EUMETSAT Satellite Application Facility on Climate Monitoring

Validation Report

CM SAF Cloud, Albedo, Radiation data record, AVHRR-based, Edition 2 (CLARA-A2)

Surface Albedo

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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

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1. Executive Summary

This CM SAF report provides information on the validation 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 and Metop-B. It is the successor of the CLARA-A1-SAL data record.

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 data record of **Surface Broadband Albedo CM-11221** from the 34-year AVHRR radiances covering the years 1982-2015.

The validation of the CLARA-A2-SAL algorithm follows the same procedure as the validation of CLARA-A1-SAL and is performed in two parts. First we evaluate the product accuracy against ground observations of surface albedo. The comparability of the large-scale satellite observations against the point-like in situ observations is problematic. To minimize the effect of this, we have formed monthly and pentad mean SAL values of individual SAL observations near the in situ station, and use these in the comparison. The issue of representativeness on a global scale is then explored further with a comparison of CLARA-A2-SAL to existing global surface black-sky albedo product MODIS MCD43C3 edition 5.

The validation results show that CLARA-A2-SAL achieves its target accuracy of 25% relative to reference observation. In the cases where the target is not met, the cause is found to be poor representativeness of the in situ albedo data for the area around the validation site. Obtaining a regional albedo that is comparable to AVHRR satellite retrievals would require airborne observations of albedo, which are not routinely available. Regardless, the CLARA-A2-SAL products have 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.

A summary of the validation results is shown in Table 1. The table contains the mean relative retrieval difference calculated from the observed level monthly mean results of all validation sites for the entire validation period 1992-2014 and the decadal stability (maximum deviation of retrieved monthly mean albedo from its 34-year mean, in relative units) as calculated from the mean albedo of the central Greenland Ice Sheet, the closest we could find to a naturally stable albedo target on Earth. For comparison, a similar stability figure is calculated for the Libya desert and a forested site in Central Europe.

Table 1: Validation result summary

Mean relative retrieval error (all sites, full period)	**-0.60 %**
Mean RMSE (all sites, full period)	**0.075**
Decadal stability over central Greenland Ice Sheet (1982-2015, in relative units)	**8.5 %**

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), 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, 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.

Continuous monitoring of global surface albedo is cost-effective only through satellite observations. The NOAA AVHRR time series of 1982-2015 offers the longest duration data record of global observations applicable for surface albedo product generation. The CM SAF project has now applied this time series into the production of the second release of the global (90N – 90S) CLARA-SAL surface albedo data record, complete with sea ice, snow, open water, and land surface albedo coverage. The purpose of this document is to describe the procedures and results of the validation of this data record against reference observations of surface albedo.

This document is divided as follows; first we shall introduce the validation reference data records and the main characteristics of the CLARA-A2-SAL data record. 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 quality as a whole, identify issues in the data for correction in future releases, and conclude with the main findings of the validation study.

4. CLARA-A2-SAL Main Characteristics

The CLARA-A2-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.

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.

An example of the CLARA-A2-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.

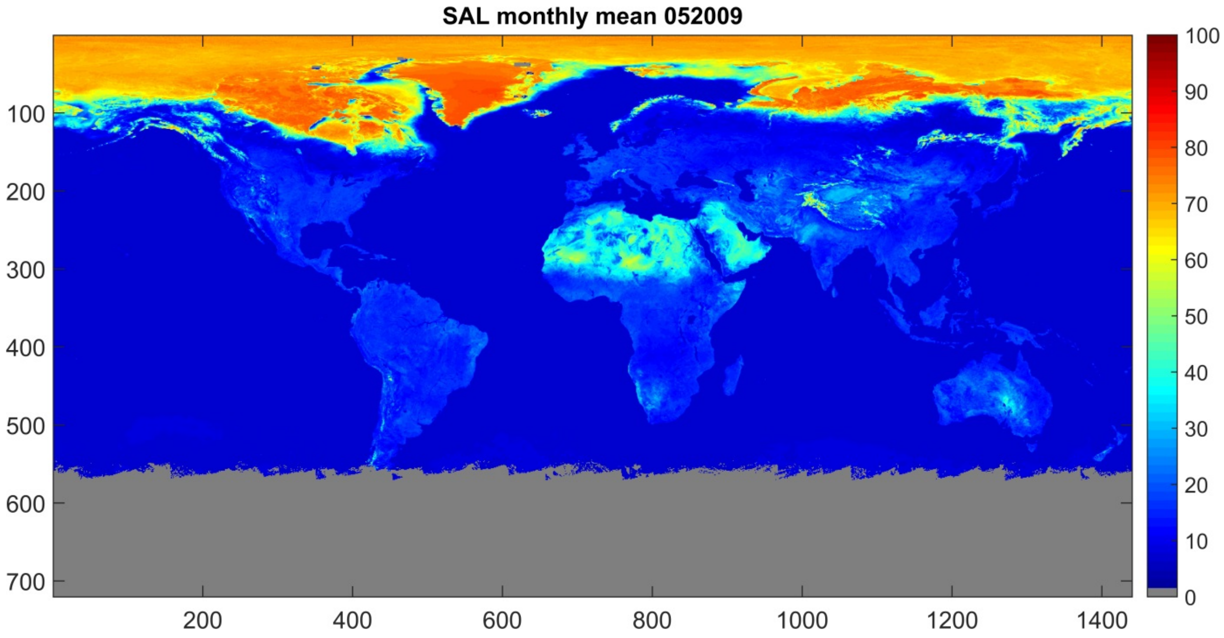

Figure 1: CLARA-A2-SAL monthly mean from May 2009.

5. Validation Data records

The reference data used needs to be quality-controlled and have a sufficient data length to provide a meaningful comparison against the CLARA-A2-SAL time series. These criteria lead us to choose the Baseline Surface Radiation Network (BSRN) and the Greenland Climate Network (GC-Net) as the primary reference data sources (Ohmura et al., 1998 & Steffen et al., 1996). 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 2: BSRN stations used in validation

Station name / location	Latitude (N)	Longitude (E)	Land use type	Time period
Neumayer, Antarctica	-70.65	-8.25	snow/ice, flat	1992-2014
Payerne, Switzerland	46.82	6.95	cultivated, hilly	1992-2011
Southern Great Plains, USA	36.61	-97.49	grass, flat	1994-2012
Syowa, Antarctica	-69	39.59	snow/ice, hilly	1998-2014

The reference data record also includes snow albedo observations from AWS stations of the Greenland Climate Network (GC-Net). These stations are unmanned; therefore extra attention was paid in pre-screening the data for anomalies. The participating stations are listed in Table 3. All GC-Net stations are on snow/ice terrain. JAR-2 station is close enough to the Ice Sheet edge to experience significant ice flow, melt ponding and impurity concentrations.

To bolster the data record further, we also added the albedo time series from the Sodankylä Arctic Research Center of FMI. The albedo observations there take place at a micrometeorological mast located over a forest. As all other BSRN sites are located over grass or cultivated fields, using the Sodankylä data gives us further insight into the product behaviour over (boreal) forests. The basic information about the Sodankylä site is listed in Table 3.

Table 3: The Sodankylä ARC site and Greenland Climate Network stations used as data sources for this study

Station name	Latitude (N)	Longitude (E)	Time period
Sodankylä ARC	67.37	26.63	2000-2014
DYE-2	66.48	-46.28	1996-2014
JAR-2	69.42	-50.06	1999-2013
Summit	72.58	-38.5	1996-1997,1999-2005, 2007-2014

The distribution of the permanent reference stations worldwide is shown in Figure 2. As the reader may see, there is a shortage of applicable validation data in Central Eurasia, the tropical regions, as well as the Southern Hemisphere. There are BSRN stations located on the Southern Hemisphere, but they often either do not record reflected solar radiation, or their data records span only a few years.

5.1. Validation methods

A limiting factor for the choice of validation data was the desired method of validation. Since surface albedo of many natural surfaces is affected by cloudiness, it was desirable to construct the temporal means of reference observations from only those points in time for which there was a valid SAL retrieval of surface albedo. The CLARA-A2-SAL algorithm was therefore pre-set to record its observed retrieved albedo with associated data on separate data files. The timestamps on these records were used to construct a CLARA-A2-SAL-comparable temporal albedo mean from the full station observation record. For monthly means only months with at least 20 matched observations were used in the validation. For pentad means the limit was set to 4. The extracted reference data were also used for a preliminary study on the accuracy of the observed, higher-resolution albedo retrievals. The results will be shown in the later sections.

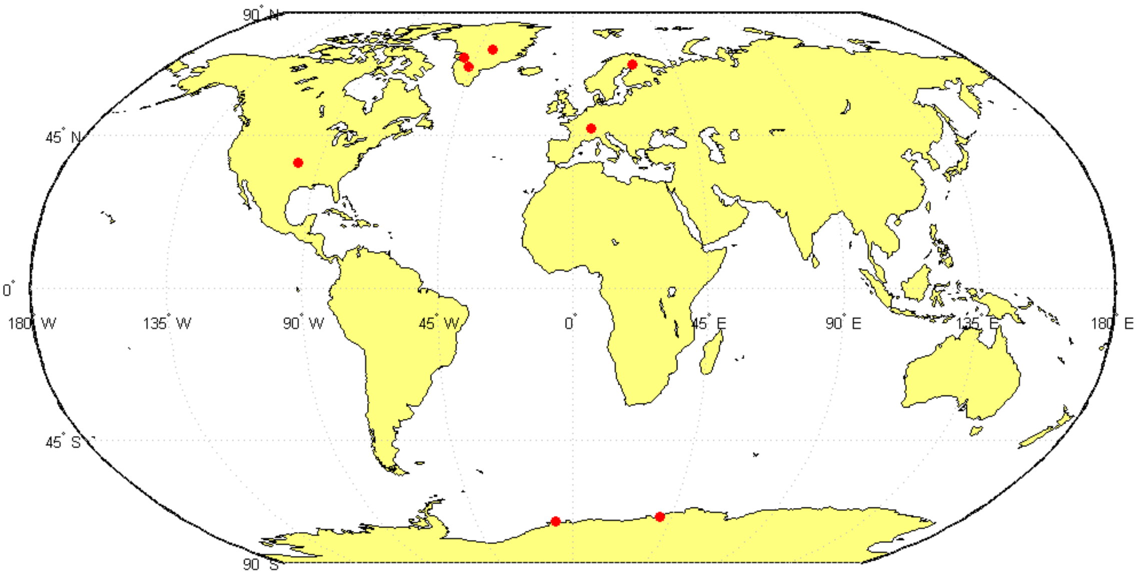

Figure 2: Geographical distribution of the validation locations excepting the Tara drift route on the Arctic Ocean.

Since the CLARA-A2-SAL albedo retrievals have all been normalized to a common Sun Zenith Angle (SZA) apart from retrievals over snow, the same procedure was applied to the reference data before constructing its temporal means. The same SZA normalization algorithm was applied to both CLARA-A2-SAL and reference data (see [RD 2] for details).

Since the snow albedo in CLARA-A2-SAL is formed by the temporal averaging after the assumption that all viewing geometries are represented in a temporal mean, the reference observation are not corrected either. This does mean, however, that there will be larger variation between CLARA-A2-SAL and reference observations at the observed level, since then we will basically be comparing bidirectional snow surface reflectances (CLARA-A2-SAL) to bihemispherical surface reflectances (blue-sky albedo, reference data). However, the temporal means will correspond to each other and be comparable, excepting periods of dramatic changes in the snow cover, such as rapid melt onset, and periods of very few observations of CLARA-A2-SAL. This is typically the case with pentad means, which is why the reader is advised to keep this in mind while studying the validation parameters, in particular the RMSE. However, representing the snow albedo of such a period through a temporal average would be problematic in any case.

To summarize, the validation method for the CLARA-A2-SAL product is as follows:

1. Record observed timestamps, albedo values and associated data at each validation site locations during processing.
2. Extract corresponding surface albedo observations from the in situ data records.
3. Utilize the values from step 2 to construct a comparable pentad/monthly mean data record for each validation site.
4. Compare results and calculate RMSE and mean relative retrieval difference (main quality indicators).

The process is illustrated graphically in Figure 3.

There are issues in the comparability of reference in situ observations to satellite retrievals of surface albedo. First and foremost is the representativeness of a point-like observation of albedo at a ground site against coarse resolution satellite retrieval (such as AVHRR-GAC). Apart from stations deep on the Greenland Ice Sheet or Antarctica, the land cover surrounding the observation point is never homogeneous enough that one could comfortably say that the satellite observes only the same type of terrain as in the ground measurement. The reader should keep this well in mind when assessing the validation results. A second issue in the data comparability is the inclusion of atmospheric effects in the reference albedo data. CLARA-A2-SAL is a black-sky albedo product, i.e. it is intended to produce the albedo of the Earth’s surface in absence of any atmosphere. However, the irradiance (global solar radiation) recorded at reference sites contains atmospheric effects that alter its spectral composition. This will alter the broadband albedo from its black-sky value. To achieve better comparability, the reference data would have to be corrected for the atmospheric effects on irradiance. However, information on aerosol, ozone or water vapour content of the atmosphere at validation sites is usually not available. Therefore we do not attempt to correct for these effects, but note that their effect may be considerable at sites where the atmosphere is optically thick either naturally (many coastal sites) or from anthropogenic reasons. A more detailed discussion on atmospheric effects in ground-based albedo measurements and the blue-sky/black-sky albedo comparability may be found in Manninen et al. (2012).

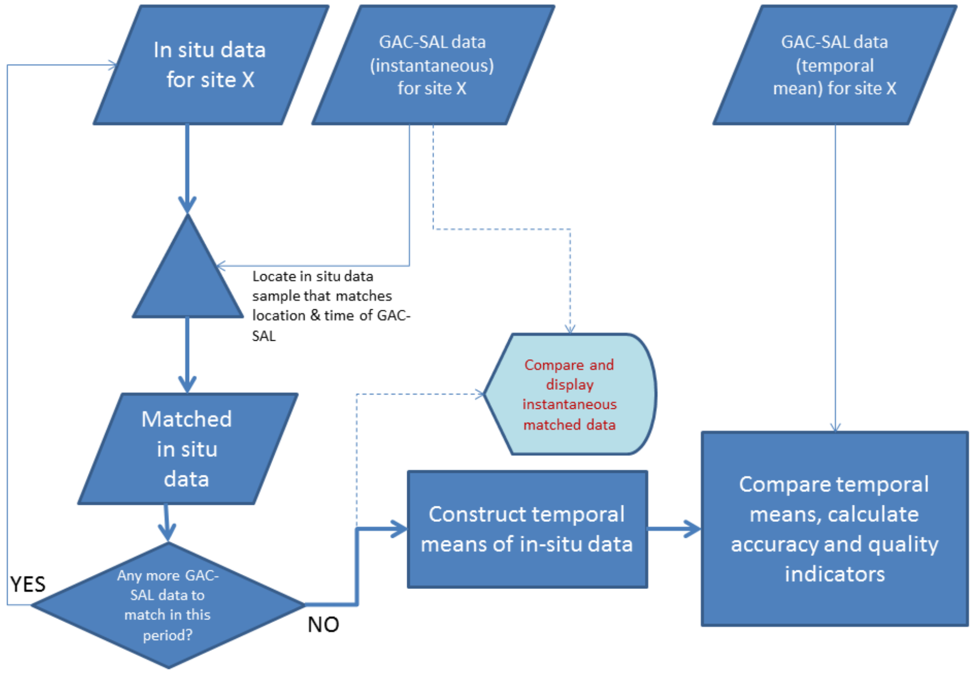

Figure 3: The CLARA-A2-SAL validation process for a ground site.

