EUMETSAT Satellite Application Facility on Climate Monitoring

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Surface Albedo

Validation Report

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Reference Documents

Reference	Title	Code
RD 1	CM-SAF Product Requirements Document	SAF/CM/DWD/PRD/1.7
RD 2	Product User Manual Surface Albedo CLARA-A1	SAF/CM/FMI/PUM/GAC/SAL/1.2
RD 3	Algorithm Theoretical Basis Document Surface Albedo CLARA-A1	SAF/CM/FMI/ATBD/GAC/SAL/1.2

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1. Executive Summary

This CM SAF report provides information on the validation of the CM SAF CLARA-SAL Edition 1 data set derived from Advanced Very High Resolution Radiometer (AVHRR) observations onboard National Oceanic and Atmospheric Administration (NOAA) platforms NOAA7 – NOAA19 and EUMETSAT's Metop-A.

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 dataset of

Broadband Surface Albedo [CM-60, SAL_AVHRR_global_DS]

from the 28-year Fundamental Climate Data Record (FCDR) of AVHRR radiances spanning the years 1982-2009.

The validation of the CLARA-SAL algorithm is performed in two parts. First we evaluate the product accuracy against ground observations of surface albedo, while keeping in mind the problem of spatial representativeness of a point-like station observation versus a large-scale satellite retrieval. The issue of representativeness on a global scale is then explored further with a comparison of CLARA-SAL to existing global surface black-sky albedo products from the CERES FSW dataset. A limited comparison to MODIS MCD43C3 edition 5 products is also presented.

The validation results show that CLARA-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 larger 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-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 error calculated from the monthly mean product results of all validation sites for the entire validation period 1994-2009 and the decadal stability (maximum deviation of retrieved monthly mean albedo from its 20-year mean, in relative units) as calculated from the regional mean albedo of the central part of the 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 Sahara desert and a forested site in Central Europe.

Table 1: Validation result summary

Mean relative retrieval error (all sites, full period)	**-10.3 %**
Mean RMSE (all sites, full period)	**0.091**
Decadal stability over central Greenland Ice Sheet (1989-2009, in relative units)	**5.8 %**

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 sets is pursued. The ultimate aim is to make the resulting data sets suitable for the analysis of climate variability and potentially the detection of climate trends. CM SAF works in close collaboration with the EUMETSAT Central Facility and liaises with other satellite operators to advance the availability, quality and usability of Fundamental Climate Data Records (FCDRs) as defined by the Global Climate Observing System (GCOS). As a major task the CM-SAF utilizes FCDRs to produce 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 sets 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 sets 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 sets also serve the improvement of climate models both at global and regional scale.

As an essential partner in the related international frameworks, in particular WMO SCOPE-CM (Sustained COordinated Processing of Environmental satellite data for Climate Monitoring), the CM SAF - together with the EUMETSAT Central Facility, assumes the role as main implementer of EUMETSAT's commitments in support to global climate monitoring. This is achieved through:

- Application of highest standards and guidelines as lined out by GCOS for the satellite data processing,
- Processing of satellite data within a true international collaboration benefiting from developments at international level and pollinating the partnership with own ideas and standards,
- Intensive validation and improvement of the CM SAF climate data records,

- Taking a major role in data set assessments performed 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, 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). 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 timeseries of 1982-2009 offers the longest duration dataset of global observations applicable for surface albedo product generation. The CM SAF project has now applied this timeseries into the production of the first Edition of the global (90N – 90S) CLARA-SAL surface albedo dataset, 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 dataset against reference observations of surface albedo.

This document is divided as follows; first we shall introduce the validation reference datasets and the main characteristics of the CLARA-SAL dataset. More details on the CLARA-SAL product generation procedure and applied algorithms are available in the CLARA-SAL Product User Manual [RD 2] and the Algorithm Theoretical Basis Document [RD 3]. 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 dataset quality as a whole, identify issues in the data for correction in future Editionn, and conclude with the main findings of the validation study.

4. CLARA-SAL Main Characteristics

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 3]):

- 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 instantaneous 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 USGS land use classification data. Open water albedo is derived from a LUT by Jin et al. (2004). Currently the open water albedo depends only on SZA and is normalized to 60 degrees everywhere; thus the ocean albedo is constant at 0.0676.
- The computed broadband albedos are normalized to a sun zenith angle (SZA) of 60 degrees (Briegleb et al., 1986). This step is omitted for snow, since no universal model currently exists for the various snow diurnal cycles.

The instantaneous products are then reprojected 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 EASE-grids with a resolution of 25 kilometers.

An example of the CLARA-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.

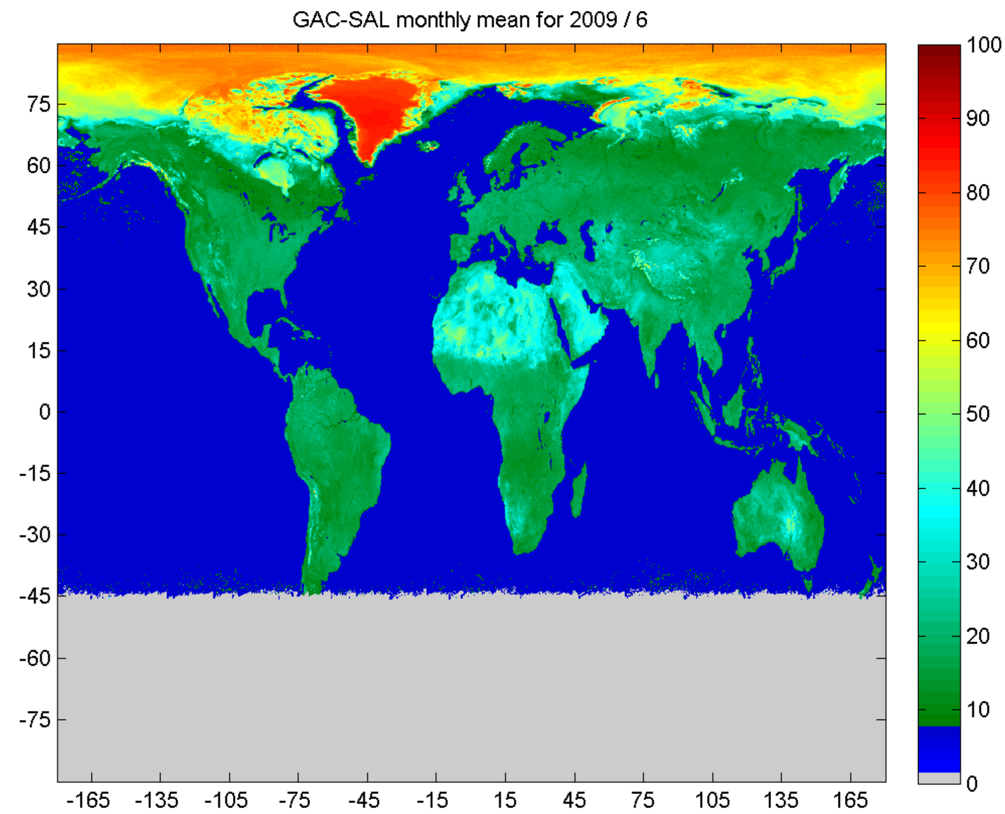

Figure 1: CLARA-SAL monthly mean from June, 2009.

