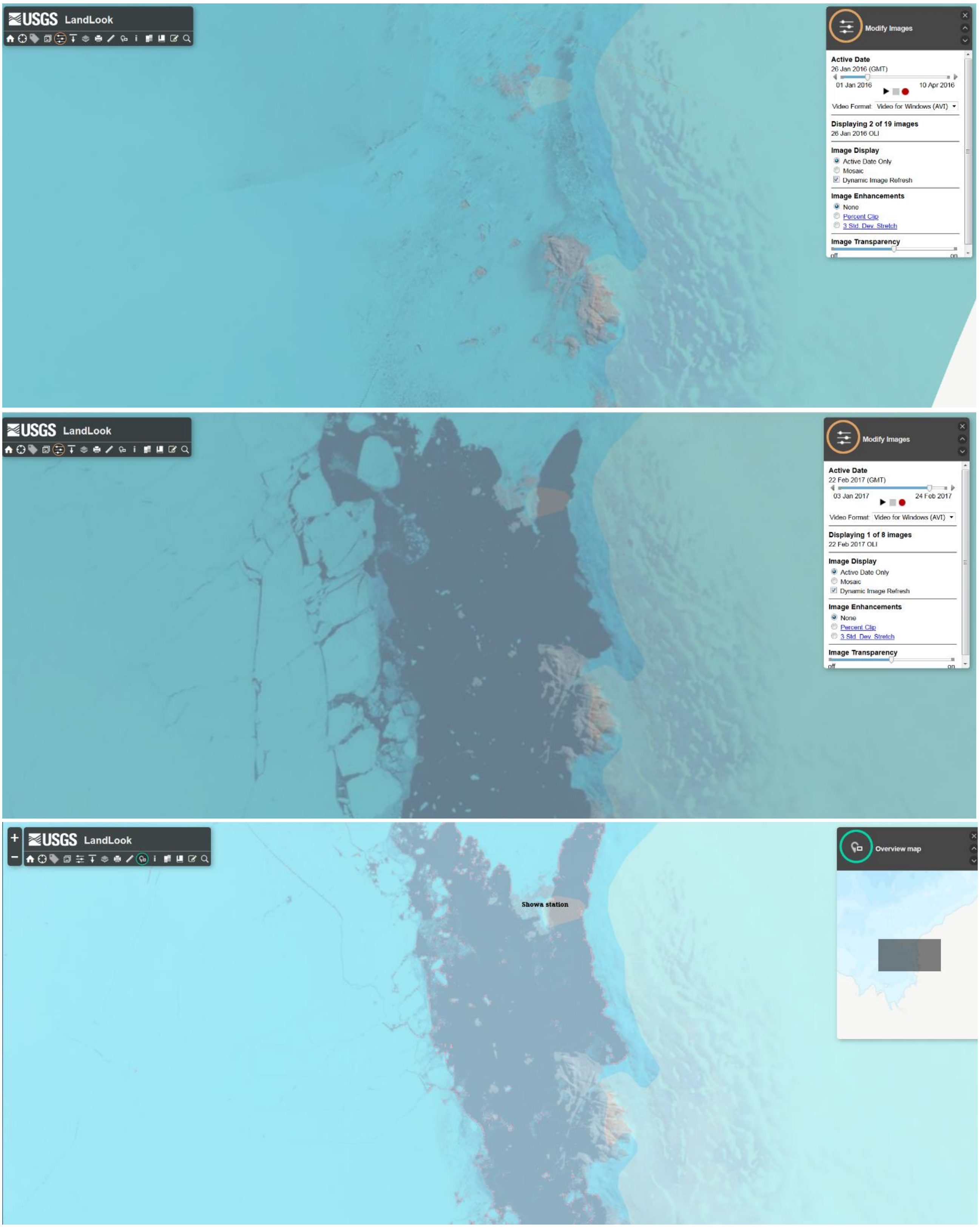

Figure 5: top: intact sea ice around Syowa station in January 2016. Middle: broken ice and large areas of open dark water around the site in Feb 2017. Bottom: Broken ice and large open water areas around the site in Feb 2018. East Ongul Island marked with text. Images from LandSat-8, courtesy of USGS LandLook viewer.

6.1.2 Neumayer station (GVN), Antarctica

Unlike Syowa station, Neumayer is located further away from the coastline and its local surface conditions are therefore more stable. This is reflected in the extended period validation as better spatial representativeness for the in situ measurement and subsequently better agreement for the 25x25 km area-averaged SAL retrievals. The retrievals are illustrated in Figure 6. Especially the GAC resolution SAL retrievals agree very well with in situ measurements, with no evidence of a systematic bias.