Lastly, it should be considered that the CLARA-A2-SAL data record spans a longer time period than the longest length of validation data records. For the period 1982-1992 we are forced to assume that the conclusions we draw from available later data will be valid. This assumption can be challenged by e.g. lower radiometric quality in earlier NOAA AVHRR data. Also, land cover data record accuracy will likely degrade as we extend it back (or far forward) in time.

6. Validation Against BSRN Station Observations

6.1. Neumayer, Antarctica

Neumayer research station is located on the Antarctic coast. The site is on the ice shelf, some ~5 km from the open water boundary. The site is permanently snow-covered. The latitude of the site limits data availability to austral summer.

The retrieved albedos are shown in Figure 4, and the associated relative retrieval differences are shown in Figure 5. Overall, CLARA-A2-SAL performs within specifications. The majority of the observations get albedo-values of 0.7-0-85 and relative retrieval differences smaller than 25 %, but there is a group of outliers getting considerably low values. These outliers appear almost every year and are more common during the end of the season, that is, in February and March. They have a particularly strong impact on the observed SAL monthly and pentad means in spring 2006. The underestimations likely result from a combination of cloud mask misclassifications and geolocation uncertainty assigning open water at Neumayer coordinates. It is worth noticing that these are also the times with smallest number of observations and high solar zenith angles.

CLARA-A2-SAL accuracy over bright terrain is highly dependent on the PPS cloud mask's ability to distinguish clouds from the underlying bright surface. At Neumayer, 11.0 % of all 6126 matched CLARA-A2-SAL overpasses produce an albedo value less than 0.65 (likely range for albedo when clouds are misclassified as snow/ice). In CLARA-A2 the PPS cloud mask is less conservative, which can be seen in the number of misinterpreted clouds. Because Neumayer is located away from the open water boundary, the coarse CLARA-A2-SAL resolution does not affect comparisons.

Apart from occasionally occurring large underestimations, the pentad means behave very similarly as the monthly means.

The product quality indicators at Neumayer are listed in Table 4 and Table 5. At Neumayer, CLARA-A2-SAL performs quite consistently within specifications.

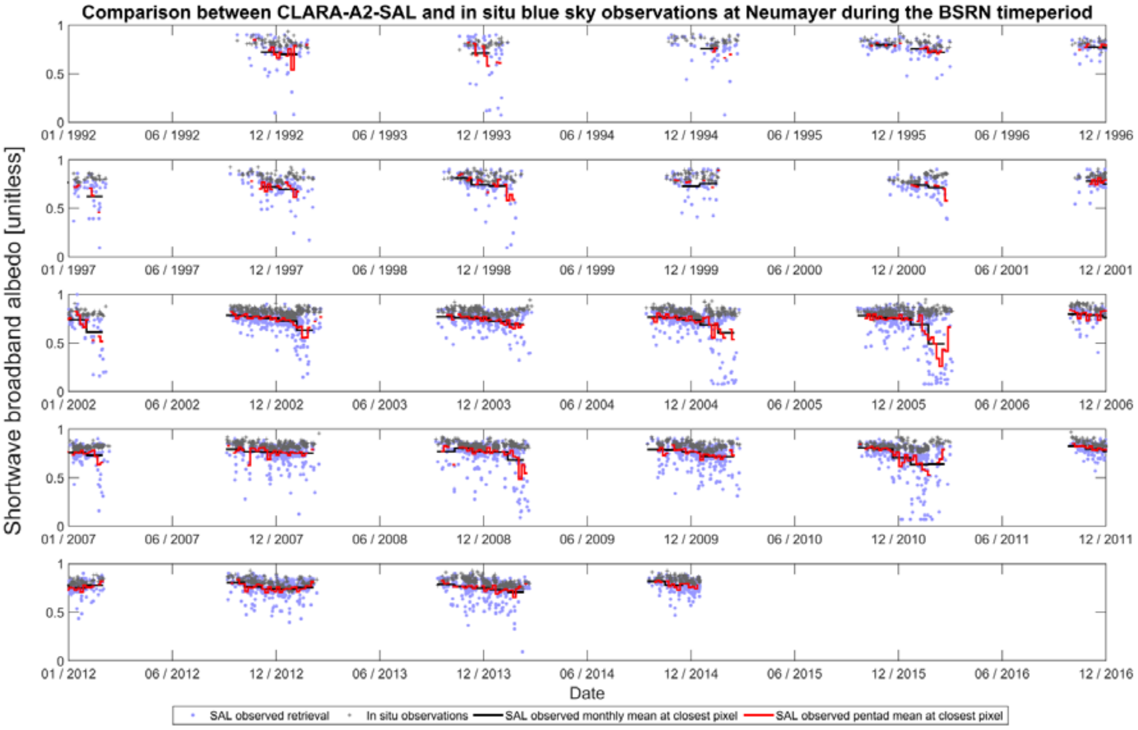

Figure 4: CLARA-A2-SAL and in situ albedo over Neumayer. Grey crosses indicate in situ observations, blue circles indicate observed CLARA-A2-SAL retrievals, and the black and red lines indicate the CLARA-A2-SAL monthly and pentad mean albedo.

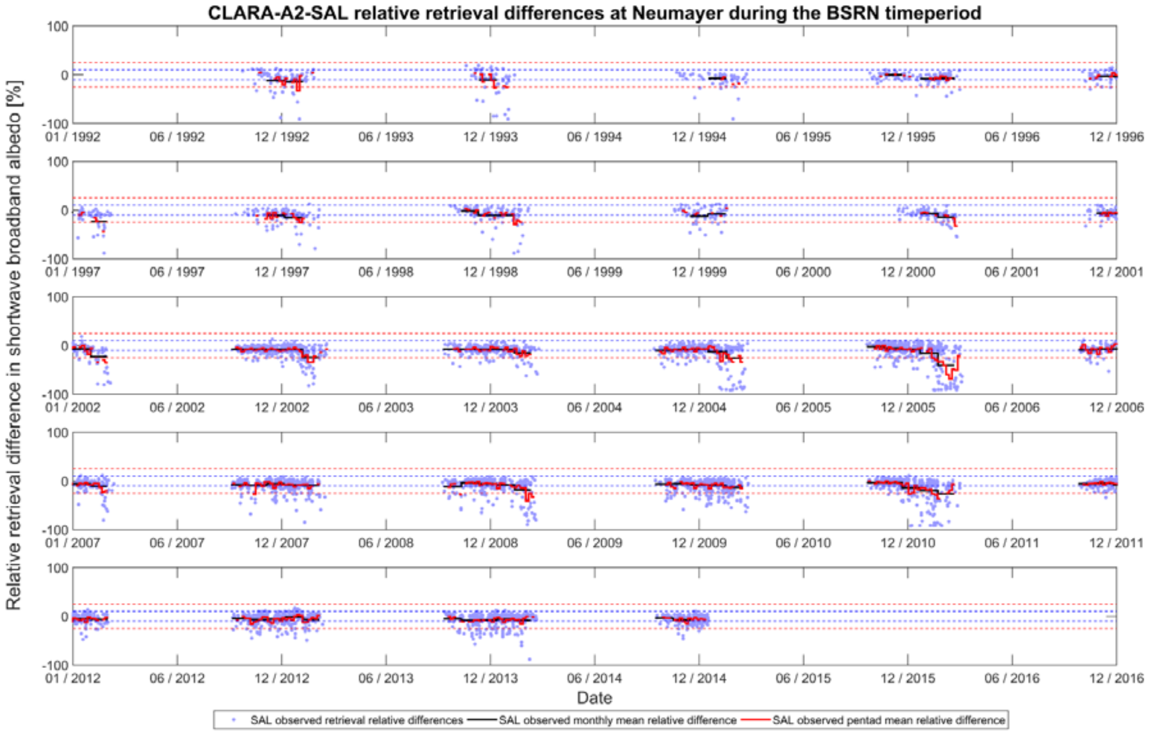

Figure 5: CLARA-A2-SAL relative retrieval difference over Neumayer. Blue circles indicate retrieval differences at observed level; the black and red lines indicate the retrieval difference of the monthly and pentad means. Red dashed line shows 25% and the blue dashed line 10% relative difference levels.

Table 4: CLARA-A2-SAL product quality indicators at the monthly mean level over Neumayer.

Data record / period	RMSE	Mean rel. difference [%]	Notes
Observed	0.14	-9.019	N=6126
Monthly means	0.093	-9.46	N=88 (valid months)
DJF	0.108	-11.24	N=43 (valid months)
MAM	-	-	N=0 (valid months)
JJA	-	-	N=0 (valid months)
SON	0.056	-6.12	N=32 (valid months)

Table 5: CLARA-A2-SAL product quality indicators at the pentad mean level over Neumayer

Data record / period	RMSE	Mean rel. difference [%]	Notes
Pentad means	0.112	-10.04	N=452 (valid pentads)
DJF	0.124	-11.55	N=294 (valid pentads)
MAM	0.232	-22.77	N=7 (valid pentads)
JJA	-	-	N=0 (valid pentads)
SON	0.07	-6.511	N=152 (valid pentads)

6.2. Payerne, Switzerland

The Payerne BSRN site is located just outside the town of Payerne in western Switzerland. The land cover of the immediate area around the site consists mostly of cultivated fields, suburban areas and forest stands. Again, this creates some issues for the representability of the Payerne region from the BSRN site data. Keeping this in mind we move ahead with the validation.

The monthly and pentad mean albedos and the associated relative retrieval differences are shown in Figure 6 and Figure 7, respectively. It is noteworthy that there is high variability within the observed SAL values. This is, again, a result of the different spatial resolution and variability in the land use type from which the satellite observations come from. Most of the relative retrieval differences of the temporal means meet the specifications with a tendency to underestimate the albedo of the in situ measurements. This can partly be explained by a large lake at the vicinity of the in situ measurement site.

The difference shows clearly also in the product quality indicators (Table 6 & Table 7). Despite the difficult land use circumstances at Payerne, CLARA-A2-SAL performs within specifications. The largest differences as compared to in situ data come in the winter months of December, October and January, when in fact the observed monthly and pentad means are slightly outside the specification. There can be several explanations for this, such as snow cover on the in situ –measurement site, but no ice on the lake. These are also the months with the largest sun zenith angles, least amount of observations per month and extensive cloud cover.

It is notable that the relative retrieval difference is stable throughout the data record. This also suggests that the algorithm is stable; the negative bias results from the poor representability of the area by the Payerne site observations. Therefore we do not find the CLARA-A2-SAL algorithm to be erroneous for grassland targets such as Payerne.

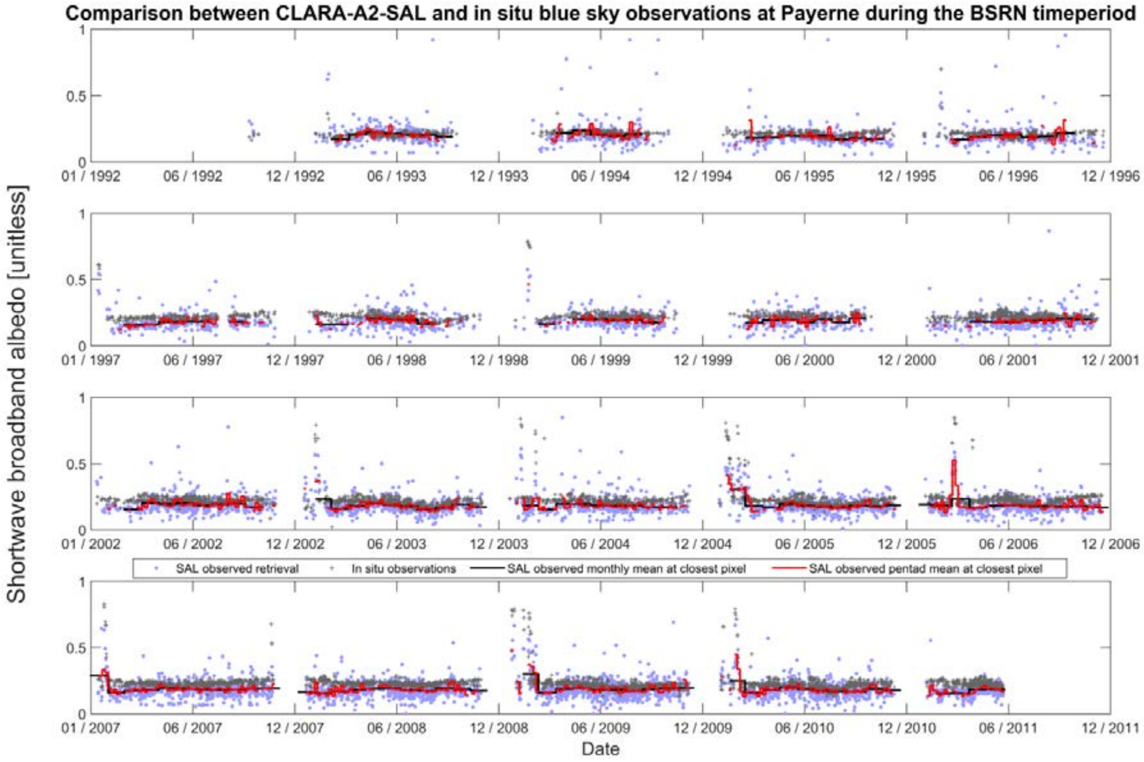

Figure 6: CLARA-A2-SAL and in situ albedo at Payerne. Grey crosses indicate observed in situ observations, blue circles indicate observed CLARA-A2-SAL retrievals, and the black and red lines indicate the CLARA-A2-SAL monthly and pentad mean albedos.

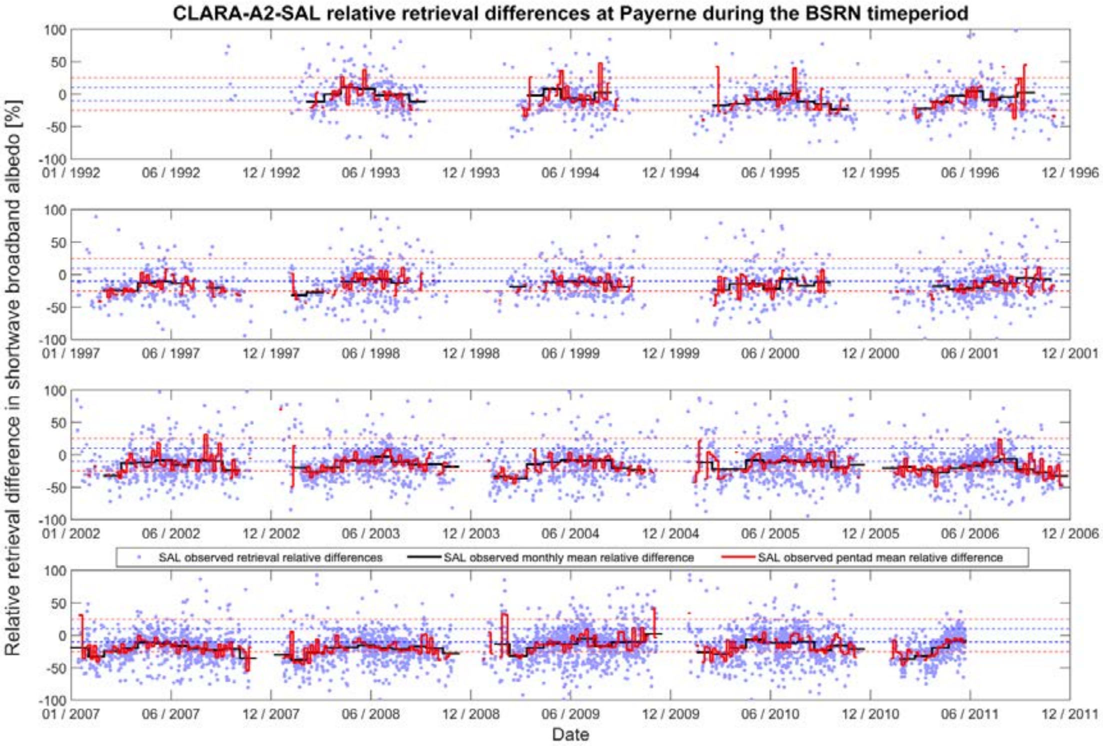

Figure 7: CLARA-A2-SAL relative retrieval difference over Payerne. Red circles indicate retrieval differences at observed level; the black and blue lines indicate the retrieval difference of the observed monthly and pentad means. Red dashed line shows 25% and the blue dashed line 10% relative difference levels.