5. Validation Data Sets

The reference data used needs to be quality-controlled and have a sufficient data length to provide a meaningful comparison against the CLARA-SAL timeseries. 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
Barrow, USA	71.32	-156.61	tundra, flat	1995-2009
Neumayer, Antarctica	-70.65	-8.25	snow/ice, flat	1995-2009
Payerne, Switzerland	46.82	6.95	cultivated, hilly	1995-2009
Southern Great Plains, USA	36.61	-97.49	grass, flat	1994-2009
Syowa, Antarctica	-69	39.59	snow/ice, hilly	1998-2009
Tateno, Japan	36.05	140.13	grass (urban), flat	1997-2009

The reference dataset 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 dataset further, we also added the albedo timeseries 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	1999-2009
DYE-2	66.48	-46.28	1996-2009
JAR-2	69.42	-50.06	1999-2007, 2009
Summit	72.58	-38.5	1996-2005, 2007-2009

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-SAL algorithm was therefore preset to record its instantaneous retrieved albedo with associated data on separate data files. The timestamps on these records were used to construct a CLARA-SAL-comparable temporal albedo mean from the full station observation record. The extracted reference data were also used for a preliminary study on the accuracy of the instantaneous, higher-resolution albedo retrievals. The results will be shown in the later sections.

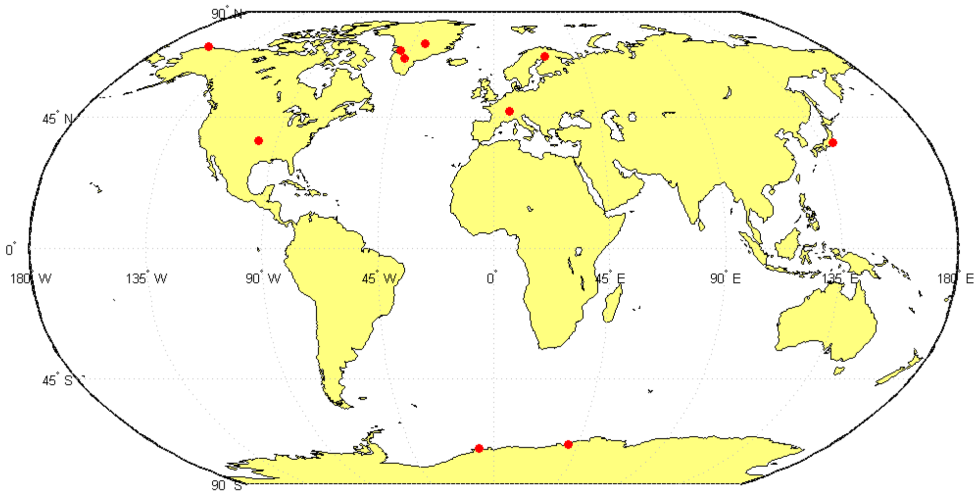

Figure 2: Geographical distribution of the validation locations excepting the Tara drift route on the Arctic Ocean.

Since the CLARA-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-SAL and reference data (see [RD 3] for details).
Since the snow albedo in CLARA-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-SAL and reference observations at the instantaneous level, since then we will basically be comparing bidirectional snow surface reflectances (CLARA-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. 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-SAL product is as follows:

- Record instantaneous timestamps, albedo values and associated data at each validation site locations during processing.
- Extract corresponding surface albedo observations from the in situ datasets.
- Utilize the values from step 2 to construct a comparable pentad/monthly mean dataset for each validation site.
- Compare results and calculate RMSE and mean relative retrieval error (main quality indicators).

The process is illustrated graphically in Figure 3.

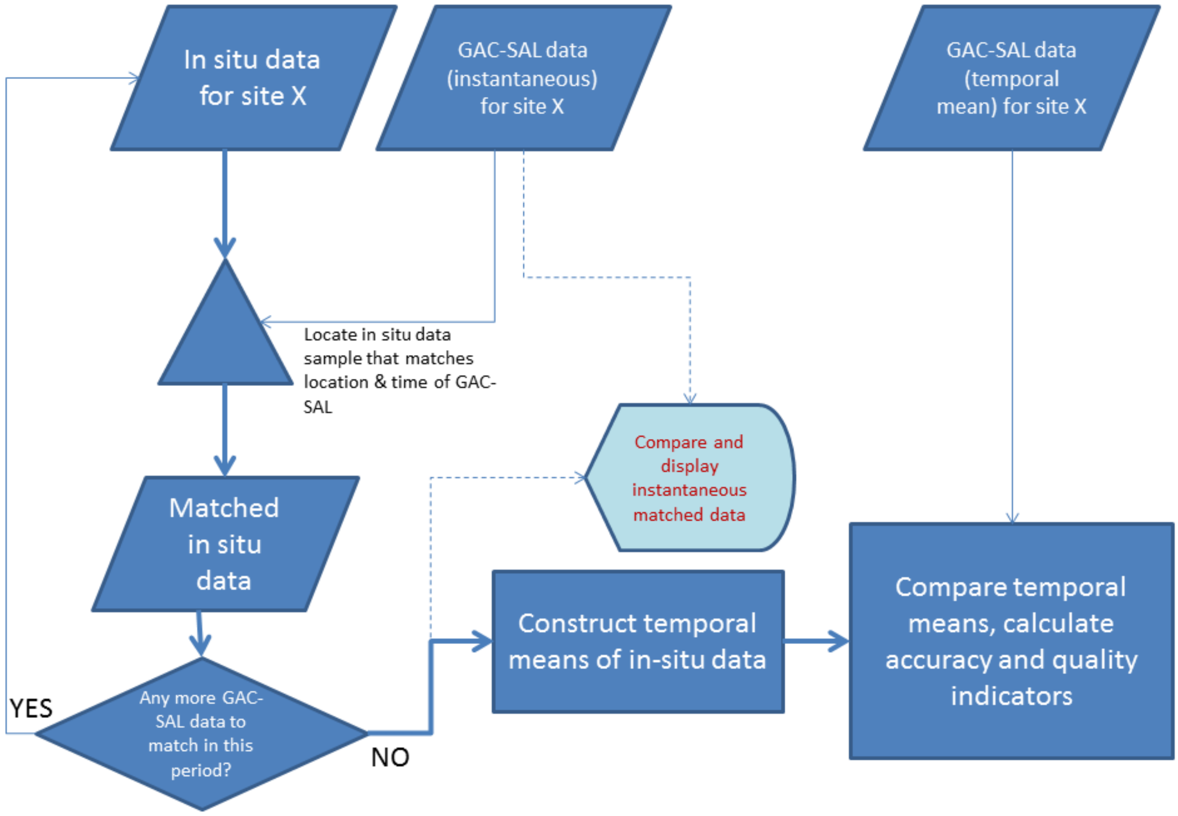

Figure 3: The CLARA-SAL validation process for a ground site

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 a 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. For example, we calculated the land/water fraction in the 0.25 degree CLARA-SAL pixel containing the Barrow BSRN site. The result was that the pixel consists of 71% of water bodies and only 29% of land surface. Considering this, it requires no leap of imagination to explain any negative bias between the in situ albedo observation and satellite data. A coastal site like Barrow will always appear as a mixed pixel at the AVHRR resolution, much less in the spatially averaged temporal means.

A second issue in the data comparability is the inclusion of atmospheric effects in the reference albedo data. CLARA-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 (urban sites like Tateno). 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).