The good agreement at Neumayer is further evidence that the disagreements at Syowa station are not caused by algorithm instability in SAL but rather spatial representativeness issues. The performance of SAL over snow and ice surfaces in the CLARA-A2 extension appear to be fully consistent with the original CLARA-A2 SAL record, meeting the target requirement of 25% relative accuracy, with no evidence of an increased bias or instability.

Table 5: Monthly mean validation metrics at Neumayer station for the extension period

	MBE	RMSE	N
Instantaneous	-7.09%	0.111	561
Monthly mean	-15.17%	0.159	18
DJF	-15.80%	0.137	10
MAM	-33.22%	0.341	2
JJA	-	-	-
SON	-8.11%	0.076	6

Table 6: Pentad mean validation metrics at Neumayer station for the extension period

	MBE	RMSE	N
Pentad mean	-14.16%	0.143	89
DJF	-16.56%	0.153	57
MAM	-32.74%	0.338	2
JJA	-	-	-
SON	-8.34%	0.143	30

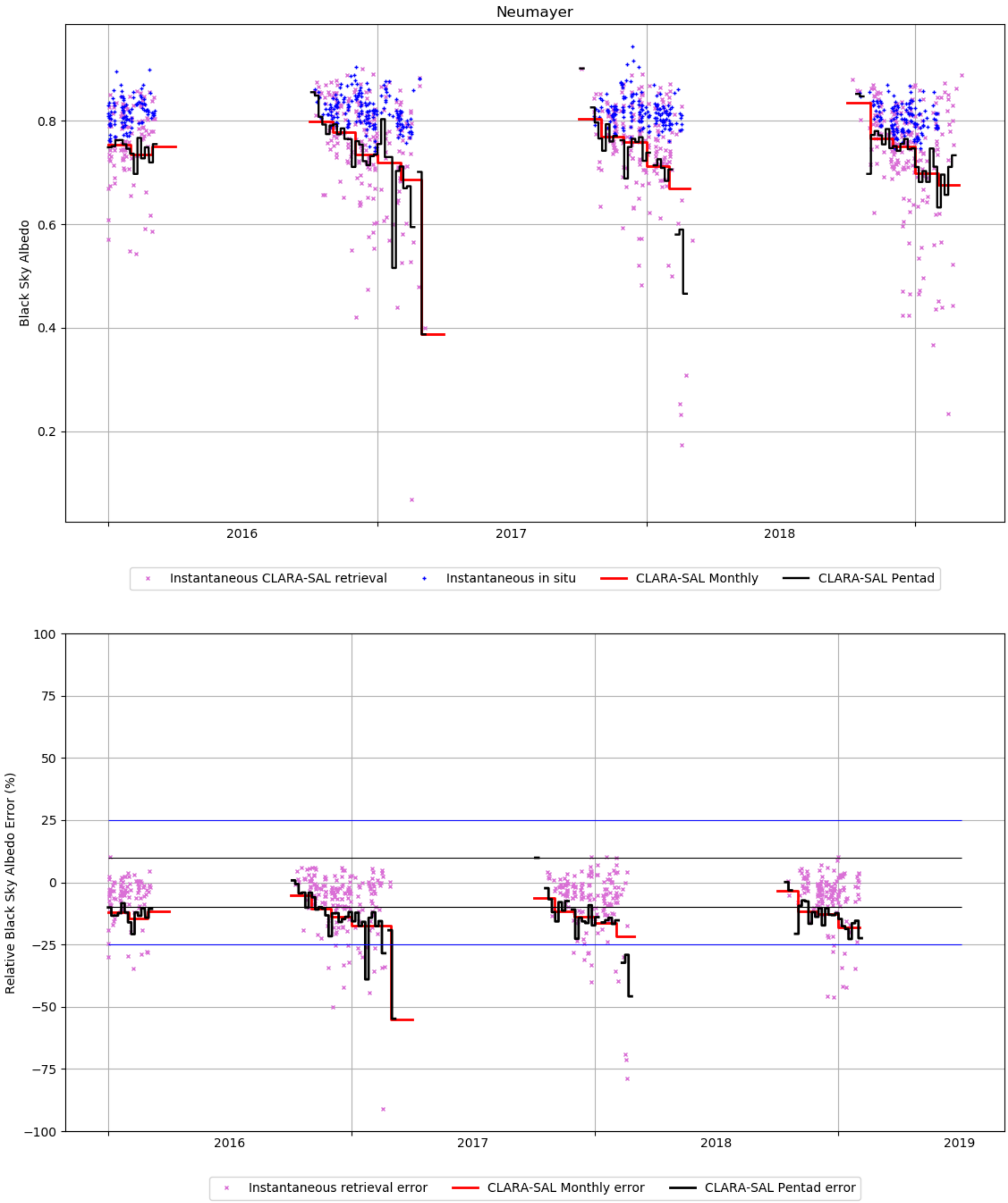

Figure 6: Top: time series representation of SAL monthly means (red stairstep), pentad means (black stairstep), spatiotemporally collocated 15-minute means of BSRN measurements at clear-sky AVHRR overpass times (blue), and the instantaneous SAL retrievals at GAC resolution (purple) at Neumayer station. Bottom: Time series representation of differences between retrieved SAL albedos and corresponding sets of BSRN measurements. Color as in top subplot. Black and blue horizontal lines

indicate 10% and 25% (target) relative retrieval errors, respectively. See text for a discussion on result representativeness.

6.1.3 Southern Great Plains (E13), continental United States