Table 6: CLARA-A2-SAL product quality indicators at the monthly mean level over Payerne.

Data record / period	RMSE	Mean rel. difference [%]	Notes
Observed	0.075	-14.03	N=9413
Monthly means	0.04	-15.3	N=153 (valid months)
DJF	0.071	-25.52	N=13 (valid months)
MAM	0.044	-16.82	N=53 (valid months)
JJA	0.026	-10.05	N=53 (valid months)
SON	0.045	-17.22	N=34 (valid months)

Table 7: CLARA-A2-SAL product quality indicators at the pentad mean level over Payerne.

Data record / period	RMSE	Mean rel. difference [%]	Notes
Pentad means	0.054	-14.62	N=840 (valid pentads)
DJF	0.113	-22.13	N=76 (valid pentads)
MAM	0.050	-16.37	N=289 (valid pentads)
JJA	0.0315	-9.62	N=298 (valid pentads)
SON	0.053	-16.95	N=177 (valid pentads)

6.3. Southern Great Plains (SGP), USA

The SGP site is located in northern Oklahoma in the U.S. Midwest. The land cover at and around the site is cultivated fields and grassland. The land cover is relatively homogeneous and therefore presents a good validation case for CLARA-A2-SAL, as site representability issues are much smaller.

The retrieved temporal mean and site albedos and associated retrieval differences are shown in Figure 8 and Figure 9, respectively. CLARA-A2-SAL is capable of capturing the albedo of the area. Sporadic snowfall events in the area may worsen retrieval accuracy, as snow cover may be full at the BSRN site and patchy regionally, or vice versa. Pentad means show more capability in tracking sporadic albedo changes from snowfalls, as expected. There is considerable variation in the retrieval differences throughout the validation period, but in most cases the temporal means meet the specifications. It is notable that the retrieval accuracy based on the observed CLARA-A2-SAL data is very similar to the monthly/pentad mean accuracy, suggesting that land cover heterogeneities do not play a role in the retrieval differences.

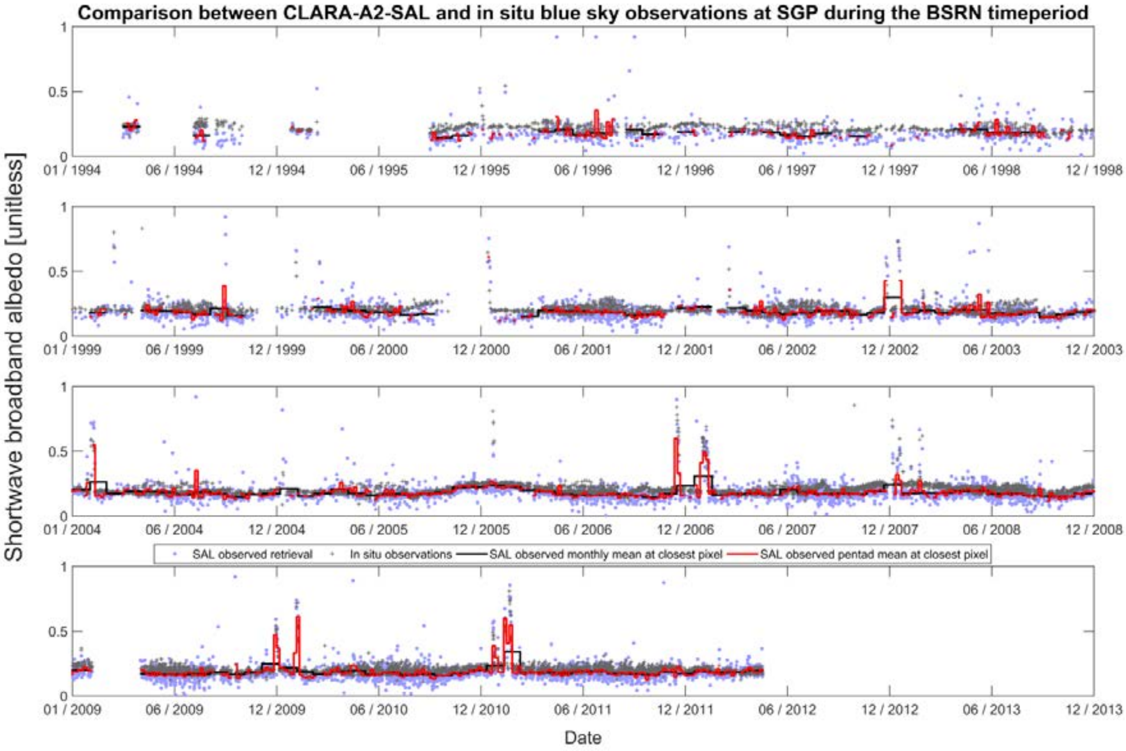

Figure 8: CLARA-A2-SAL and in situ albedo at SGP. Black crosses indicate observed in situ observations, blue circles indicate observed CLARA-A2-SAL retrievals, and the black and red lines indicate the CLARA-A2-SAL monthly and pentad mean albedo.

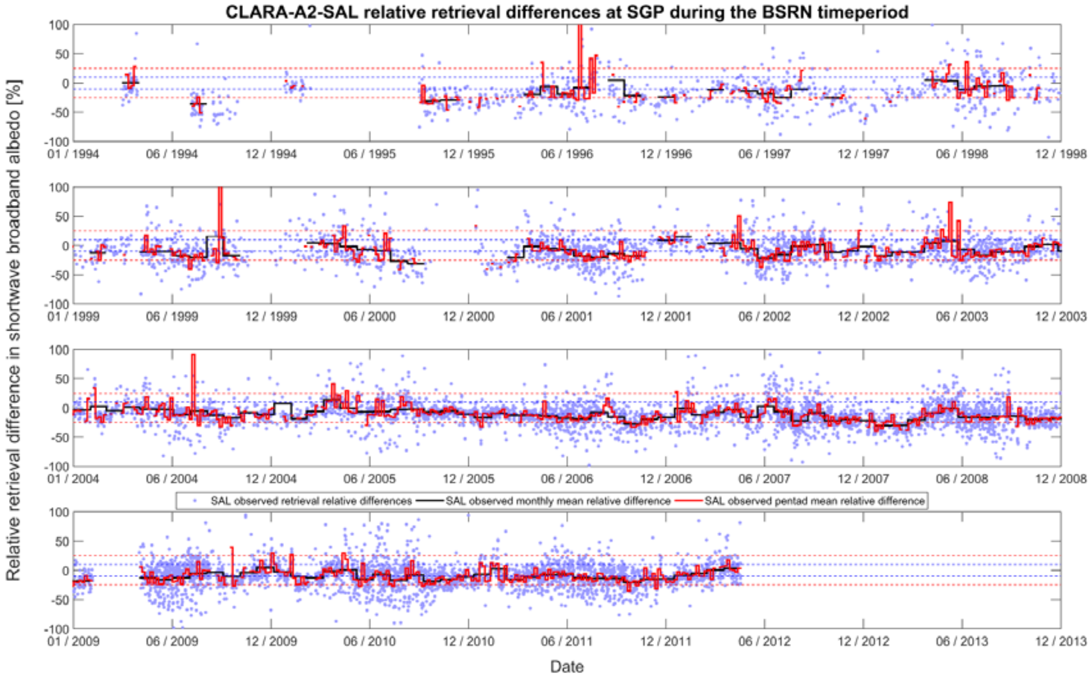

Figure 9: CLARA-A2-SAL relative retrieval difference over SGP. Blue circles indicate retrieval differences at observed level; the black and red lines indicate the retrieval difference of the monthly and pentad means. Red dashed line shows 25% and the blue dashed line 10% relative difference levels.

Table 8: CLARA-A2-SAL product quality indicators at the monthly mean level over SGP.

Data record / period	RMSE	Mean rel. difference [%]	Notes
Observed	0.063	-9.98	N=9673
Monthly means	0.030	-10.09	N=165 (valid months)
DJF	0.034	-9.44	N=33 (valid months)
MAM	0.0199	-5.03	N=44 (valid months)
JJA	0.034	-12.67	N=48 (valid months)
SON	0.034	-13.13	N=40 (valid months)

Table 9: CLARA-A2-SAL product quality indicators at the pentad mean level over SGP

Data record / period	RMSE	Mean rel. difference [%]	Notes
Pentad means	0.039	-9.97	N=922 (valid pentads)
DJF	0.046	-11.35	N=193 (valid pentads)
MAM	0.031	-4.23	N=242 (valid pentads)
JJA	0.040	-10.96	N=269 (valid pentads)
SON	0.041	-13.90	N=218 (valid pentads)

Table 8 and Table 9 show the quality indicators for SGP. Retrieval quality is well within specifications and very similar for both monthly and pentad means, and no significant variation between different times of year, as can be expected at a flat-terrain rural site with homogeneous crop/grass land cover. RMSE is also low, indicating that the mean relative retrieval differences do not result from mutually cancelling large under/overestimations.

6.4. Syowa (Showa) station, Antarctica

Syowa research station is located in Dronning Maud Land on the coastal edge of the ice shelf, near a region of nunataks. These rock outcroppings cause issues in the comparability between the observed CLARA-A2-SAL retrievals and the in situ observations.

The retrieval result comparison and the relative differences are displayed in Figure 10 and Figure 11, respectively. CLARA-A2-SAL is capable of tracking the negative trend in site albedo as summer and snowmelt / melt ponding progresses. The increase in site albedo as austral summer ends and the surface refreezes appears to be more difficult to track for some years (2002/2003, 2004/2005, 2005/2006). As expected, the temporal mean CLARA-A2-SAL products are more in line with the in situ observations, which is assuredly not over the bare nunatak area. The observed retrievals have a slight negative bias when compared to the in situ observations, most likely from the bare nunatak reflectance contribution in the Syowa site pixel.

Retrieval accuracy is generally well within specifications. There is a stronger than normal melt season during austral summer 2001 at the observation site, which the areal average does not detect. There also appear to be a fair number of retrievals where the cloud mask assigns open water in the pixel containing Syowa coordinates. Again, geolocation problems may assign these coordinates away from the true location on the ice shelf edge. Natural melt ponding and ice shelf shrinkage may also create true open water conditions near enough to the station to induce this assignment.

The quality indicators for Syowa are listed in Table 10 and Table 11. Pentad retrievals are on the same order of accuracy as the monthly means, although significant over/underestimations can occur for single pentads.

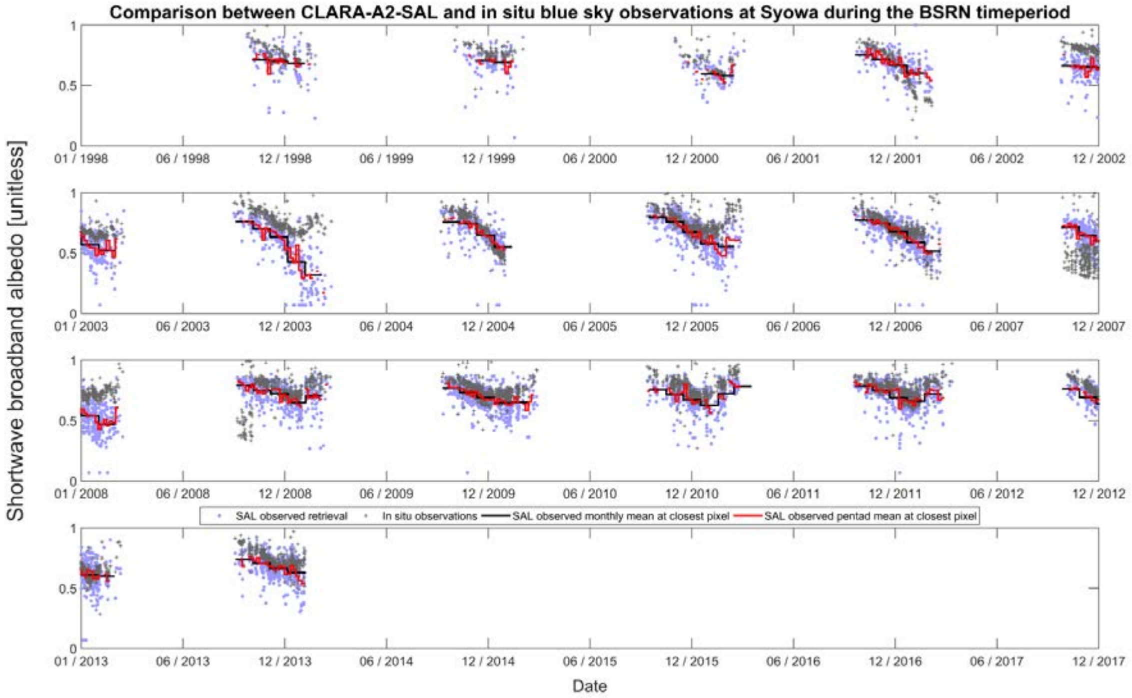

Figure 10: CLARA-A2-SAL and in situ albedo over Syowa. Red circles indicate observed in situ observations, black crosses indicate observed CLARA-A2-SAL retrievals, and the black and blue lines indicate the CLARA-A2-SAL monthly and pentad mean albedo.