Lastly, it should be considered that the CLARA-SAL dataset spans a longer timeperiod than the longest length of validation datasets. For the period 1982-1994 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 dataset accuracy will likely degrade as we extend it back (or far forward) in time.

6. Validation Against BSRN Station Observations

6.1. Barrow, Alaska

We begin by showing the results from the BSRN site at Barrow, Alaska. The retrieved albedo over the Barrow data availability period (1995-2009) is shown in Figure 4. Note that the high latitude of Barrow limits the available albedo retrieval period, there is no data from winter periods. CLARA-SAL correctly observes the snowmelt each spring. There are often differences between the monthly mean CLARA-SAL albedo and the instantaneous CLARA-SAL retrievals over the same month, especially during winter-time. This results from the difference in spatial scale; the instantaneous values are retrieved at the satellite pixel containing the Barrow site in nominal GAC resolution (~5 km at nadir), whereas the monthly mean CLARA-SAL albedo is the aggregate of all CLARA-SAL retrievals that occurred within the 0.25 degree region containing Barrow. The region around Barrow BSRN site is very heterogeneous and snow cover in the area is not uniform during the melting period. Thus the large-scale mean albedo value will often naturally disagree with the point-like albedo mean at the BSRN site.

The relative retrieval error at monthly/pentad mean level is shown in Figure 5. Largest errors occur over the melting period when terrain heterogeneity effects are at their largest. AVHRR geolocation inaccuracies also cause issues at a coastal site like Barrow; applying the station co-ordinates in retrieving instantaneous satellite data often result in CLARA-SAL albedo of 0.0676, which is the current CLARA-SAL albedo of open water. This occurred in 18.9% of all 5285 matched overpass/station observation pairs during 1995-2009. The Barrow site is located ~1.5 km from the shoreline, thus some level of misclassification is expected using coarse GAC data. As explained in the previous section, the CLARA-SAL 0.25 degree pixel around the site contains 71% of water bodies, thus the satellite data is always a mix between land and open water albedo, the exact mix depending on the AVHRR geolocation accuracy for that period.

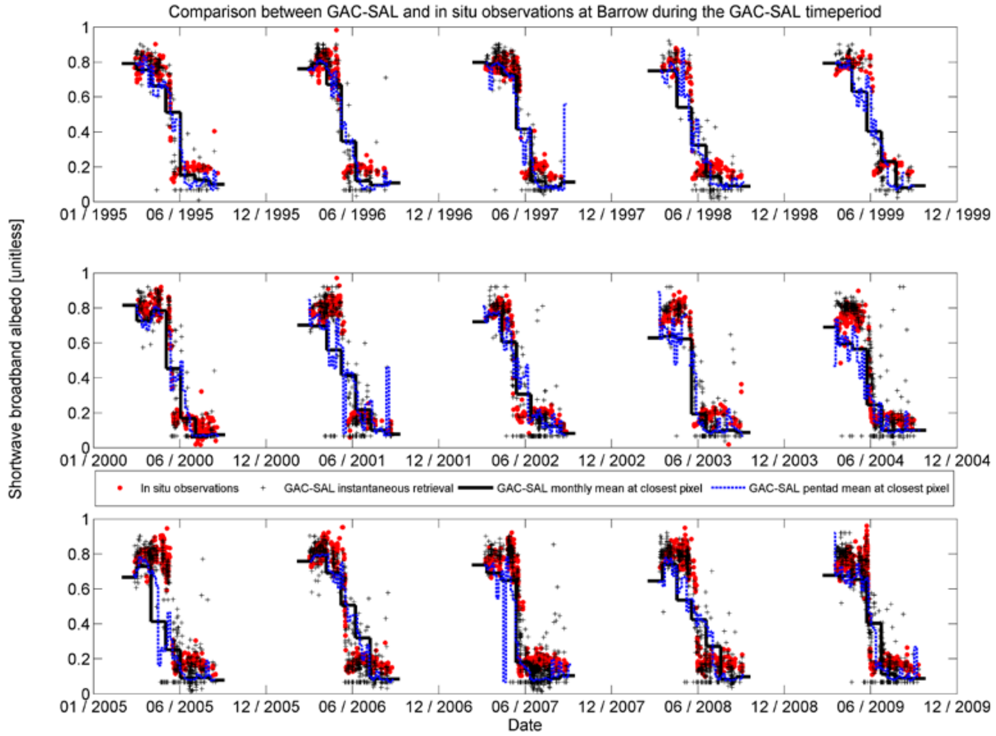

Figure 4: CLARA-SAL and in situ albedo over Barrow. Red circles indicate instantaneous in situ observations, black crosses show instantaneous CLARA-SAL retrievals, and the black and blue lines show the CLARA-SAL monthly & pentad mean albedo.

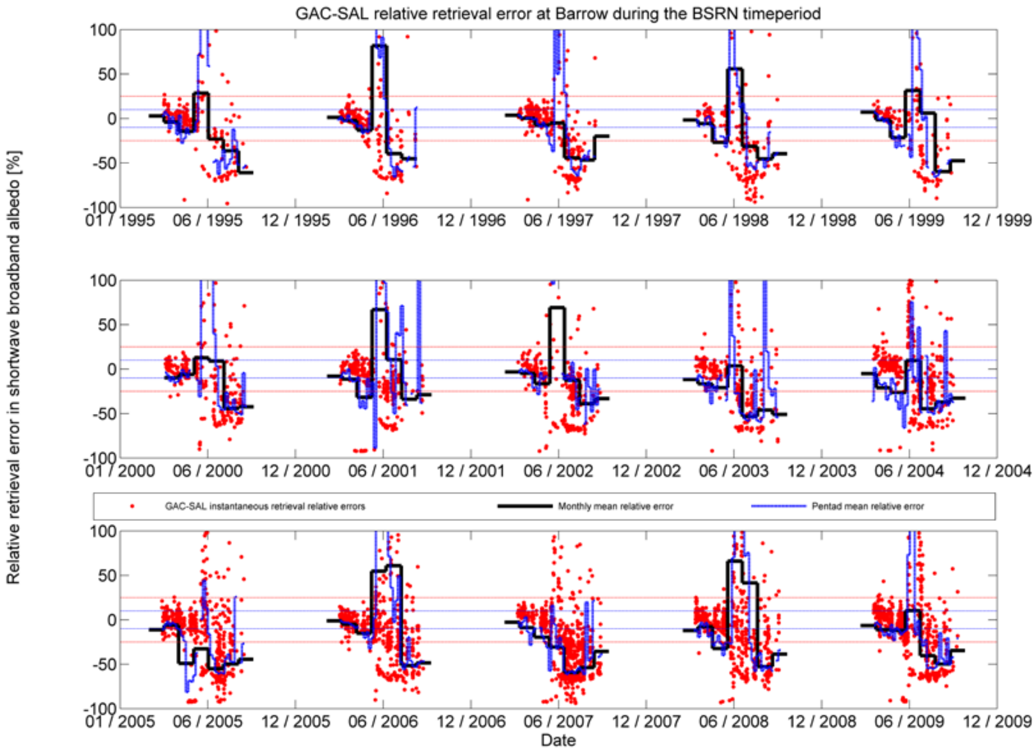

Figure 5: CLARA-SAL relative retrieval error over Barrow. Red circles indicate retrieval errors at instantaneous level; the black and blue lines show the retrieval error of the monthly and pentad means. Red and blue dashed lines show 25% and 10% relative error levels.