Moving on to retrievals over vegetation, we assess the CLARA-A2 extension performance over the Southern Great Plains (SGP; also called E13) BSRN site in the U.S. The retrievals and in situ measurements are illustrated in Figure 7, and retrieval metrics shown in Table 7 and Table 8.

Here, retrieval performance is expected not to be severely impacted by spatial representativeness, as the agriculturally developed region around the site contains a limited range of land cover types, most of which are open fields. Temporally aggregated SAL retrievals appear very stable between 2016-2018. Note that the BSRN site has not provided new in situ measurements to the BSRN database after mid-2017. Available results are consistent with the overall full period evaluation results at SGP (Table 2).

Overall, relative to the full CLARA-A2 validation, the extension shows a slightly more negative retrieval bias at SGP relative to the in situ reference, yet still fully within the target requirement. The difference is small (6-10% relative) enough that it is difficult to ascertain if it results from uncorrected drift in the AVHRR instruments' radiometric calibration, or if it results from the recomputed SAL – in-situ collocation algorithm, which now uses a more accurate geodistance calculation (Haversine) for the pentad/monthly mean matchups.

Table 7: Monthly mean validation metrics at Southern Great Plains (E13) station

	MBE	RMSE	N
Instantaneous	-17.54%	0.076	841
Monthly mean	-19.68%	0.043	17
DJF	-20.95%	0.047	5
MAM	-17.77%	0.039	6
JJA	-22.43%	0.046	3
SON	-18.62%	0.039	3

Table 8: Pentad mean validation metrics at Southern Great Plains (E13) station

	MBE	RMSE	N
Pentad mean	-18.92%	0.048	104
DJF	-19.90%	0.049	30
MAM	-16.10%	0.046	38