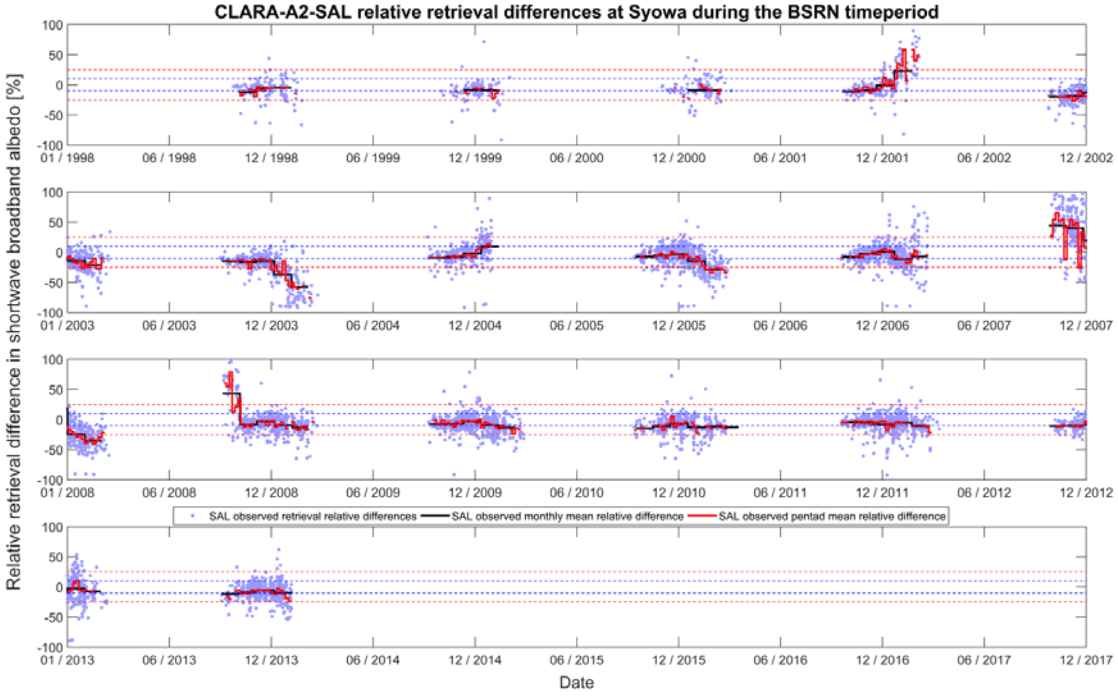

Figure 11: CLARA-A2-SAL relative retrieval difference over Syowa. Red circles indicate retrieval differences at observed level; the black and blue lines indicate the retrieval difference of the monthly and pentad mean. Red dashed line shows 25% and the blue dashed line 10% relative difference levels.

Table 10: CLARA-A2-SAL product quality indicators at the monthly mean level over Syowa.

Data record / period	RMSE	Mean rel. difference [%]	Notes
Observed	0.154	-5.22	N=6590
Monthly means	0.115	-7.71	N=70 (valid months)
DJF	0.117	-9.90	N=42 (valid months)
MAM	0.115	-12.85	N=1 (valid months)
JJA	-	-	N=0 (valid months)
SON	0.111	-4.13	N=27 (valid months)

Table 11: CLARA-A2-SAL product quality indicators at the pentad mean level over Syowa

Data record / period	RMSE	Mean rel. difference [%]	Notes
Pentad means	0.124	-7.40	N=381 (valid pentads)
DJF	0.122	-9.23	N=233 (valid pentads)
MAM	0.23	-23.08	N=11 (valid pentads)
JJA	-	-	N=0 (valid pentads)
SON	0.117	-3.04	N=137 (valid pentads)

7. Validation against GC-Net Station Observations

We have included three stations from the Greenland Climate Network (GC-Net) as validation sites. The data from these stations is generated by an automated weather station (AWS) housing an upward- and a downward-looking LI-COR 200SZ pyranometer. As the stations operate independently in harsh conditions, the data has been screened to eliminate periods of poor data quality. Even after this procedure, the reader should keep in mind that the albedo data from the GC-Net sites cannot be completely screened for instrument tilt effects resulting from snow compaction on and around the measurement tower, or frost formation on the detector domes.

Stroeve et al. (2001) observes that the LI-COR albedo values may be biased by +0.04 against shortwave broadband albedo since the pyranometer only observes the waveband of 0.4-1.1 micrometers. Stroeve and Nolin (2002) also note that the bias may be variable according to snow grain size, with large differences between fresh, small-grained snow and old large-grained snow. This makes correction for the effect very challenging. Furthermore, the FMI RASCALS expedition to Summit camp in 2010 found good agreement between the GC-Net AWS albedo, full broadband albedometer (Kipp & Zonen CM-14), and spectrogoniometer (Finnish Geodetic Institute FIGIFIGO) albedo measurements without any correction to AWS. We therefore do not correct the AWS albedo but rather note that there is an extra source of uncertainty in the relative retrieval difference, its magnitude being assumed as roughly 5% when observed albedo is 0.8.

7.1. Summit Camp, Greenland

Summit camp is located near the top of the Greenland Ice Sheet at over 3200 m a.s.l. It is located on the accumulation zone of the ice sheet; its elevation and latitude create conditions where the air temperature never induces snow melt. Thus the albedo on-site is known to be stable, even though insolation provides energy for snow metamorphism at surface level. Thus small-scale diurnal effects in albedo are expected.

The CLARA-A2-SAL & station albedo retrievals and the relative retrieval differences are shown in Figure 12 and Figure 13, respectively. Years 1998 and 2006 have been excluded from the analysis due to poor in situ data quality throughout the summer period. The site latitude excludes winter periods due to lack of illumination. The data for CLARA-A2-SAL appears to slightly underestimate the site albedo during the whole measuring period. It is also worth noticing that the dry and relatively small-grained snow around Summit camp has a very high reflectance and exhibits strong BRDF effects. The CLARA-A2-SAL algorithm becomes saturated on occasion when observing such a bright target. Regardless, as the quality indicators in Table 12 and Table 13 show, CLARA-A2-SAL performs well within specifications throughout the year. Since the snow cover around Summit is fairly homogeneous, data comparability issues are expected to be negligible.

It should be kept in mind that even though the relative retrieval differences are on average less than 5%, the possible bias in LI-COR observations versus full broadband albedo is not taken into account. Still, even considering a 5% increase in retrieval difference, CLARA-A2-SAL would still perform within specifications.

The pentad and monthly CLARA-A2-SAL means behave in an identical fashion. This is to be expected as the target is stable in time as well as spatially homogenous.

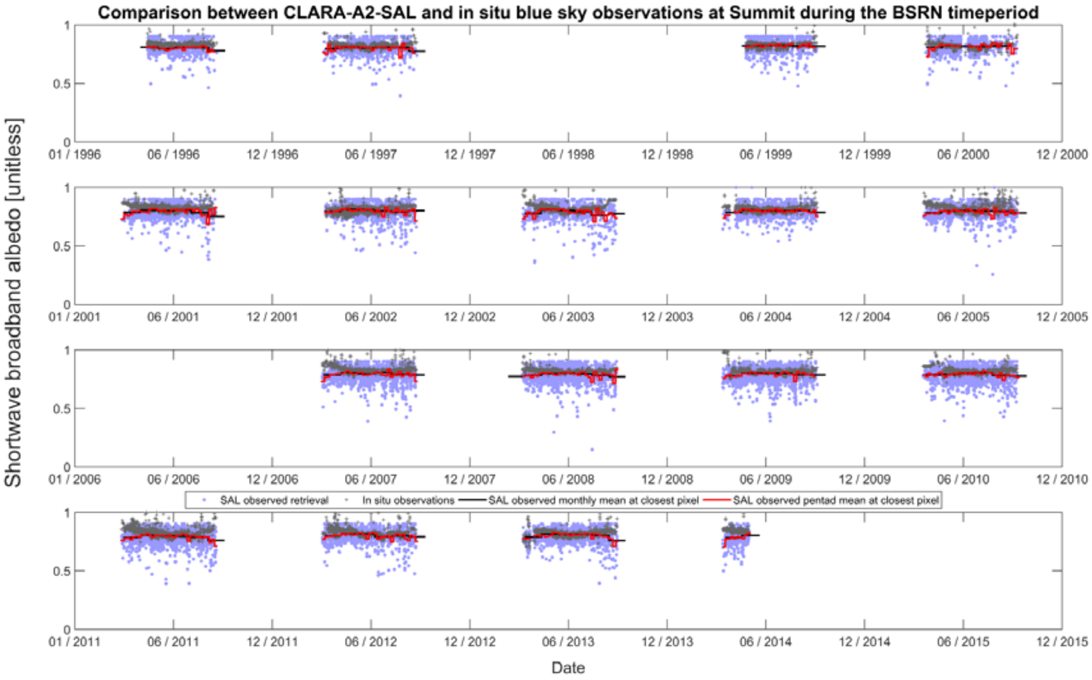

Figure 12: CLARA-A2-SAL and in situ albedo over Summit camp. Black crosses indicate observed in situ observations, blue circles indicate observed CLARA-A2-SAL retrievals, and the black and red lines indicate the CLARA-A2-SAL observed monthly and pentad mean albedo.

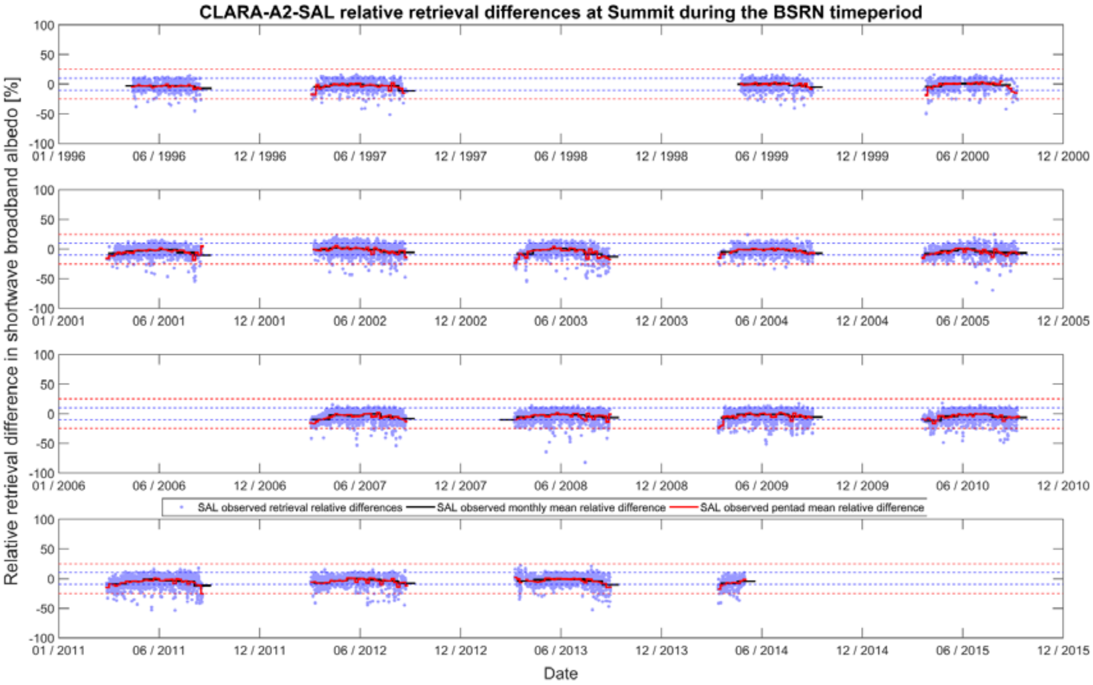

Figure 13: CLARA-A2-SAL relative retrieval difference over Summit camp. Blue circles indicate retrieval differences at observed level; the black and red lines indicate the retrieval difference of the observed monthly and pentad mean. Red dashed line shows 25% and the blue dashed line 10% relative error levels.

Table 12: CLARA-A2-SAL product quality indicators at the monthly mean level over Summit camp.

Data record / period	RMSE	Mean rel. difference [%]	Notes
Observed	0.075	-2.83	N=22496
Monthly means	0.044	-3.88	N=96(valid months)
DJF	-	-	N=0 (valid months)
MAM	0.047	-4.43	N=33 (valid months)
JJA	0.025	-2.14	N=48 (valid months)
SON	0.073	-8.20	N=15 (valid months)

Table 13: CLARA-A2-SAL product quality indicators at the pentad mean level over Summit camp.

Data record / period	RMSE	Mean rel. difference [%]	Notes
Pentad means	0.054	-4.14	N=540 (valid pentads)
DJF	-	-	N=0 (valid pentads)
MAM	0.062	-4.97	N=213 (valid pentads)
JJA	0.039	-2.80	N=284 (valid pentads)
SON	0.089	-8.84	N=43 (valid pentads)

7.2. DYE-2

The DYE-2 site is located in Southern Central Greenland at 2165 m a.s.l. It is located on the percolation zone of the Greenland Ice Sheet (GrIS) (Steffen and Box, 2001). Combined with the lower elevation and latitude, large snow metamorphism effects in albedo are expected as well as some snow melt of the surface. The site is located near the abandoned DYE-2 early warning radar facility.

The retrieved albedos and associated retrieval differences are shown in Figure 14 and Figure 15, respectively. The in situ albedo shows more variability than at Summit camp, as expected. Summers 2007-2008, 2010-2011 and 2011-2012 appear to show a pronounced dip in site albedo at midsummer. This is understandable especially for 2007 considering the high temperature anomaly of the time. The quality indicators are listed in Table 14 and Table 15. It should be noted that the very high mean accuracies achieved partly result from mutually cancelling over- and underestimations. At the same time, we note that the monthly mean retrieval differences at DYE-2 vary between 19.54% - 4.07% (relative). Thus the algorithm clearly meets its specifications.

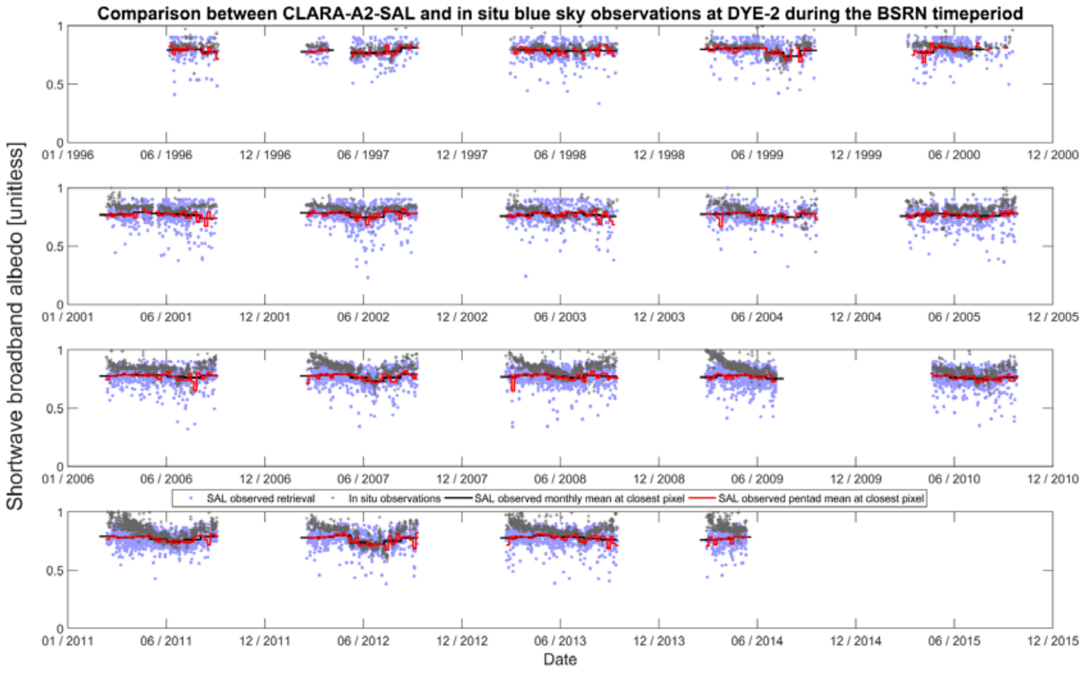

Figure 14: CLARA-A2-SAL and in situ albedo over DYE-2. Grey crosses indicate observed in situ observations, blue circles indicate observed CLARA-A2-SAL retrievals, and the black and red lines indicate the CLARA-A2-SAL monthly and pentad mean albedo.