The numerical retrieval quality data for Barrow at the monthly mean level is shown in Table 4, and pentad data is shown in Table 5. It should be noted that the large overestimation that typically happens in June is compensated in the means by the following underestimations in July and August. Thus the JJA mean relative error over the whole dataset is within target specification. The terrain heterogeneity explains why the JJA monthly mean relative errors are very different from the pentad mean retrieval errors. To make the effect clearer, we also show the mean absolute retrieval error at Barrow in Table 4Table 5.

The pentad means show more variation in retrieval accuracy, as expected. Mean relative errors over the timeseries are within specifications, but the high RMSE shows the difficulty in comparing the albedo at a site like Barrow. Its proximity to the coast, the ruggedness of the terrain and heterogeneous freeze/snow melt during spring and autumn create highly variable conditions for CLARA-SAL. This is reflected in the results, even though the overall quality is within specifications (mostly due to mutually cancelling errors).

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

Dataset	RMSE	Mean rel. error [%]	Mean abs. retrieval error (relative to in situ) [%]	Notes
Instantaneous	0.132	-7.34	34.82	N= 5285
Monthly means	0.102	-15.24	27.59	N=103 (valid months)
DJF	-	-	-	N=0 (valid months)
MAM	0.119	-10.75	11.45	N=44 (valid months)
JJA	0.092	-12.01	39.59	N=45 (valid months)
SON	0.070	-39.74	39.75	N=14 (valid months)

Table 5: CLARA-SAL product quality indicators at the pentad mean level over Barrow.

Dataset	RMSE	Mean rel. error [%]	Mean abs. retrieval error (relative to in situ) [%]	Notes
Pentad means	0.144	-4.45	40.88	N=478 (valid pentads)
DJF	-	-	-	N=0 (valid pentads)
MAM	0.161	-13.19	15.40	N=200 (valid pentads)
JJA	0.133	4.26	59.87	N=253 (valid pentads)
SON	0.103	-22.67	52.71	N=25 (valid pentads)

6.2. Neumayer, Antarctica

Our first polar site is the Neumayer research station 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. Again, the latitude of the site limits data availability to austral summer.

The retrieved albedos are shown in Figure 6, and the associated relative retrieval errors are shown in Figure 7. Overall, CLARA-SAL performs within specifications. Apart from year 2000, the relative retrieval errors are typically around 10% and nearly always below 25%.

The trouble with year 2000 has been traced to problems in processing poor quality AVHRR data from NOAA-15. We are currently considering the elimination or post-processing correction of all or some of NOAA-15 data from the CLARA-SAL TCDR to remove these artifacts.

CLARA-SAL accuracy over bright terrain is highly dependent on the PPS cloudmask's ability to distinguish clouds from the underlying bright surface. Over the Antarctic coast, only 3.3% of all 2561 matched CLARA-SAL overpasses produce an albedo value between 0.1 and 0.65 (likely range for albedo when clouds are misclassified as snow/ice). Because Neumayer is located further away from the open water boundary than Barrow, the coarse CLARA-SAL resolution does not affect comparisons as much.

Apart from occasionally occurring large underestimations, the pentad means behave very similarly as the monthly means. The underestimations likely result from a combination of cloud mask misclassifications and geolocation uncertainty assigning open water at Neumayer coordinates.

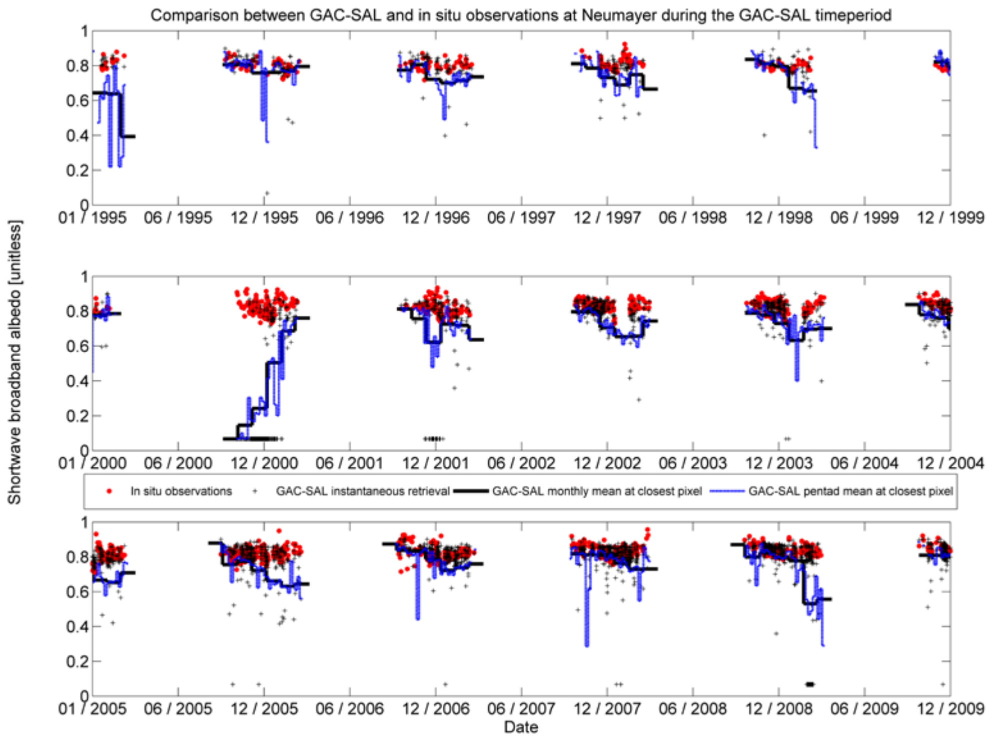

Figure 6: CLARA-SAL and in situ albedo over Neumayer. Red circles indicate instantaneous in situ observations, black crosses indicate instantaneous CLARA-SAL retrievals, and the black and blue lines indicate the CLARA-SAL monthly and pentad mean albedo.