	MBE	RMSE	N
JJA	-22.95%	0.055	18
SON	-19.20%	0.042	18

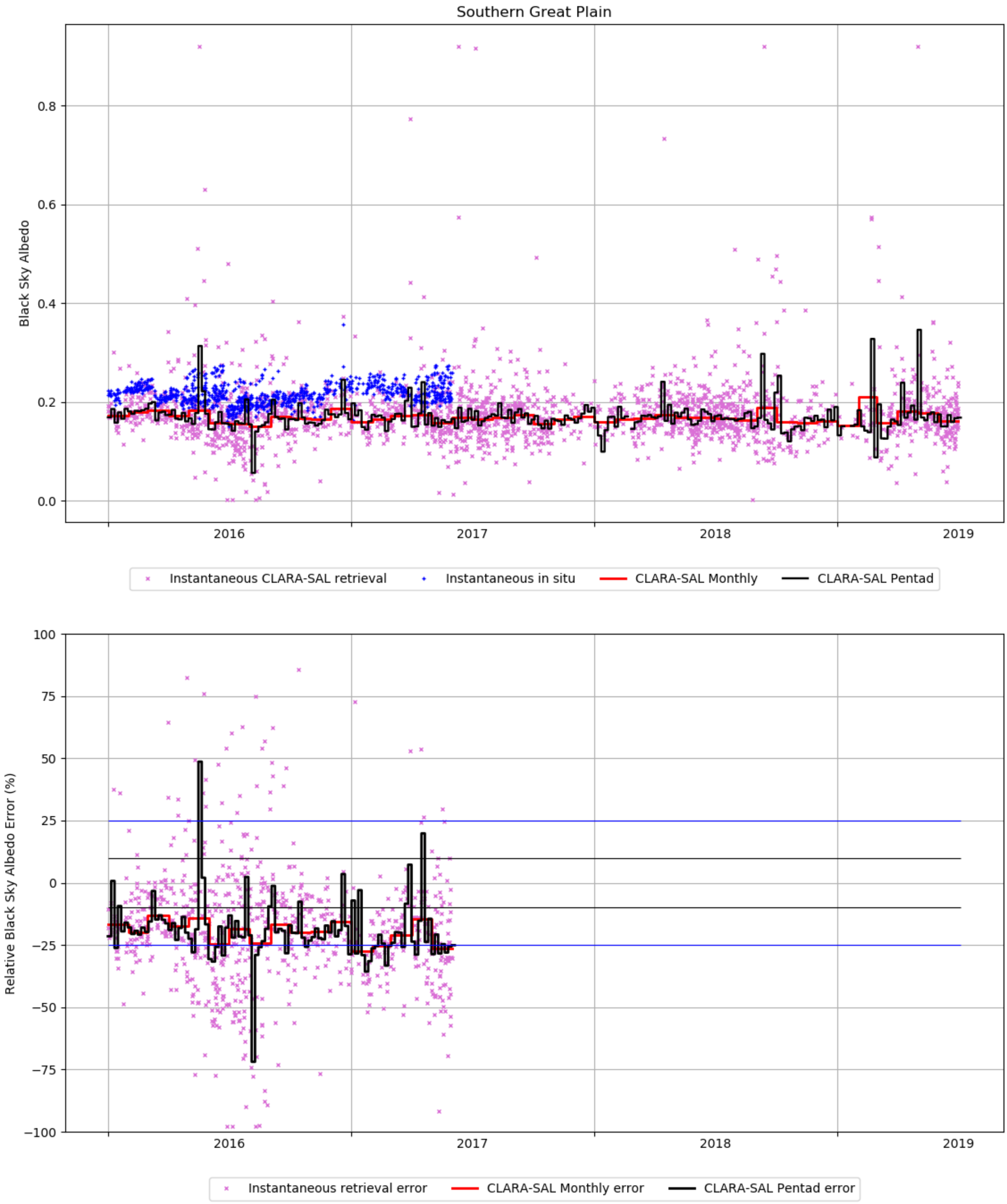

Figure 7: Top: time series representation of SAL monthly means (red stairstep), pentad means (black stairstep), spatiotemporally collocated 15-minute means of BSRN measurements at clear-sky AVHRR overpass times (blue), and the instantaneous SAL retrievals at GAC resolution (purple) at Southern Great Plains (E13) station. Bottom: Time series representation of differences between retrieved SAL albedos and corresponding sets of BSRN measurements. Color as in top subplot. Black and blue

horizontal lines indicate 10% and 25% (target) relative retrieval errors, respectively. See text for a discussion on result representativeness.

6.2 CLARA-A2 SAL stability

We evaluate the stability record by comparing the monthly mean albedos of the extension against the original CLARA-A2 record over a region of the central Greenland Ice Sheet (73-75 N, 38-42 W). This region's surface albedo remains naturally quite stable on monthly timescales even during the melting season. The time-evolution of the SAL retrievals over this area are shown in Figure 8. The albedo retrievals of the extension fit within the estimated retrieval uncertainty envelope of SAL for this region (blue shading) apart from May-June 2019. Despite the intensity of the 2019 melting season over the ice sheet, it is not clear if the albedo level decrease is anomalous for natural reasons or e.g. because of unaccounted-for drift in AVHRR calibration. Nevertheless, the deviation remains modest and is not considered grounds for rejection of the extension record. Maximum recorded deviation from the interannual mean is 8.39%, with standard deviation about the interannual mean albedo at 0.0148 [albedo scaled between 0…1].