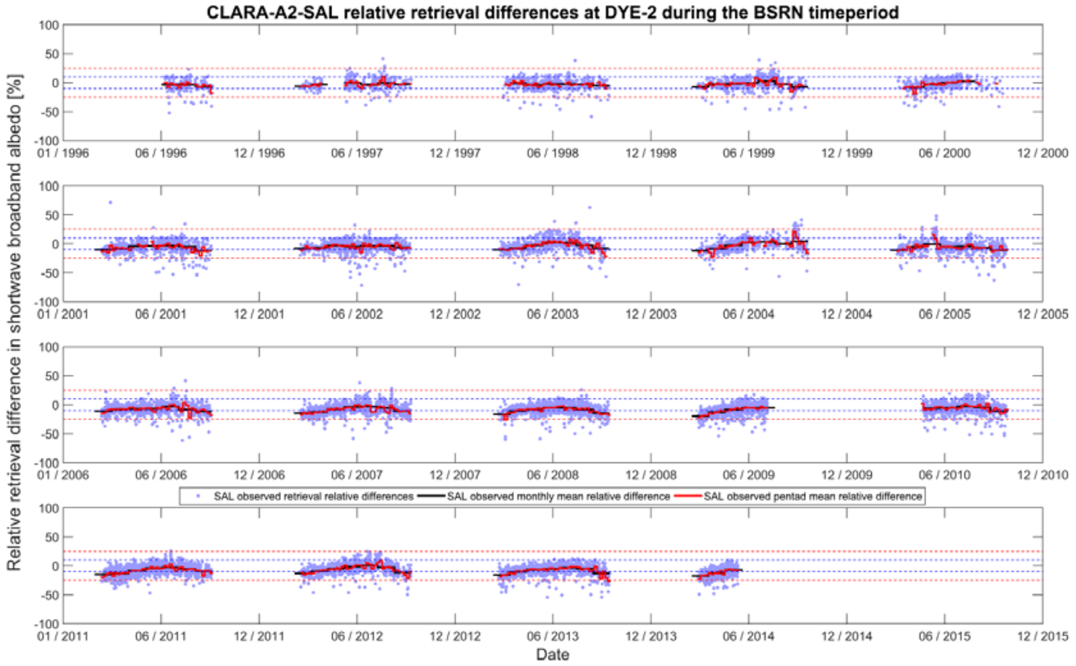

Figure 15: CLARA-A2-SAL relative retrieval difference over DYE-2. Blue circles indicate retrieval differences at observed level; the black and red lines indicate the retrieval difference of the observed monthly and pentad mean. Red dashed line shows 25% and the blue line 10% relative difference levels.

Table 14: CLARA-A2-SAL product quality indicators at the monthly mean level over DYE-2.

Data record / period	RMSE	Mean rel. difference [%]	Notes
Observed	0.095	-5.86	N=15161
Monthly means	0.067	-6.15	N=116 (valid months)
DJF	-	-	N=0 (valid months)
MAM	0.085	-8.50	N=49 (valid months)
JJA	0.034	-3.09	N=51 (valid months)
SON	0.085	-8.67	N=16 (valid months)

Table 15: CLARA-A2-SAL product quality indicators at the pentad mean level over DYE-2.

Data record / period	RMSE	Mean rel. difference [%]	Notes
Pentad means	0.074	-6.19	N=660 (valid pentads)
DJF	-	-	N=0 (valid pentads)
MAM	0.08	-7.97	N=279 (valid pentads)
JJA	0.07	-3.52	N=292 (valid pentads)
SON	0.102	-9.39	N=89 (valid pentads)

7.3. JAR-2

JAR-2 is the most challenging of our Greenland validation sites, since it is located on the ablation region of the ice sheet near its western edge. Snow melt and melt pond formation are common occurrences every summer, the area also has sufficient slope to induce some ice flow. Data comparability thus depends largely on the similarity of snow status and melt ponds in the AWS sensor footprint and in the surrounding area.

The albedo retrievals and associated retrieval differences are shown in Figure 16 and Figure 17. At the observed level, the in situ data varies considerably even over short timeframes during the summers. It is perhaps fortuitous that the large-scale region appears to go through similar changes as the AWS site, since the observed monthly mean CLARA-A2-SAL is generally able to observe similar mean features in the albedo. The annual melt-refreeze cycle is observed, although its observed magnitude varies considerably from year to year. For summer 2006 it seems that CLARA-A2-SAL is not able to pick. However, the in situ observations vary considerably and there are many observations with higher albedo value that the observed CLARA-A2-SAL monthly mean. This indicates that the conditions during this time have also been varying.

The CLARA-A2-SAL quality indicators for JAR-2 are listed in Table 16 and Table 17. Again, mean monthly and pentad accuracies improve as a result of mutually cancelling over- and underestimations, the RMSE is still typically under 0.15. Individual relative overpass differences may reach over 100% (in 3% of all 10890 matched cases, therefore not shown in figures to maintain clarity).

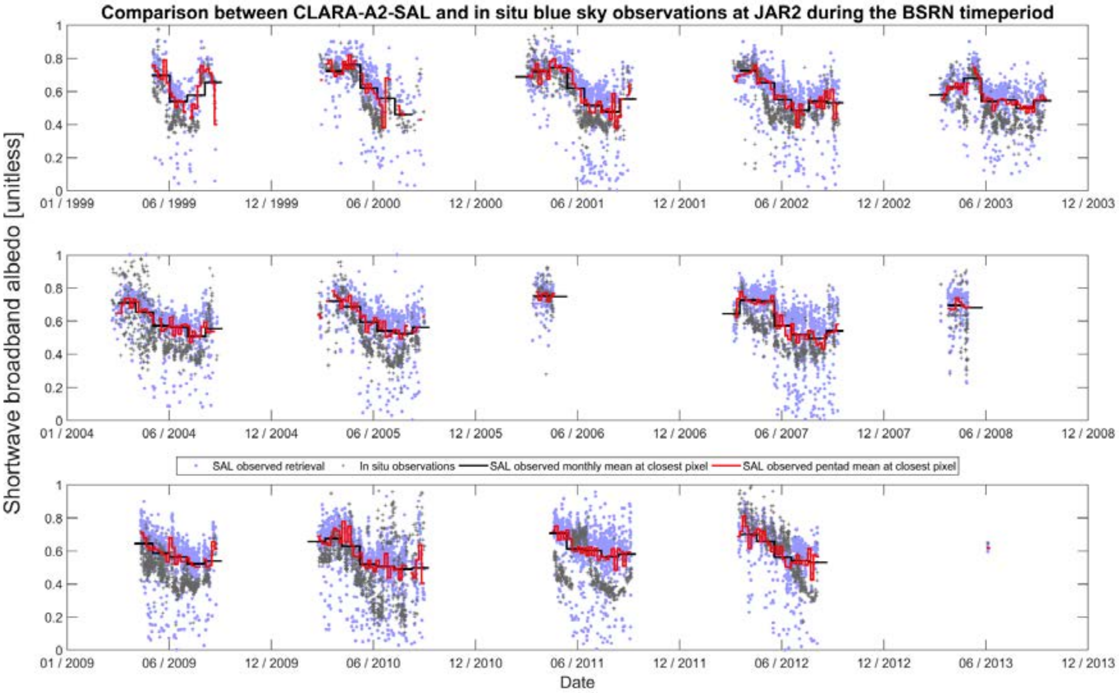

Figure 16: CLARA-A2-SAL and in situ albedo at JAR-2. Red circles indicate observed in situ observations, black crosses indicate observed CLARA-A2-SAL retrievals, and the black and blue lines indicate the observed CLARA-A2-SAL monthly and pentad mean albedo.

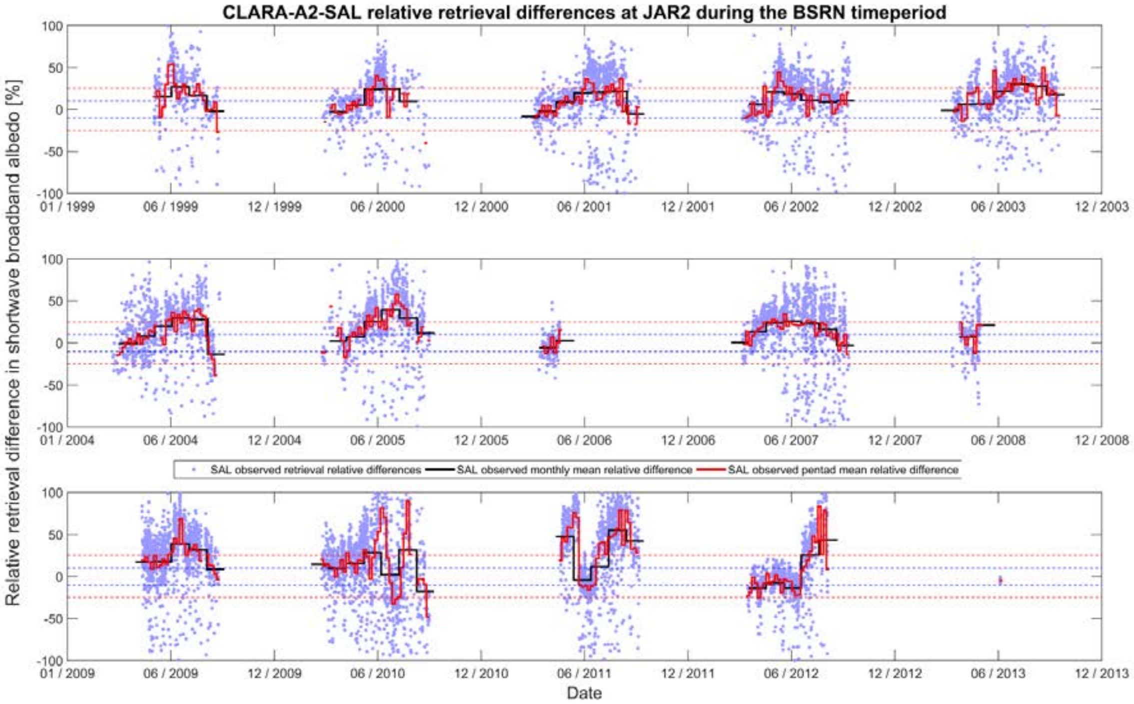

Figure 17: CLARA-A2-SAL relative retrieval difference over JAR-2. Red circles indicate retrieval differences at observed level; the black and blue lines indicate the retrieval difference of the observed monthly and pentad mean. Red dashed line shows 25% and the blue dashed line shows 10% relative difference levels.

Table 16: CLARA-A2-SAL product quality indicators at the monthly mean level over JAR-2.

Data record / period	RMSE	Mean rel. difference [%]	Notes
Observed	0.185	21.58	N=10890
Monthly means	0.094	14.21	N=74 (valid months)
DJF	-	-	N=0 (valid months)
MAM	0.078	7.22	N=28 (valid months)
JJA	0.107	22.23	N=36 (valid months)
SON	0.080	4.91	N=10 (valid months)

Table 17: CLARA-A2-SAL product quality indicators at the pentad mean level over JAR-2.

Data record / period	RMSE	Mean rel. difference [%]	Notes
Pentad means	0.114	15.08	N=398 (valid pentads)
DJF	-	-	N=0 (valid pentads)
MAM	0.099	8.11	N=157 (valid pentads)
JJA	0.122	22.91	N=203 (valid pentads)
SON	0.126	1.98	N=38 (valid pentads)

8. Validation against Sodankylä Albedo Observations

The Arctic Research Center of FMI is stationed near the town of Sodankylä in Northern Finland (67.368N, 26.633 E). It houses a wide array of measurement equipment, including a pair of Kipp & Zonen pyranometers mounted on a 50-meter mast located over a Scots pine / spruce forest stand. The global and reflected solar radiation data record from these sensors has been extracted and processed in similar manner as the BSRN and GC-Net sites.

As measurements take place over a forest stand, the in situ albedo equates to a boreal forest surface albedo as seen from above. However, the region around the site has a variety of other land cover types, mostly forest and aapa mires. The town of Sodankylä is situated some 6 km distant.

The monthly and pentad mean retrievals and the associated retrieval uncertainties are shown in Figure 18 and Figure 19. The results clearly show how CLARA-A2-SAL tracks the snow melt during spring. However, the level of SAL is much higher in the March and April than the level of in situ measurements. This is largely caused by the differences in the land use types. The open bogs and a relatively large river are open areas which are still covered by snow and ice. The in situ measurements see the spruce forest. During the melting season the trees typically do not have snow cover. Thus the observed CLARA-A2-SAL retrievals have much more variety in albedo values, and they are typically higher than the in situ measurements from the mast.

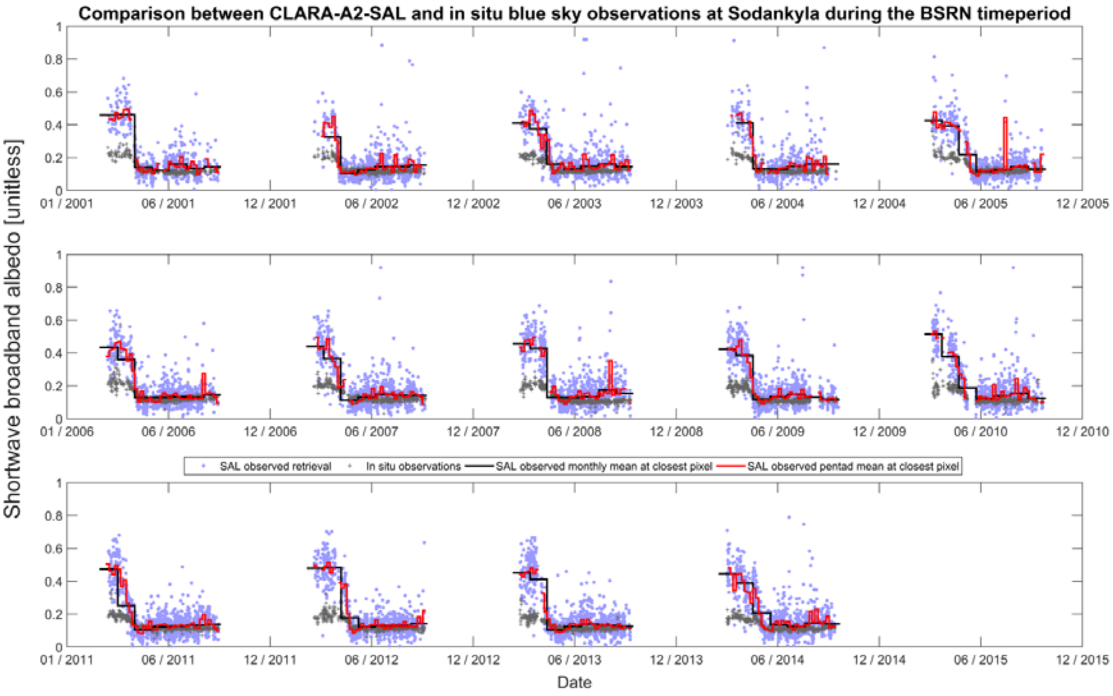

Figure 18: CLARA-A2-SAL and in situ albedo over Sodankylä. Red circles indicate observed in situ observations, black crosses indicate observed CLARA-A2-SAL retrievals, and the black and blue lines indicate the CLARA-A2-SAL monthly and pentad mean albedo.