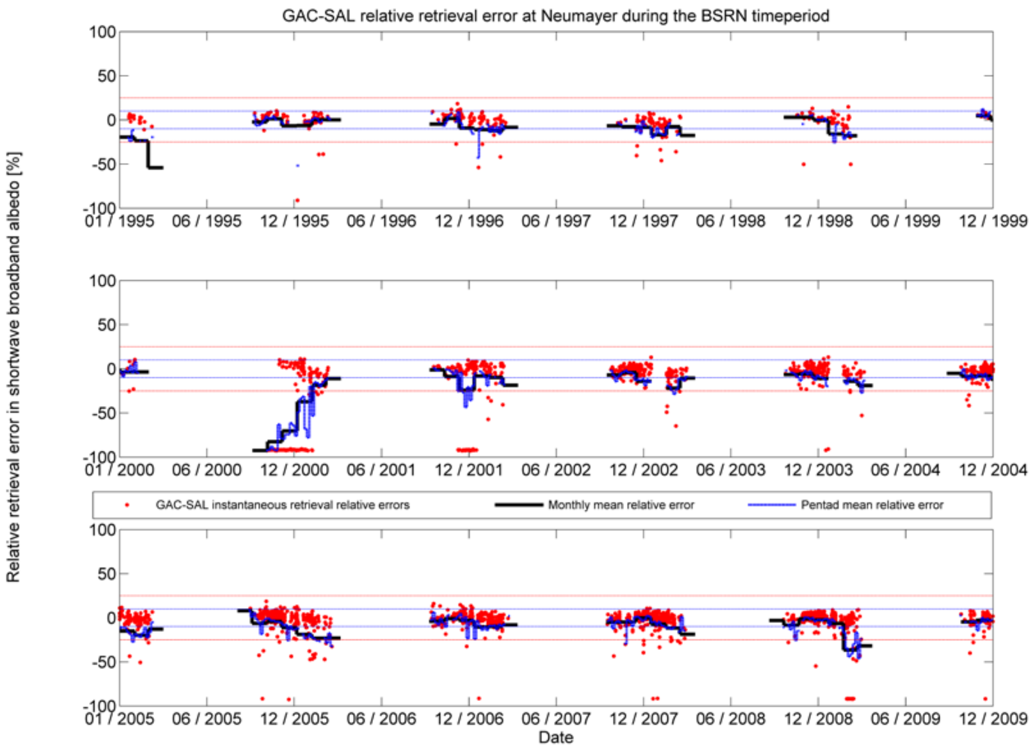

Figure 7: CLARA-SAL relative retrieval error over Neumayer. Red circles indicate retrieval errors at instantaneous level; the black and blue lines indicate the retrieval error of the monthly and pentad means. Red dashed line shows 25% and the blue dashed line 10% relative error levels.

The product quality indicators at Neumayer are listed in Table 6 and Table 7.

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

Dataset / period	RMSE	Mean rel. error [%]	Notes
Instantaneous	0.196	-7.19	N=2561
Monthly means	0.173	-12.37	N=88 (valid months)
DJF	0.149	-13.52	N=43 (valid months)
MAM	0.186	-17.92	N=13 (valid months)
JJA	-	-	N=0 (valid months)
SON	0.196	-8.56	N=32 (valid months)

Table 7: CLARA-SAL product quality indicators at the pentad mean level over Neumayer

Dataset / period	RMSE	Mean rel. error [%]	Notes
Pentad means	0.174	-12.20	N=381 (valid pentads)
DJF	0.176	-14.89	N=216 (valid pentads)
MAM	0.155	-14.55	N=23 (valid pentads)
JJA	-	-	N=0 (valid pentads)
SON	0.174	-7.74	N=142 (valid pentads)

At Neumayer, CLARA-SAL performs quite consistently within specifications..

6.3. 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-level albedos and the associated relative retrieval errors are shown in Figure 8 and Figure 9, respectively. It is noteworthy that the instantaneous and temporal mean CLARA-SAL values have a clear difference between them. This is, again, a result of the different spatial resolution and the averaging necessary to create the 0.25-degree temporal mean products.

The difference shows clearly also in the product quality indicators (Table 8 & Table 9). If evaluated on the basis of instantaneous-level overpasses, CLARA-SAL performs within specifications. However, both overall as well as the seasonal monthly & pentad mean accuracies are below specifications. The quality indicators for monthly and pentad means are virtually identical, implying that temporal variation of the site does not play a part in the results.

It is notable that the relative retrieval error is stable throughout the dataset. This also suggests that the algorithm is stable; the negative bias results from the poor representability of the 0.25 degree area by the Payerne site observations. Therefore we do not find the CLARA-SAL algorithm to be erroneous for grassland targets such as Payerne.

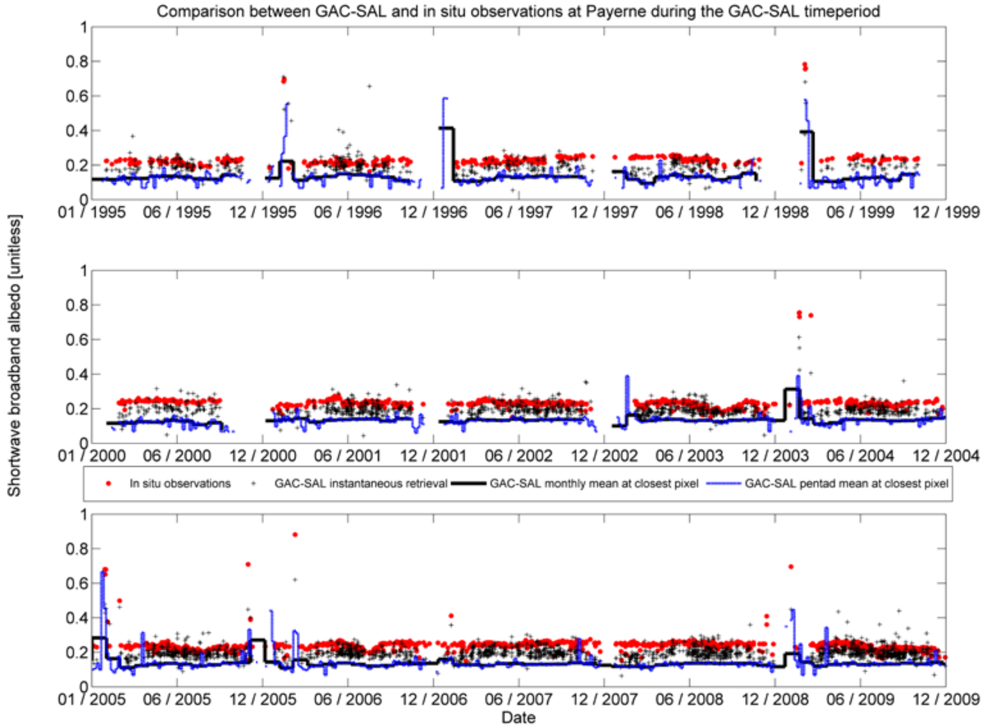

Figure 8: CLARA-SAL and in situ albedo at Payerne. Red circles indicate instantaneous in situ observations, black crosses indicate instantaneous CLARA-SAL retrievals, and the black and blue lines indicate the CLARA-SAL monthly and pentad mean albedos.