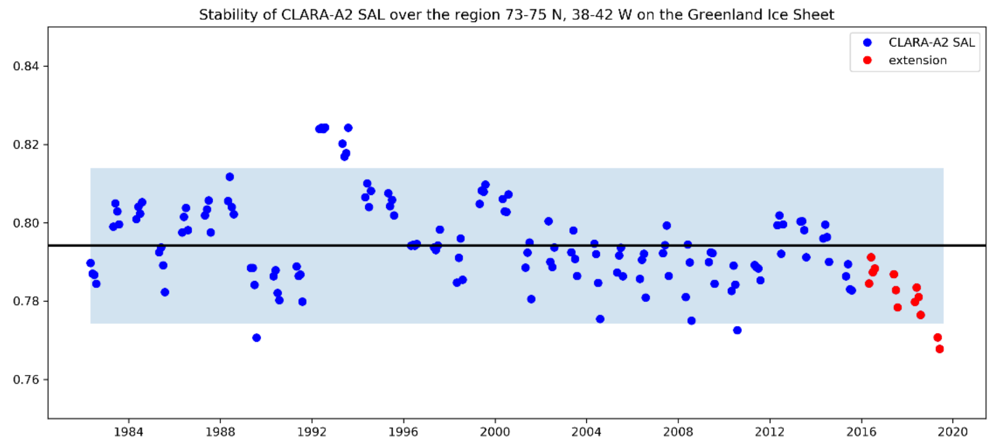

Figure 8: Retrieved monthly mean albedos over central Greenland Ice Sheet from the CLARA-A2 record (blue) and its extension (red).

7 Conclusions

With this report we document the validation of the extended CLARA-A2 data record specifically for the surface albedo (SAL) dataset. The evaluation was carried out as a comparison of quality-controlled in situ albedo measurements against both grid cell-averaged SAL albedo estimates (official dataset) as well instantaneous albedo/reflectance estimates at AVHRR GAC resolution, recorded during the data record computation. **We find that the primary metric, that is, GAC resolution retrievals are within the target requirement of 10% relative retrieval accuracy.** For the grid cell level retrievals, variable spatial representativeness at the evaluation sites creates challenges in result interpretation owing to the point-to-pixel validation method used.

Of the three BSRN sites highlighted here for the extension period, two (Syowa and Neumayer) are located over Antarctic snow and ice cover, and one (Southern Great Plains) are vegetation targets over Europe and North America. Over snow and ice, the comparison over Neumayer yields retrieval accuracies in line with the evaluation of the original CLARA-A2 SAL record. Over Syowa, only 2016 repeats prior retrievals, with 2017-2019 displaying an apparent degradation in accuracy. However, a deeper analysis of local conditions proves this to be an illusory ‘degradation’, as it results fully from a marked change in sea ice conditions from closed ice to open water in the area around the site (Syowa is located on an island off the Antarctic mainland). Good agreement between in situ measured albedo and the GAC-resolution SAL retrievals over both Syowa and Neumayer further reinforces the finding that the algorithm performance remains essentially stable over snow and ice.

Variable spatial representativeness of small-scale in situ albedo measurements against spatially aggregated satellite observations remains a key challenge in evaluating true algorithm precision. Albedo retrievals over a region in the central part of the Greenland Ice Sheet remain stable and in line with the original CLARA-A2 record, apart from summer 2019 where a slight negative deviation is noted. Given the intensity of the melting season over the ice sheet, however, albedo decrease from natural sources (e.g. snow grain growth) cannot be discounted. Given the reasoning above, we conclude that the performance of the CLARA Edition 2.1 for surface albedo retrievals is in line with the original dataset and the data record extension may be recommended for release.

8 References

Gascard, J.-C., et al. (2008), Exploring Arctic Transpolar Drift During Dramatic Sea Ice Retreat, Eos Trans. AGU, 89(3), 21, doi:10.1029/2008EO030001.

Govaerts, Y.M., and Lattanzio, A. (2007). Retrieval error estimation of surface albedo derived from geostationary large band satellite observations: Application to Meteosat-2 and Meteosat-7 data. Journal of Geophysical Research, 112, D05102.

Holland, M., Serreze, M., and Stroeve, J.. The sea ice mass budget of the arctic and its future change as simulated by coupled climate models. Climate Dynamics, 34(2):185–200.

Hudson, S. R. (2011). Estimating the global radiative impact of the sea ice–albedo feedback in the Arctic, Journal of Geophysical Research, 116, D16102, doi:10.1029/2011JD015804.

Jin, Z., Charlock, T.P. Smith, Jr, William L. and Rutledge, K. (2004). A parameterization of ocean surface albedo. Geophysical Research Letters, 31, L22301.

Liang, S. (2000). Narrowband to broadband conversions of land surface albedo I: Algorithms. Remote Sensing of Environment, 76, 213–238.

Manninen, T., Andersson, K., and Riihelä, A. (2011). Topography correction of the CM-SAF surface albedo product SAL. EUMETSAT Meteorological Satellite Conference, proceedings.