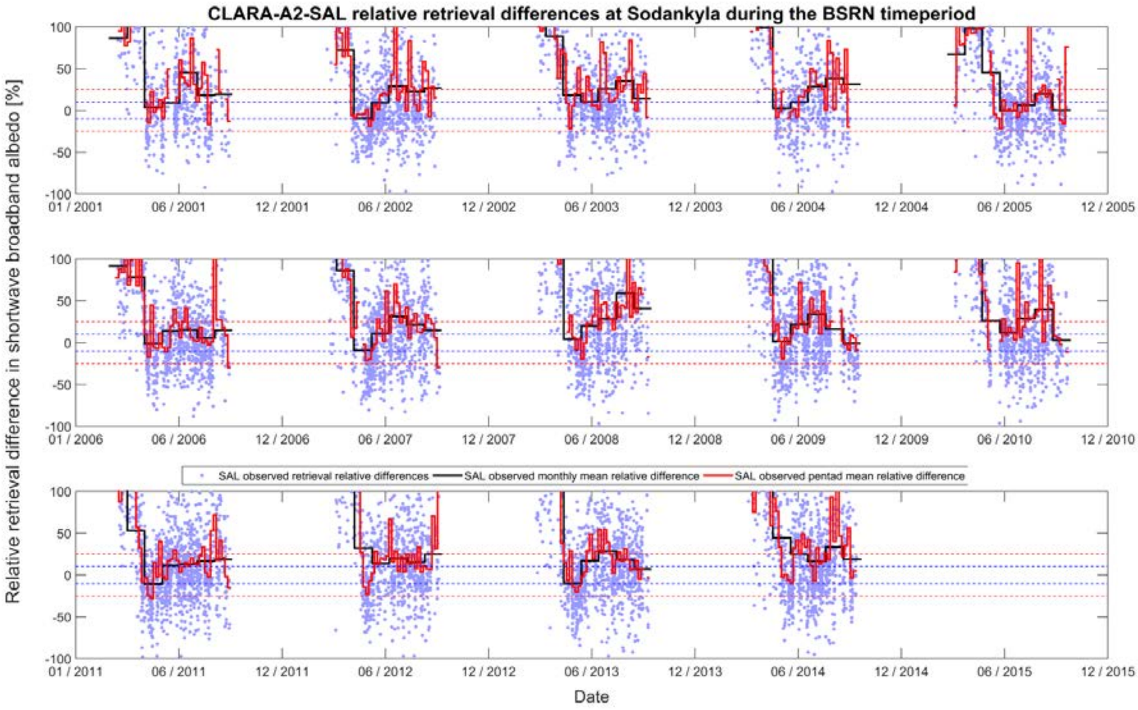

Figure 19: CLARA-A2-SAL relative retrieval difference over Sodankylä. Red circles indicate retrieval differences at observed level; the black and blue lines indicate the retrieval difference of the monthly and pentad mean. Red dashed line shows 25% and the blue dashed line shows 10% relative difference levels.

Table 18 and Table 19 show the retrieval quality of CLARA-A2-SAL over the Sodankylä site. The monthly mean values are within specifications for all other months except MAM, largely for the reasons explained above. These melting period differences are large enough to put the overall relative difference out of specifications. Along the previously mentioned overestimation during winter/spring, there is a notable overestimation during autumn as well. However, the SON period data at Sodankylä latitude is sparse; practically speaking only September provides valid comparisons. CLARA-A2-SAL retrievals over September are generally very similar to August, but there is a slight negative trend in the in situ data between August and September. This along with data sparsity explains the difference in the retrieval quality. The reason for the in situ "dimming" not observed by the CLARA-A2-SAL retrievals is likely phenological; senescent understory vegetation can lower the albedo of an evergreen forest stand. Since the satellites almost never see the Sodankylä site at nadir, understory effects are likely concealed by the forest canopy. The river Kitinen also runs through the area and is within the albedometer field of view; its contribution to the reflected radiation flux is expected to be largest during spring and autumn when the vegetation canopy is at its sparsest.

Table 18: CLARA-A2-SAL product quality indicators at the monthly mean level over Sodankylä.

Data record / period	RMSE	Mean rel. difference [%]	Notes
Observed	0.117	33.3	N=13313
Monthly means	0.119	43.17	N=96 (valid months)
DJF	-	-	N=0 (valid months)
MAM	0.181	75.39	N=40 (valid months)
JJA	0.027	21.30	N=42 (valid months)
SON	0.024	16.71	N=14 (valid months)

Table 19: CLARA-A2-SAL product quality indicators at the pentad mean level over Sodankylä.

Data record / period	RMSE	Mean rel. difference [%]	Notes
Pentad means	0.114	41.86	N=520 (valid pentads)
DJF	-	-	N=0 (valid pentads)
MAM	0.170	64.84	N=212 (valid pentads)
JJA	0.047	28.12	N=248 (valid pentads)
SON	0.039	17.41	N=60 (valid pentads)

9. Summary of land-based validation site results

The validation results for all land-based sites are summarized in Table 20. Only monthly mean validation results are shown as the pentad mean results are highly similar.

Table 20: Validation results summary for monthly means over all land-based sites.

Site	RMSE	Mean relative retrieval difference [%]
Neumayer, Antarctica	0.093	-9.46
Payerne, Switzerland	0.04	-15.3
Southern Great Plains, USA	0.03	-10.09
Syowa, Antarctica	0.115	-7.71
Summit Camp, Greenland	0.044	-3.88
DYE-2, Greenland	0.067	-6.15
JAR-2, Greenland	0.094	14.21
Sodankylä, Finland	0.119	43.17

10. Validation against Tara Expedition Observations

To assess the performance of CLARA-A2-SAL over sea ice, we validate the Arctic pentad products against Tara ice camp observations. The French schooner Tara functioned as a drifting ice station between September 2006 and January 2008, the crew performing meteorological observations throughout the period (Gascard et al., 2008; Vihma et al., 2008). The upward and downward shortwave radiation fluxes were measured at Tara from 12 May to 19 September, 2007, using Eppley PSP pyranometers. The sensors were set up at the height of 2 m above the snow surface and regularly checked and maintained.

The validation is made by forming pentad means of the all sky Tara observations corresponding to the CLARA-A2-SAL pentad mean products. The results are shown in Figure 20. CLARA-A2-SAL follows the increasing spring melt and thus lower albedo around Tara ice camp; the retrieved albedo is mostly in line with the in situ observations, although it seems to react more slowly to the changes observed by the Tara measurements. Differences do occur when the melt pond fraction around the pyranometer differs from the area mean, as explained in Riihelä et al. (2010).

The RMSE between pentad means calculated from in situ observations and the retrieved CLARA-A2-SAL pentad means is 0.095 and the mean relative difference is -8.56. The large value of RMSE is to be expected taking into consideration that the comparisons made using point-like ice camp observations and the satellite product of a larger area.

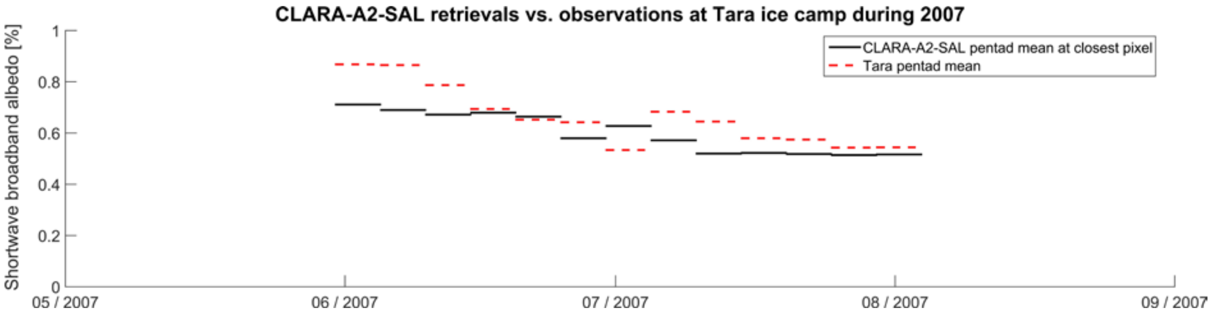

Figure 20: Mean CLARA-A2-SAL pentad retrievals (black lines) versus CLARA-A2-SAL-equivalent pentad means at Tara (red dashed lines).

11. Comparison against MODIS 16-day BSA shortwave albedo product

The previous validation results show the CLARA-A2-SAL product accuracy against ground truth over small scales. It is, however, equally valuable to know how CLARA-A2-SAL compares to other satellite-based albedo products. Note, however, that this study is termed “comparison” instead of “validation” for a reason. Differences between satellite-based products do not automatically equate to errors in one or the other product.

Fully global and long-term satellite albedo products are not numerous; the best-known surface albedo products come from MODIS (MCD43C3), CERES (FSW) and AVHRR Polar Pathfinder (APP-X). In this comparison we shall focus on comparing CLARA-A2-SAL with the MODIS MCD43C3 albedo product.

We have chosen the year 2009 for the comparison. To match the CLARA-A2-SAL products from 2009 to the MODIS 16-day albedo means, the following procedures were followed:

1) The MCD43C3 product was coarsened to 0.25-degree resolution by averaging 5 x 5 pixel regions (blocks, not a moving window) with the assumption that the spatial matching is thus sufficiently good to allow a general comparison of the products.
2) The MCD43C3 products are 16-day means whereas CLARA-A2-SAL products are pentads and monthly means. For simplicity, it was decided to create a MODIS-equivalent CLARA-A2-SAL product by averaging the pentads which fit within the MODIS 16-day period, plus minus one day. Three pentads were generally available for averaging per MODIS product.
3) Areas where either CLARA-A2-SAL or MODIS had no data-values were excluded.
4) Only the MODIS retrievals with highest quality (quality flag value 0) were used in the comparison.

Figure 21, Figure 22 and Figure 23 show an example of the comparison. The MODIS product is resampled to 0.25 degree resolution, a corresponding (average) composite is constructed from the CLARA-A2-SAL pentads, and the two are then studied for relative differences. The example results are from May 2009.The differences between CLARA-A2-SAL and MODIS are quite small, the relative difference is typically between -10% - 10%. The larger differences typically appear in mountainous areas, where CLARA-A2-SAL values are higher than MODIS values, and Arctic Siberia, where CLARA-A2-SAL gives lower values than MODIS. It seems that, in general, CLARA-A2-SAL estimates higher values to mountainous and vegetated areas and lower values to flat areas with bare or sparsely vegetated areas such as deserts, tundra and steppe, regardless of latitude. This is to be expected, since in CLARA-A2-SAL the topography effect has been taken into account, resulting in higher albedo values in mountainous areas.

We also calculated the global land/snow surface mean albedo per MODIS product period. The result for 2009 is shown in Figure 24. The two products are in good agreement; the difference being that for some periods CLARA-A2-SAL tends to be 2-3% higher. The products differ the most in the period from February to the end of July. The difference in the general level of albedo is caused by the fact that the MODIS product is normalized to local noon, which, for surfaces other than snow, produces the minimum daily albedo. Taking this into consideration, CLARA-A2-SAL values should be slightly higher than the MODIS product values.

The reader should thus keep in mind that the two products are unlikely to conform fully even under ideal circumstances. Also, the MCD43C3 is defined over a broader waveband (0.3 – 5 microns) than CLARA-A2-SAL. However, as solar energy on the SWIR spectrum is minimal, the expected impact on the comparability is also deemed very small.

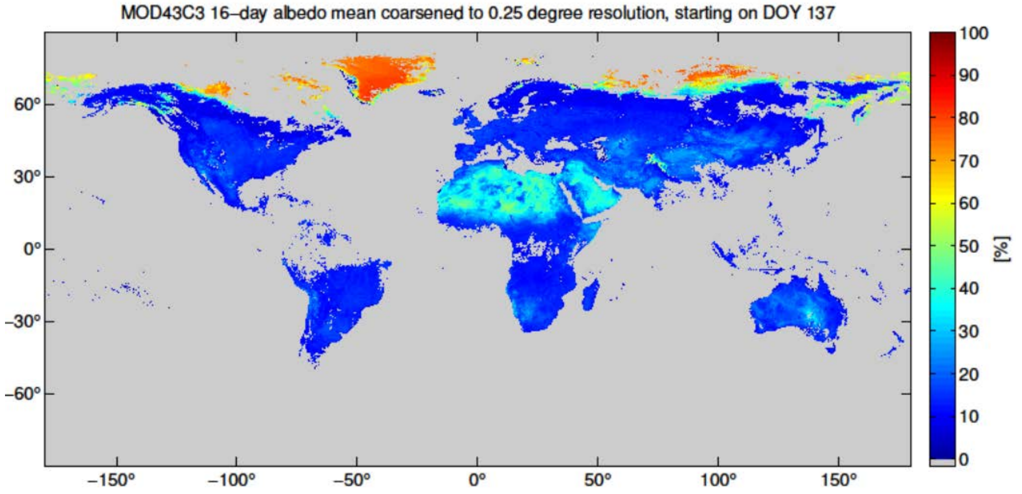

Figure 21: MCD43C3 16-day BSA shortwave albedo product starting from DOY 137 of 2009. Product has been resampled to 0.25 degree spatial resolution.

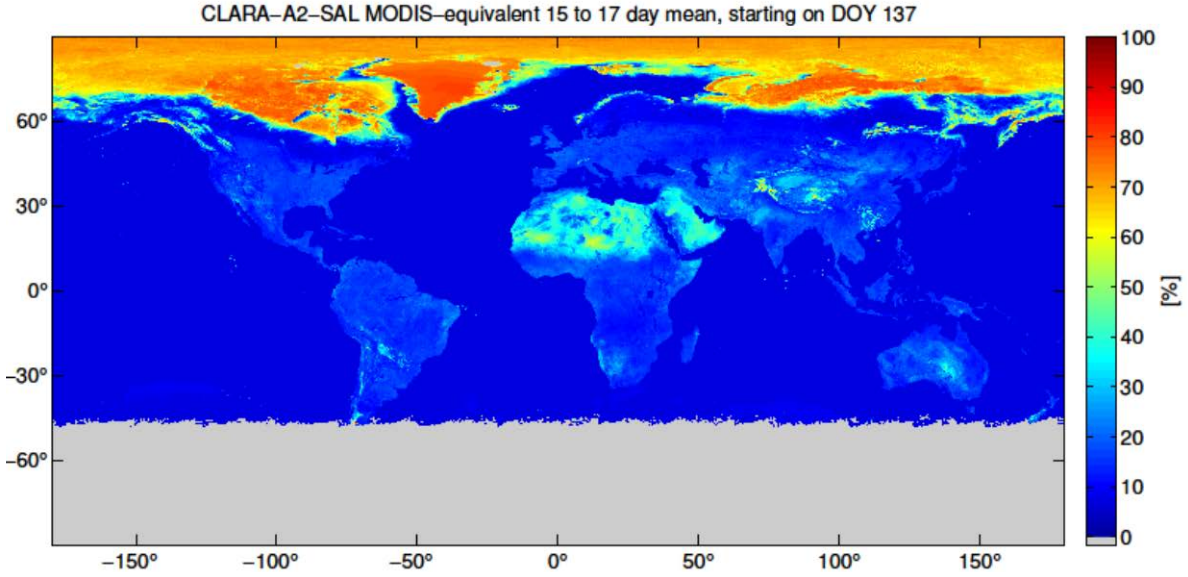

Figure 22: A composite of three CLARA-A2-SAL pentads fitting within (±1 day) the 16-day MCD43C3 period starting on DOY 137 of 2009.