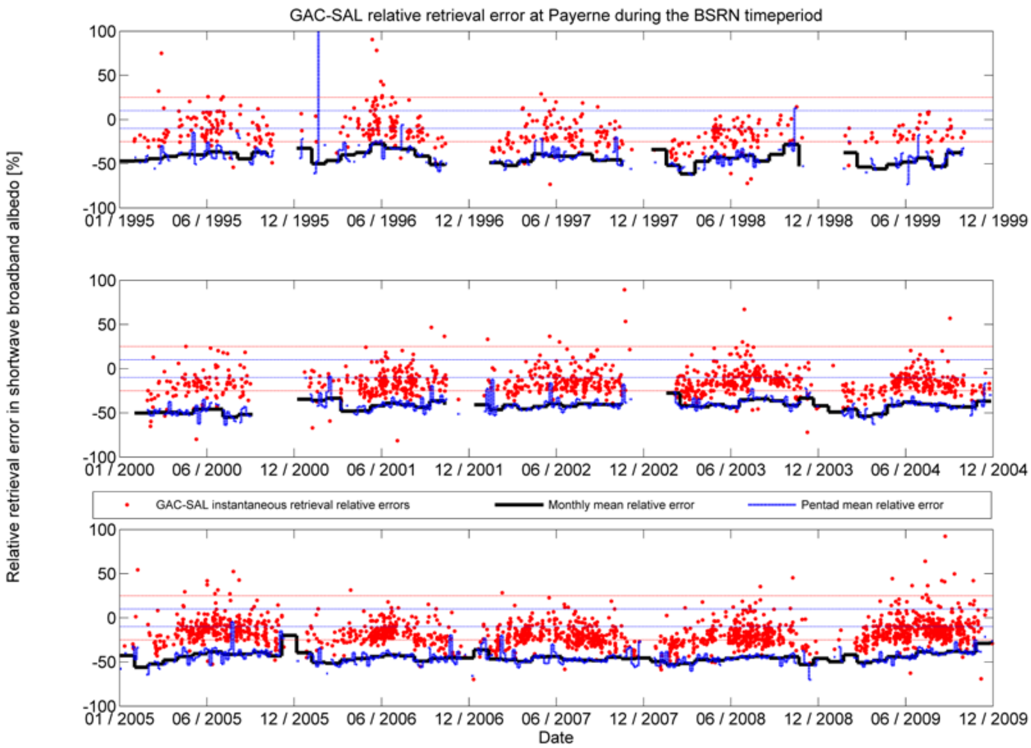

Figure 9: CLARA-SAL relative retrieval error over Payerne. Red circles indicate retrieval errors at instantaneous level; the black and blue lines indicate the retrieval error of the monthly and pentad means. Red dashed line shows 25% and the blue dashed line 10% relative error levels.

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

Dataset / period	RMSE	Mean rel. error [%]	Notes
Instantaneous	0.055	-15.89	N=3489
Monthly means	0.11	-43.44	N=164 (valid months)
DJF	0.134	-42.79	N=32 (valid months)
MAM	0.112	-46.65	N=45 (valid months)
JJA	0.096	-41.61	N=45 (valid months)
SON	0.101	-42.46	N=42 (valid months)

Table 9: CLARA-SAL product quality indicators at the pentad mean level over Payerne.

Dataset / period	RMSE	Mean rel. error [%]	Notes
Pentad means	0.11	-42.40	N=752 (valid pentads)
DJF	0.142	-40.82	N=94 (valid pentads)
MAM	0.116	-45.64	N=228 (valid pentads)
JJA	0.096	-41.09	N=244 (valid pentads)
SON	0.100	-40.95	N=186 (valid pentads)

6.4. 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-SAL, as site representability issues are much smaller.

The retrieved temporal mean and site albedos and associated retrieval errors are shown in Figure 10 and Figure 11, respectively. CLARA-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 are relatively more deviations in retrieval accuracy during the 1990s when fewer AVHRR data were available. As the amount of data increases during the 2000s, the retrieval error settles to a roughly -10% level. It is notable that the retrieval accuracy based on the instantaneous CLARA-SAL data is very similar to the monthly/pentad mean accuracy, suggesting that land cover inhomogeneities do not play a role in the 0.25 degree area albedo.

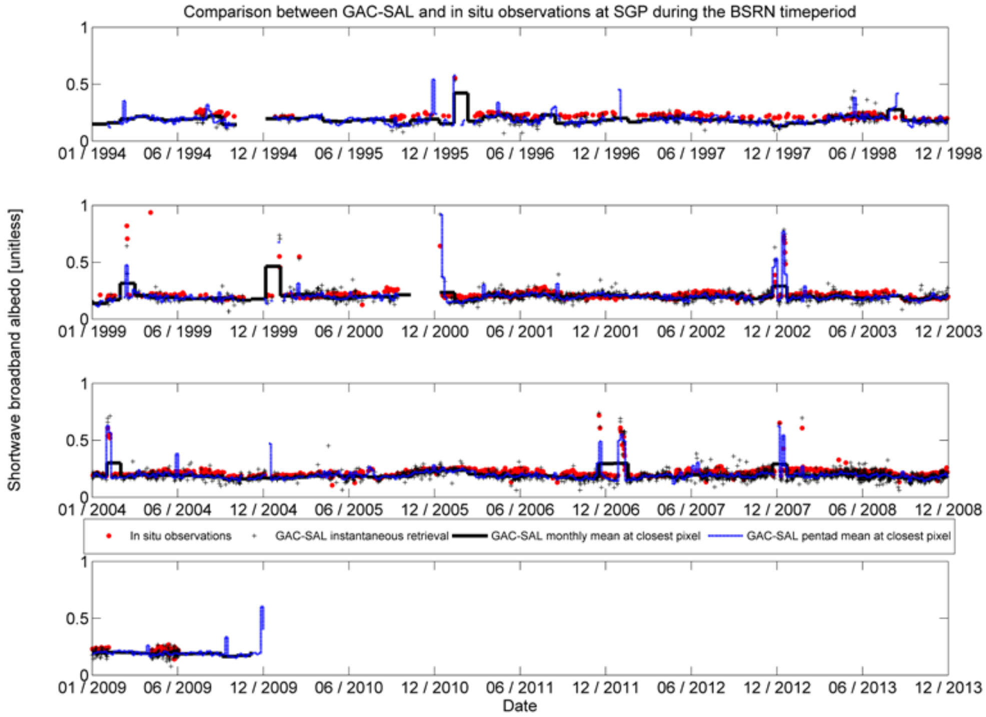

Figure 10: CLARA-SAL and in situ albedo at SGP. Red circles indicate instantaneous in situ observations, black crosses indicate instantaneous CLARA-SAL retrievals, and the black and blue lines indicate the CLARA-SAL monthly and pentad mean albedo.

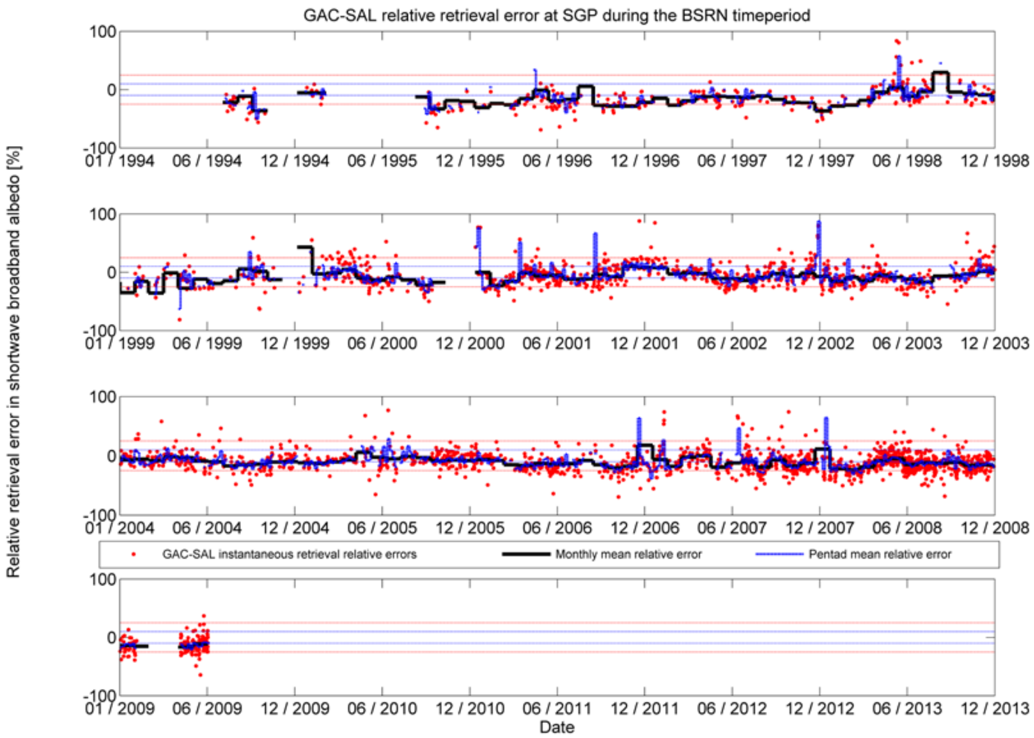

Figure 11: CLARA-SAL relative retrieval error over SGP. Red circles indicate retrieval errors at instantaneous level; the black and blue lines indicate the retrieval error of the monthly and pentad means. Red dashed line shows 25% and the blue dashed line 10% relative error levels.