Manninen, T., Riihelä, A., and de Leeuw, G. (2012): Atmospheric effect on the ground-based measurements of broadband surface albedo, Atmos. Meas. Tech. Discuss., 5, 385-409, doi:10.5194/amtd-5-385-2012

Ohmura, A., Dutton, E.G., Forgan, B., Fröhlich, C., Gilgen, H., Hegner, H., Heimo, A., König-Langlo, G., McArthur, B., Müller, G., Philipona, R., Pinker, R., Whitlock, C.H., Dehne, K., and Wild, M. (1998). Baseline Surface Radiation Network (BSRN/WCRP): New Precision Radiometry for Climate Research. Bull. Amer. Meteor. Soc., 79, 2115 - 2136.

Rahman, H. and Dedieu, G. (1994): SMAC: a simplified method for the atmospheric correction of satellite measurements in the solar spectrum. International Journal of Remote Sensing, 15, 123-143.

Riihelä, A., Laine, V., Manninen, T., Palo, T., Vihma, T. (2010). Validation of the CM SAFsurface broadband albedo product: Comparisons with in situ observations over Greenland and the ice-covered Arctic Ocean. Remote Sensing of Environment, 114 (11), 2779-2790.

Riihelä, A., Manninen, T., Laine, V., Andersson, K and Kaspar, F. (2013): CLARA-SAL: a global 28 yr timeseries of Earth's black-sky surface albedo. Atmospheric Chemistry and Physics, 13, 3743-3762.

Roujean, J.L., Leroy, M., and Deschamps, P-Y. (1992): A bidirectional reflectance model of the earth's surface for the correction of remote sensing data. Journal of Geophysical Research, 97(18), 20455–20468.

Steffen, K., J. E. Box, and W. Abdalati, (1996). "Greenland Climate Network: GC-Net", in Colbeck, S. C. Ed. CRREL 96-27 Special Report on Glaciers, Ice Sheets and Volcanoes, trib. to M. Meier, pp. 98-103.

Stroeve, J. and Nolin, A. (2002). Comparison of MODIS and MISR-derived surface albedo with in situ measurements in Greenland. Proceedings of EARSeL-LISSIG-Workshop Observing our Cryosphere from Space, Bern, March 11 – 13, 2002.

Vihma, T., Jaagus, J., Jakobson, E., and Palo, T. (2008). Meteorological conditions in the Arctic Ocean in spring and summer 2007 as recorded on the drifting ice station Tara, Geophysical Research Letters, 35, L18706, doi:10.1029/2008GL034681.

Wu, A. Li, Z. and Cihlar, J. (1995). Effects of land cover type and greenness on advanced very high resolution radiometer bidirectional reflectances: Analysis and removal. Journal of Geophysical Research, 100(D5), 9179–9192.

Xiong, X., Stamnes, K., & Lubin, D. (2002). Surface albedo over the Arctic Ocean derived from AVHRR and its validation with SHEBA data. Journal of applied Meteorology, 41(4), 413-425.

9 Glossary

AOD	Aerosol Optical Depth
APP-X	AVHRR Polar Pathfinder Extended
AVHRR	Advanced Very High Resolution Radiometer (NOAA)
BB	Broadband
BRDF	Bidirectional Reflectance Distribution Function
BSRN	Baseline Surface Radiation Network
CERES	Clouds and the Earth's Radiant Energy System
CDOP	Continuous Development and Operations Phase
CLARA-A2	SAL CMSAFncLouds, Albedo and Radiation – Surface Albedo produc
CMSAF	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
FMI	Finnish Meteorological Institute
GC-Net	Greenland Climate Network
GCOS	Global Climate Observing System
KNMI	Koninklijk Nederlands Meteorologisch Instituut (Royal Netherlands Meteorological Institute)
LUC	Land Use Classification
LUT	Look-Up Table
MODIS	Moderate Resolution Imaging Spectroradiometer
NH	Northern Hemisphere
NOAA	National Oceanic and Atmospheric Administration
NTB (C)	Narrow-to-Broadband (Conversion)

PPS	Polar Platform System
RMIB	Royal Meteorological Institute of Belgium
SAF	Satellite Application Facility
SMAC	Simplified method for the atmospheric correction of satellite measurements in the solar spectrum
SMHI	Swedish Meteorological and Hydrological Institute
SZA	Sun Zenith Angle
TOA	Top of Atmosphere
USGS	United States Geological Survey
VZA	Viewing Zenith Angle