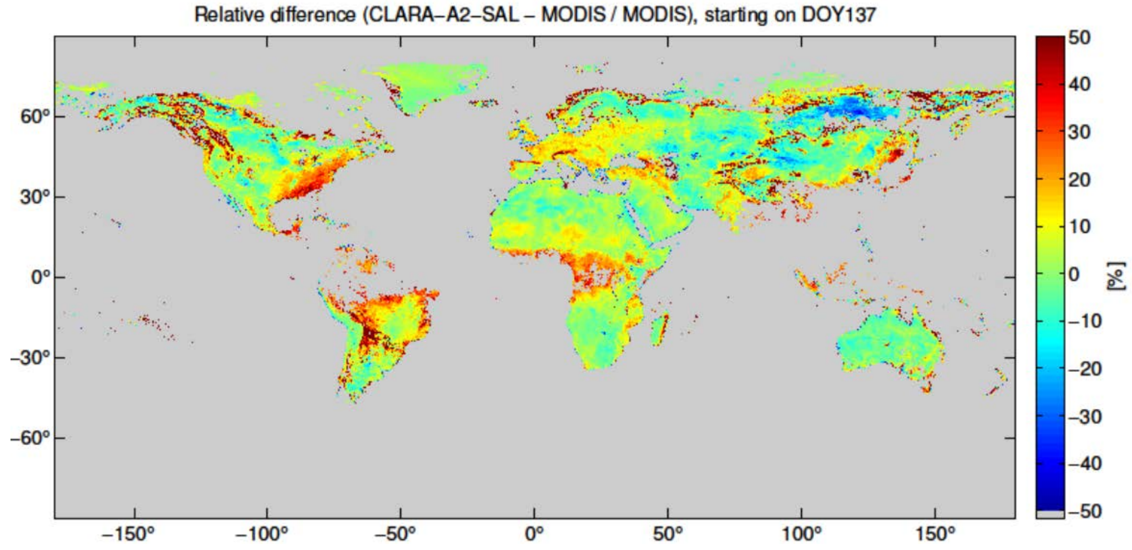

*Figure 23: **Relative** difference (in %) between CLARA-A2-SAL and MCD43C3 over the 16-day MODIS product period starting on DOY 137 of 2009.*

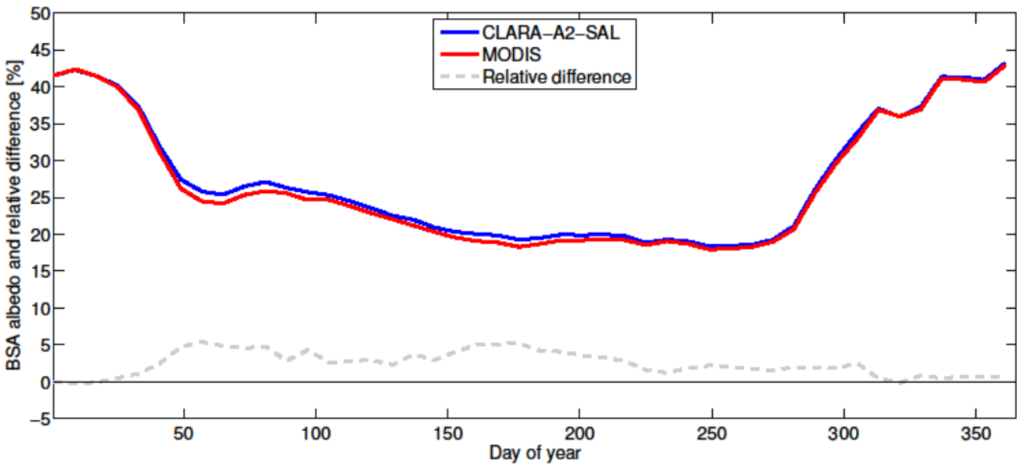

Figure 24:Land/snow surface global black-sky albedo mean for 2009 from the MCD43C3 and CLARA-A2-SAL pentad composites. Red and blue lines indicate MODIS and CLARA-A2-SAL albedo, respectively, and the dashed grey line shows the relative difference (in % using left y-axis) between the products. The albedo has not been weighted for irradiance or area.

Yet another way of comparing the products is to look at the latitudinal albedo means. This calculation was performed on the 2009 products, and the results for the land/snow areas are shown in Figure 25.

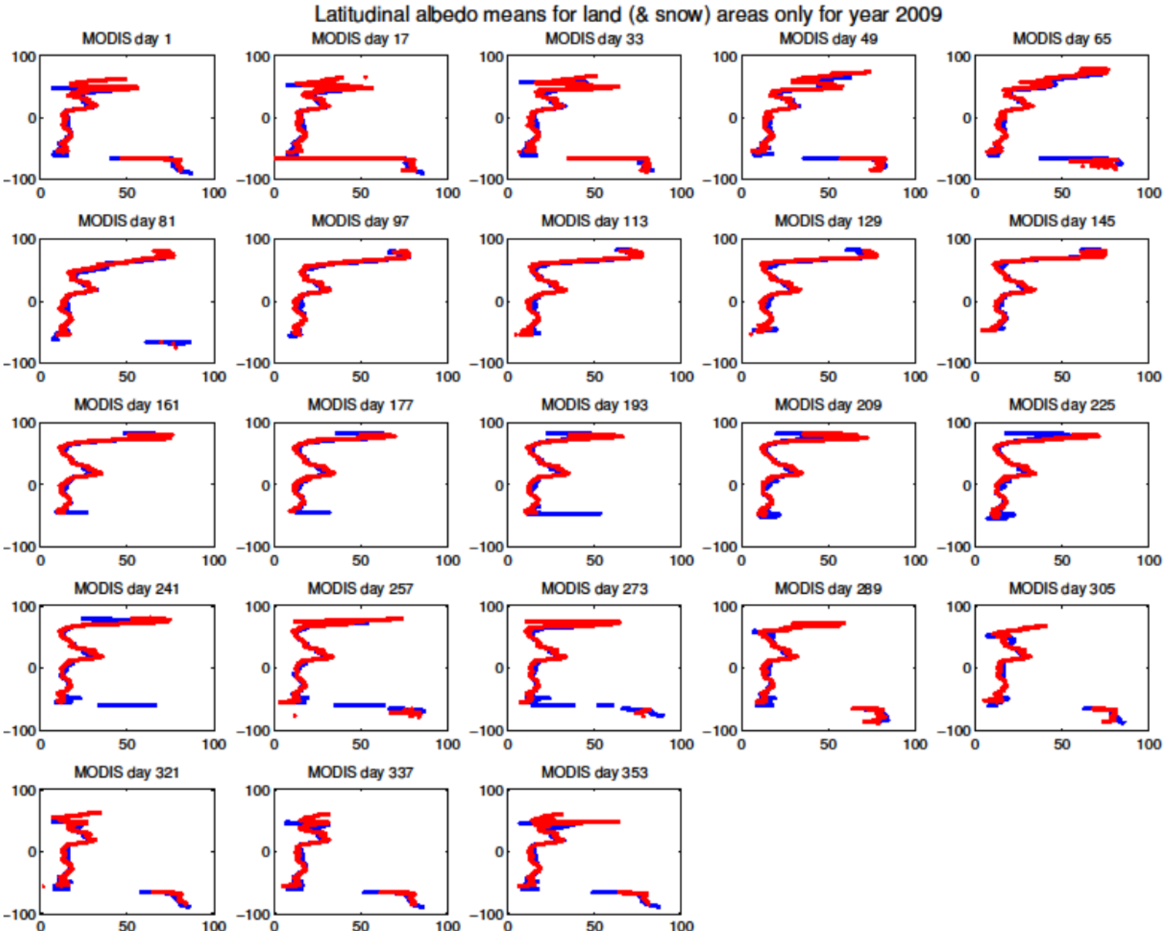

Figure 25:MCD43C3 (red) and CLARA-A2-SAL (blue) latitudinal BSA albedo means for 2009. Only every second MODIS 16-day product is compared here for clarity. Y-axis indicates latitude (degrees) and the x-axis indicates BSA albedo (in %)

The comparison shows that there are no considerable differences between the two products except in polar regions. The mean latitudinal albedo is similar over the large Northern Hemisphere landmasses.

Relative differences in the latitudinal means are shown in Figure 26. Over most of the northern hemisphere, the relative difference between MODIS and CLARA-A2-SAL is between 10 and 25%. The largest differences appear in polar regions. The large difference “spike” occurring often between 50S is the Patagonia region. The topography (and whether or not its effect is corrected for) and ruggedness of the region create differences in the albedo means. The other spike at and 60S coincides with the Antarctic coast. At the equator and just south of it CLARA-A2-SAL seems to get higher values than MODIS, which was also seen in the relative difference map, as there are large areas of tropical forests at the equator and just south of it. The northern spike at around 50N appearing typically in the northern hemisphere autumn, winter and spring, that is, the snow season,

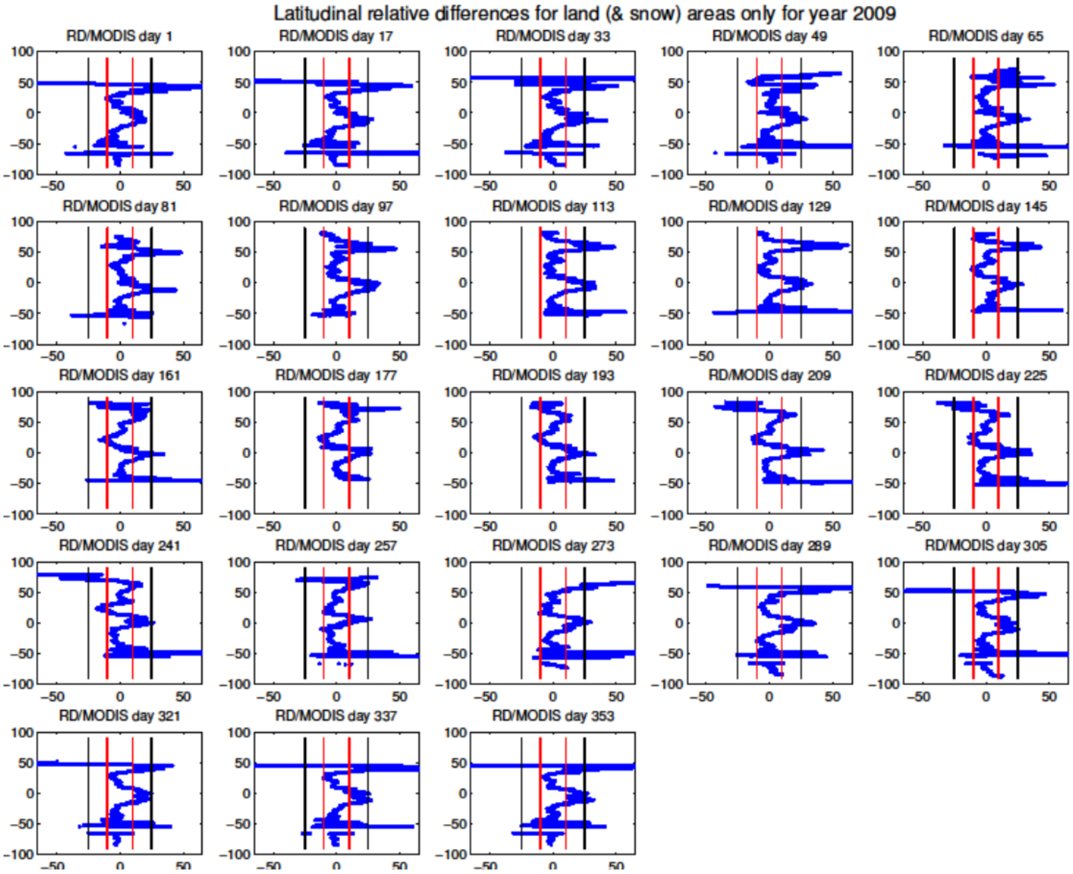

Figure 26: Relative difference between MODIS and CLARA-A2-SAL (CLARA-A2-SAL-MCD43C3)/MCD43C3) as a latitudinal mean. Study period is the year 2009. Y-axis indicates latitude (degrees), X-axis indicates relative difference (in %).

12. Discussion on Product Stability

The results thus far shown in this report have illustrated the retrieval quality of CLARA-A2-SAL over certain validation sites and a comparison to another well-known satellite albedo product. Our last remaining task is to study the temporal stability of CLARA-A2-SAL over regions known to exhibit stable albedo over long time-periods. To do this, we have chosen three study sites; Libya desert at 29.1 N, 24.5 E, previously used by Govaerts and Lattanzio (2007) as a calibration study target, Central Greenland Ice Sheet (75 N -42.5 E) and Dome C calibration site at Antarctica (-75.1 N, 123.4 E). In addition to this we have also done a similar study over a temperate forest site in Central Europe, the Black forest (Schwarzwald, 48N, 8E).

The stability analysis results for Dome C are shown in Figure 27 and for Libya desert in Figure 28. The study regions were limited to ±2 pixels around the site, thus showing small-scale variation of CLARA-A2-SAL over Sahara and Antarctica. Anomalies from the long-term mean occur at Libya site mostly during the early 1990’s, as well as 2000-2001. It is notable that the periods of highest anomalies coincide with the periods with considerable variation also in the amount of satellite data available for the CLARA-A2-SAL monthly means. The mid-1990s and 1999-2001 are both such periods owing to changes in the NOAA constellation. The regional mean is quite stable in the 2000s when the amount of available data has been steadily growing.

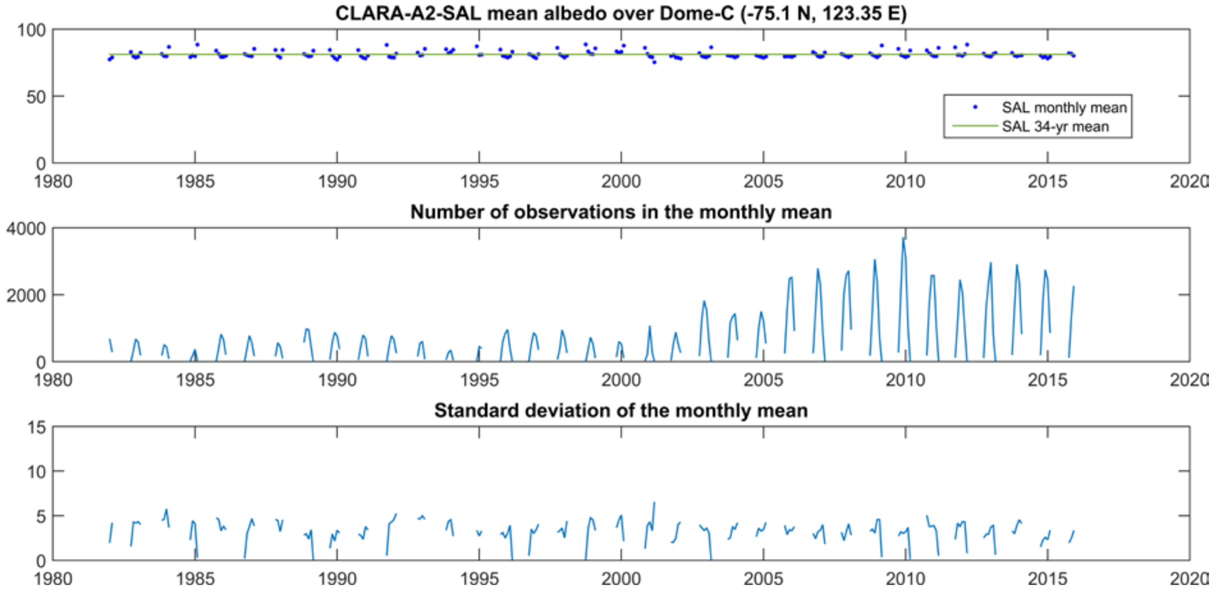

Figure 27: The Stability analysis of Dome-C calibration site.