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

Dataset / period	RMSE	Mean rel. error [%]	Notes
Instantaneous	0.048	-9.62	N=2823
Monthly means	0.038	-10.77	N=166 (valid months)
DJF	0.047	-11.06	N=42 (valid months)
MAM	0.038	-9.37	N=40 (valid months)
JJA	0.029	-10.23	N=41 (valid months)
SON	0.034	-12.29	N=43 (valid months)

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

Dataset / period	RMSE	Mean rel. error [%]	Notes
Pentad means	0.043	-9.41	N=793 (valid pentads)
DJF	0.055	-9.04	N=181 (valid pentads)
MAM	0.043	-7.43	N=218 (valid pentads)
JJA	0.034	-10.41	N=195 (valid pentads)
SON	0.038	-10.93	N=199 (valid pentads)

Table 10 and Table 11 show the quality indicators for SGP. Retrieval quality is well within specifications and very similar for both monthly and pentad means, 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 errors do not result from mutually cancelling large under/overestimations.

6.5. 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 instantaneous CLARA-SAL retrievals and the in situ observations. Their area coverage remains small in the 0.25 degree temporal mean scale, and thus the problem should be ameliorated.

The retrieval result comparison and the relative errors are displayed in Figure 12 and Figure 13, respectively. CLARA-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, 2003/2004, 2005/2006). As expected, the temporal mean CLARA-SAL products are more in line with the in situ observations, which is assuredly not over the bare nunatak area. The instantaneous 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. The year 2000/2001 is affected by problems with NOAA15 processing, as explained before. There is also 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. No data on the actual melt conditions at Syowa was available at the time of writing.

The quality indicators for Syowa are listed in Table 12 and Table 13. Product quality over austral spring (SON) is severely affected by the data from year 2000 – mean relative retrieval error when year 2000 is excluded from analysis is -7.01%. Pentad retrievals are on the same order of accuracy as the monthly means, although significant over/underestimations can occur for single pentads.

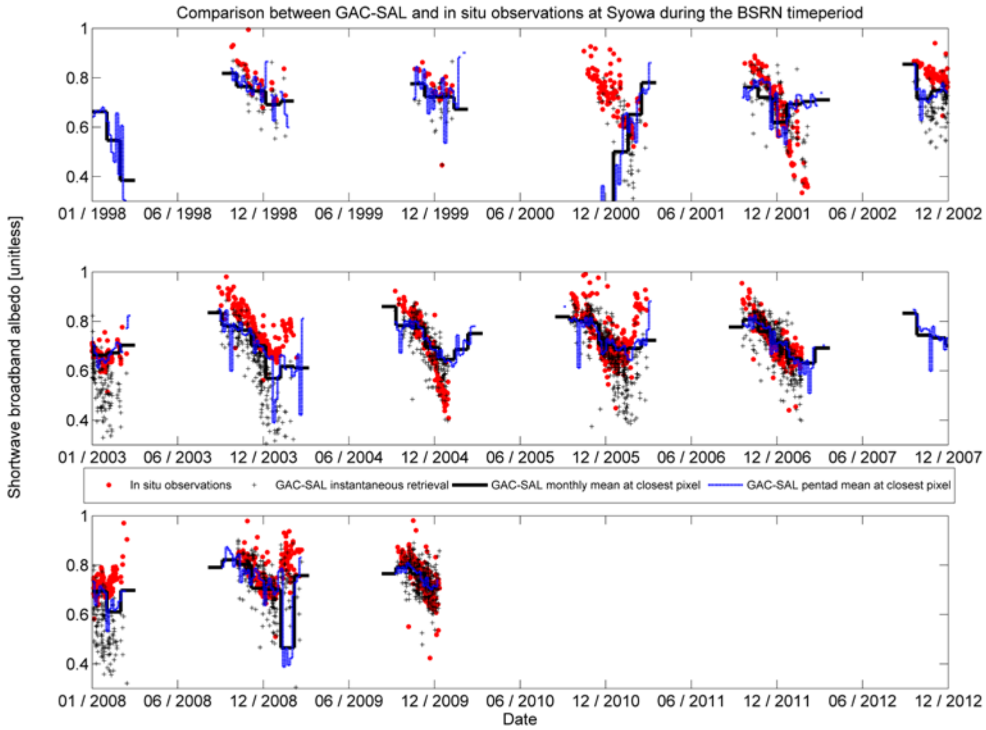

Figure 12: CLARA-SAL and in situ albedo over Syowa. Red circles indicate instantaneous in situ observations, black crosses indicate instantaneous CLARA-SAL retrievals, and the black and blue lines indicate the CLARA-SAL monthly and pentad mean albedo.

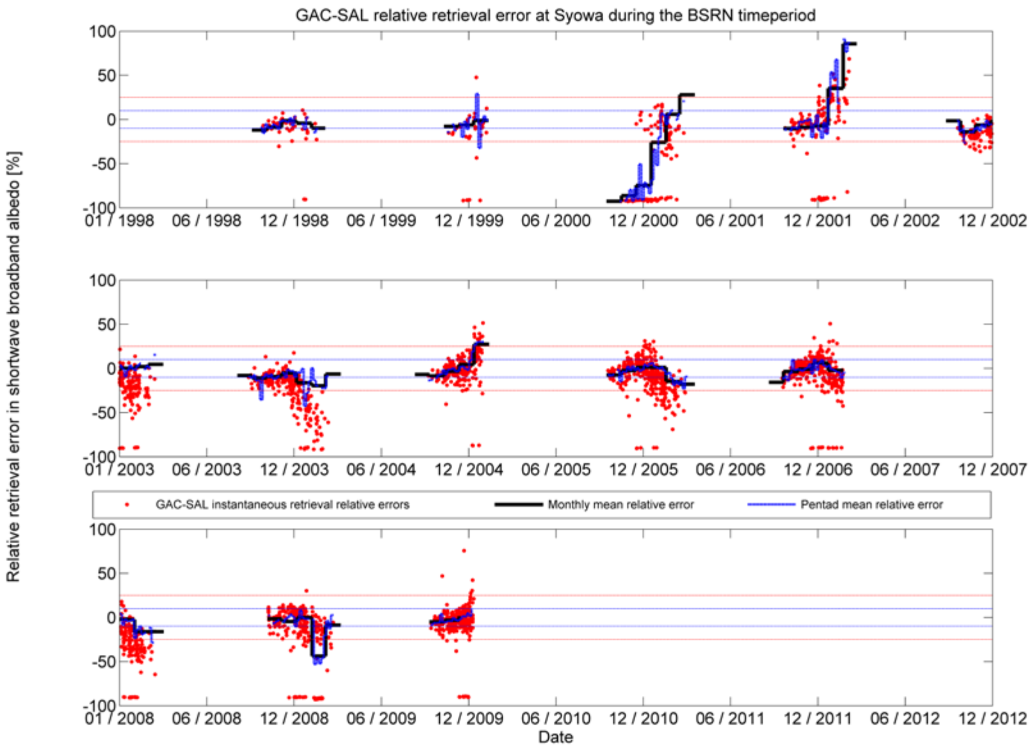

Figure 13: CLARA-SAL relative retrieval error over Syowa. Red circles indicate retrieval errors at instantaneous level; the black and blue lines indicate the retrieval error of the monthly and pentad mean. Red dashed line shows 25% and the blue dashed line 10% relative error levels.