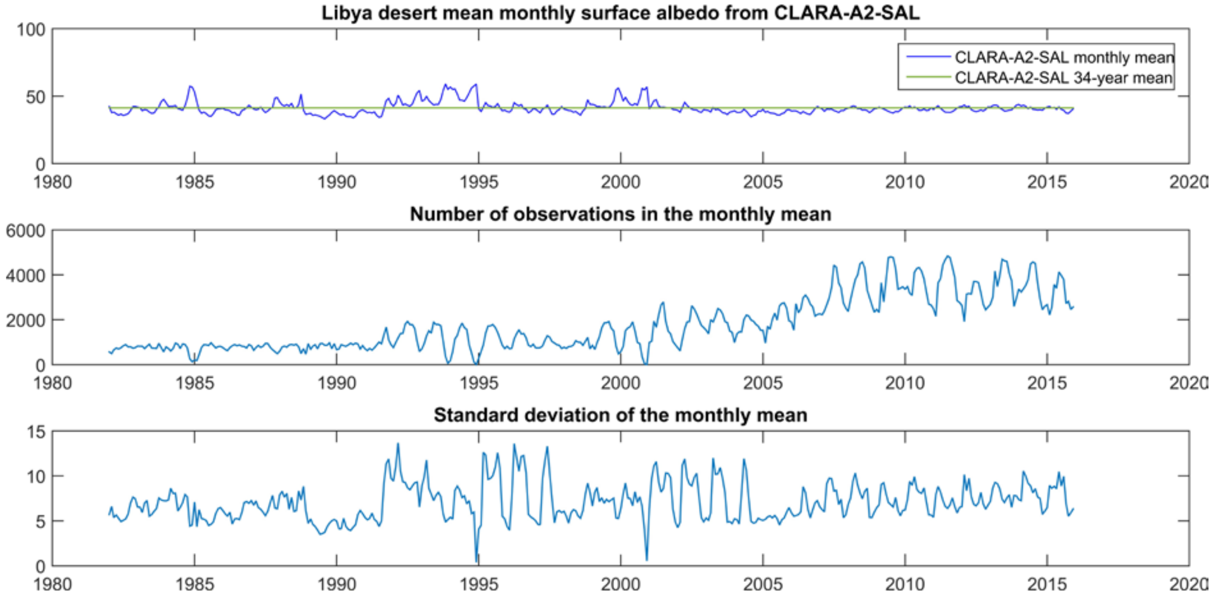

Figure 28:Stability analysis of the Libya desert region.

Over the Greenland Ice Sheet (GrIS) (Figure 28) the situation is similar to Dome C. Variations from the 34-year mean are typically around 5% absolute values. The largest relative deviation from the interannual mean is 8.5%, while the mean deviation is 1.27%. The large maximum deviation is likely caused by the less conservative cloud mask used in CLARA-A2-SAL than in CLARA-A1-SAL. The central part of the GrIS is known to be a stable target which does not experience snow melt, nor are there any man-made changes in the terrain. The atmosphere over the region is also typically thin and dry; therefore the CLARA-A2-SAL atmospheric correction works well.

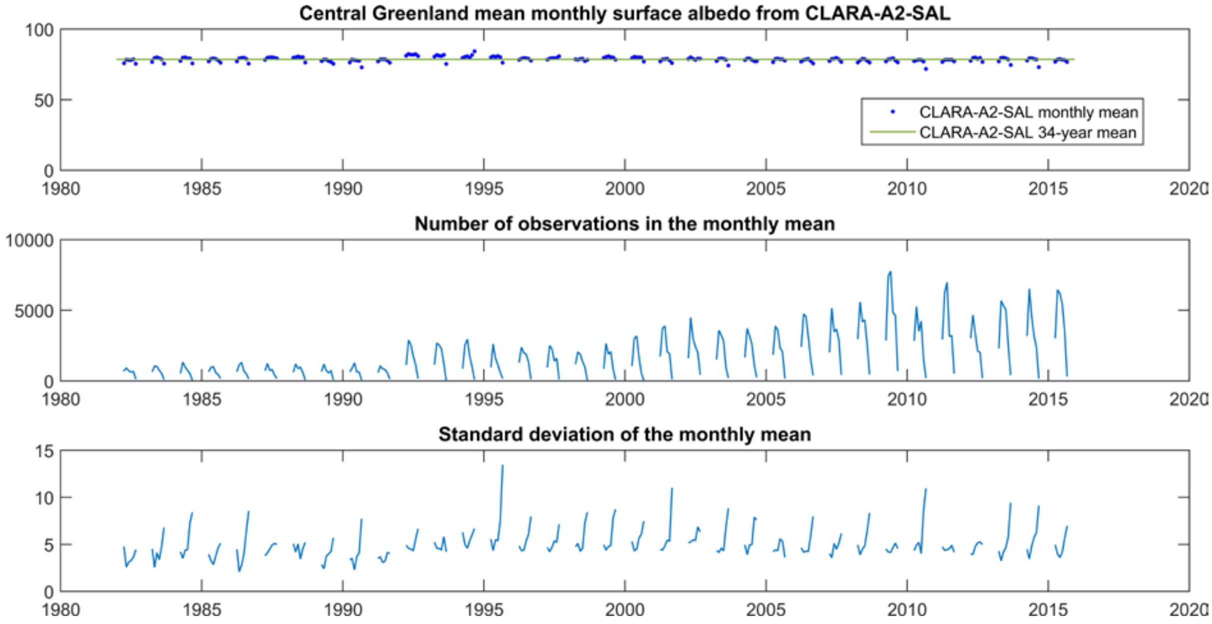

Figure 29:CLARA-A2-SAL stability over the Central Greenland Ice Sheet region.

Apart from the desert and snow sites, we also investigated the stability of the CLARA-A2-SAL over a temperate forest site in Central Europe. We chose the black forest (Schwarzwald, 48N, 8E) as the site is one of the few larger continuous forest areas in Central Europe. The area contains considerable topographical features as well, allowing us some insight into the topography correction handling. Figure 30 shows the results from investigating the single CLARA-A2-SAL pixel closest to 48N, 8E for years 1982-2015. The time series is quite stable over the 34-year period, the variation is due to winter-time snow cover. The winter/spring snow-cover is variable, as also seen in the large standard deviation of the monthly mean during most January-March periods. The increase in available AVHRR data from year 2000 onwards is once again evident.

For comparison, we also show the same pixel extracted from the pentad CLARA-A2-SAL products in Figure 31. Snow deposition events stand out clearer in the pentad time series. Despite the temperate latitude of 48 degrees North, the winter months still suffer from a relatively small amount of available overpasses for pentad mean calculation. Winter-time cloudiness of course is also a factor here.

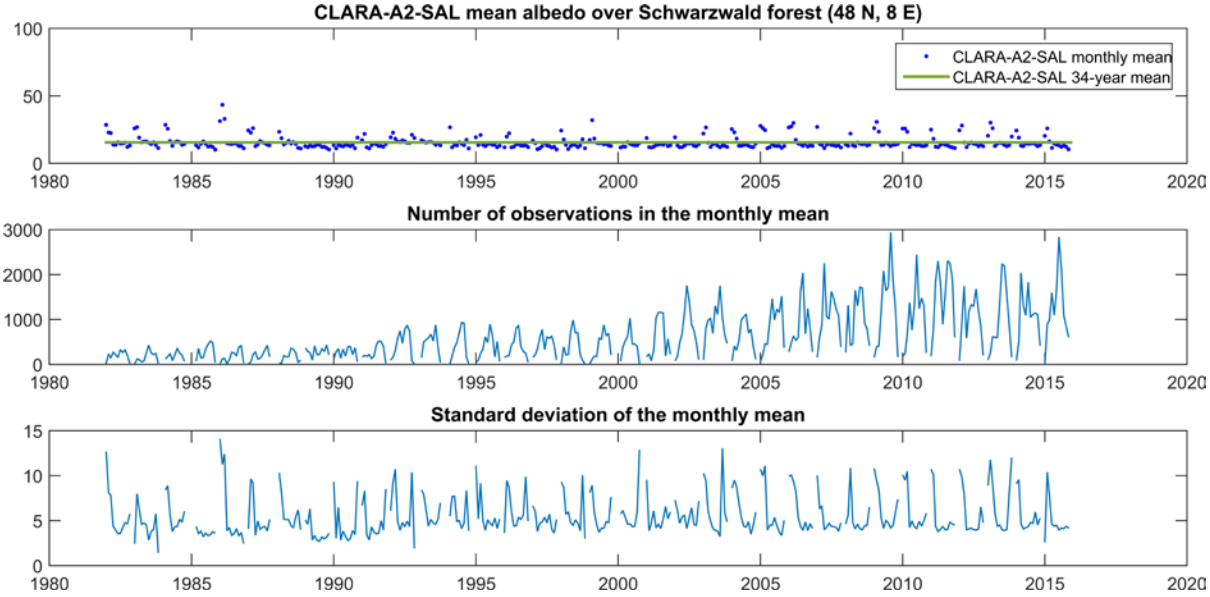

Figure 30:CLARA-A2-SAL stability over Schwarzwald forest, Germany (48 N, 8 E). Monthly means.

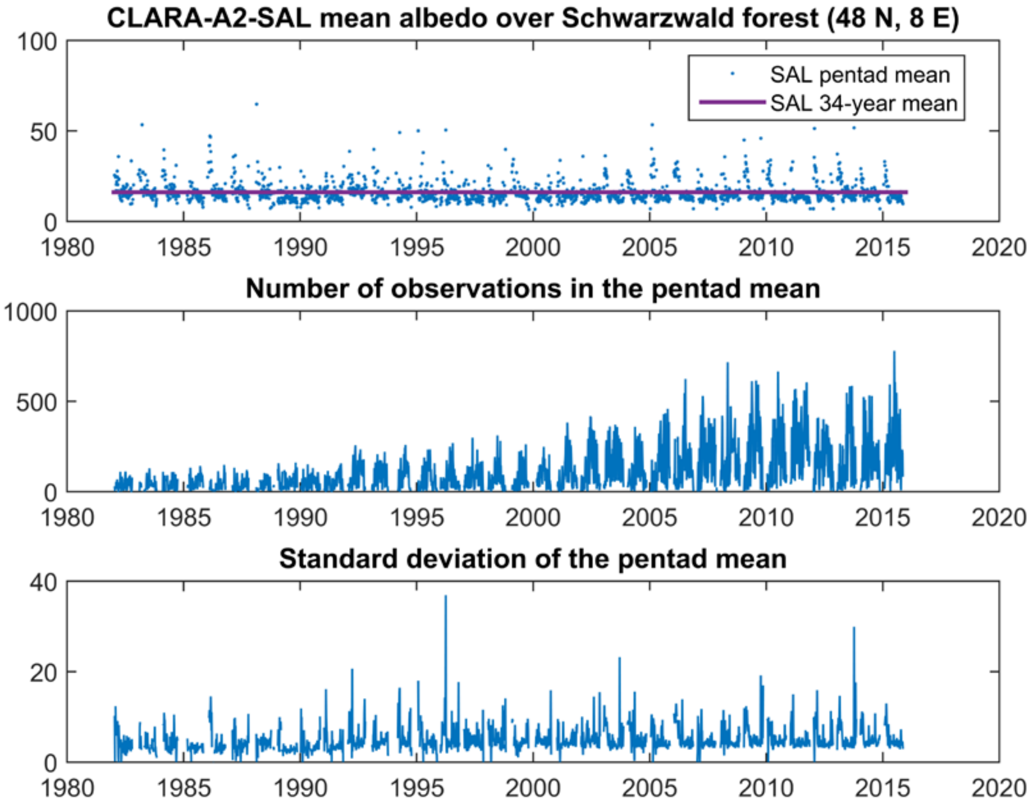

Figure 31: CLARA-A2-SAL stability over Schwarzwald forest, Germany (48 N, 8 E). Pentad means.

13. Conclusions

This report has presented the findings of the validation study on the CLARA-A2-SAL TCDR release 2. The CLARA-A2-SAL product performance has been validated against in situ data from the BSRN and GC-Net networks of surface albedo observation sites. The products were also compared to black-sky shortwave albedo products from MODIS (MCD43C3).

The BSRN and GC-Net time series are limited in length; most validation sites have albedo records from the mid-1990s onwards. This means that the CLARA-A2-SAL product quality between 1982 and 1992 has to be assumed to be equal to the quality determined in this study. There may be issues with this assumption; the USGS land cover data record which forms one of the necessary inputs for CLARA-A2-SAL processing for this period may not be accurate when applied to periods far from its compilation time, and the quality of the radiance data from older AVHRR instruments may not be on a par with newer data. The reader is advised to be aware of these potential issues.

The CLARA-A2-SAL products fulfil their target accuracy for 7 out of 8 studied validation sites and time periods. The cases where the target is not met are traceable to poor comparability between in situ and satellite data owing to vastly different spatial footprints. Coastal, urban and other heterogeneous land cover sites present a challenge for validation in this regard. It is worthwhile to note that CLARA-A2-SAL accuracy over the Southern Great Plains BSRN site (Oklahoma, USA), where the land cover is fairly homogenous over large areas, is well within the target accuracy requirement. The same is true for sites over perennial and homogenous snow cover in Greenland and Antarctica.

The comparisons to MODIS albedo product shows that CLARA-A2-SAL produces a 2-3% (relative) higher global mean albedo over land areas (snow included). A study of latitudinal means shows that CLARA-A2-SAL tracks latitudinal albedo features similarly to the MODIS product; differences to MODIS mostly occur over the tropical regions and Patagonia (where the topography correction in CLARA-A2-SAL causes differences), as well as the polar regions.

Finally, we have studied CLARA-A2-SAL stability over regions where we expect very little variation in surface albedo; the Libya desert, Dome C at Antarctica and the inner parts of the Greenland Ice Sheet. Over GrIS, CLARA-A2-SAL is very stable during the validation period, maximum deviation from the interannual mean being 8.5% (relative) and the mean deviation of the whole 34 years is 1.27%. The Libya site shows a much larger variability.

Overall, the CLARA-A2-SAL TCDR has been found to meet the target accuracy specified in the Product Requirement Document of CM SAF [AD 1]. Therefore, the product team at FMI recommends its release to the user community.

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Abbreviations

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	CM SAF cLouds, Albedo and Radiation – Surface Albedo product
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
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