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

Dataset / period	RMSE	Mean rel. error [%]	Notes
Instantaneous	0.226	-14.15	N=2509
Monthly means	0.188	-7.24	N=60 (valid months)
DJF	0.154	-2.85	N=30 (valid months)
MAM	0.115	-2.68	N=6 (valid months)
JJA	-	-	N=0 (valid months)
SON	0.235	-13.88	N=24 (valid months)

Table 13: CLARA-SAL product quality indicators at the pentad mean level over Syowa

Dataset / period	RMSE	Mean rel. error [%]	Notes
Pentad means	0.175	-7.14	N=281 (valid pentads)
DJF	0.167	-4.44	N=162 (valid pentads)
MAM	0.126	-6.05	N=12 (valid pentads)
JJA	-	-	N=0 (valid pentads)
SON	0.191	-11.35	N=107 (valid pentads)

6.6. Tateno, Japan

The Tateno site is located in a suburban area north of Tokyo. The land cover around the site is highly heterogeneous (see Figure 14). Considering that the radiation sensors at the site are over a grass field patch, the comparability of the observations to the CLARA-SAL data must be considered poor.

The retrieval results and associated relative retrieval errors are shown in Figure 15 and Figure 16, respectively. The results show that the BSRN site and the 0.25-degree CLARA-SAL exhibit reverse seasonal cycles; the in situ data shows a minor brightening over the winter/spring, whereas the CLARA-SAL albedo diminishes somewhat over the same period. The quality indicators in Table 14 and Table 15 show the same effect; while CLARA-SAL as a whole performs within specifications, the DJF period underperforms because of poor comparability between the small- and large-scale data in this case.

Causes for the different seasonal albedo cycles are difficult to confirm. Man-made surfaces should exhibit little seasonal variation in albedo. As the region around Tateno site is urban, we would thus not expect any phenological albedo cycles to appear in the satellite product. On the other hand, the high degree of urbanization at Tateno translate to a very high and variable aerosol loading in the atmosphere. According to García et al. (2009), the AOD at 550nm at Tateno over the April-June period reaches a level of 0.5-0.6, which drops down to 0.2-0.3 during the September-November period. As CLARA-SAL currently incorporates a constant AOD of 0.1 in its atmospheric correction, the monthly means will certainly show a cycle resulting from the seasonal changes in the atmosphere.

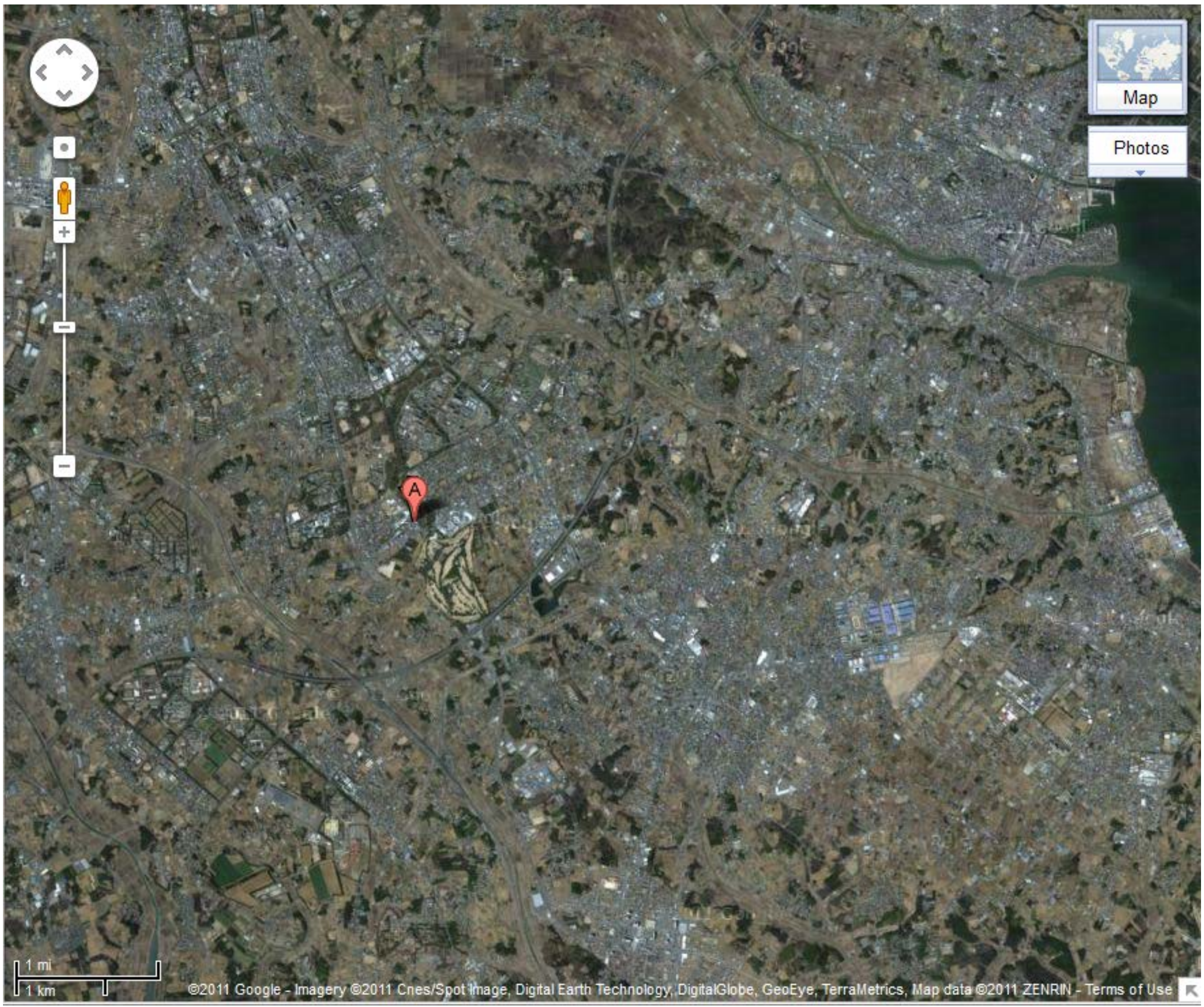

Figure 14: Google Maps image of the region around Tateno BSRN site. The site is at the location marked with "A". © 2011 Google. Imagery: © 2011 Cnes/Spot Image, Digital Earth Technology, Digitalglobe, GeoEye, TerraMetrics. Map data: © 2011 ZENRIN

Once again, the pentads show a very similar behavior to the monthly means, with some exceptions where large overestimations occur. These appear to occur mainly during the summertime, and are likely linked to misclassified clouds as the retrieved surface albedo for these cases is in the 0.4 – 0.6 range, which would match the retrieval result from typical cloud reflectances.

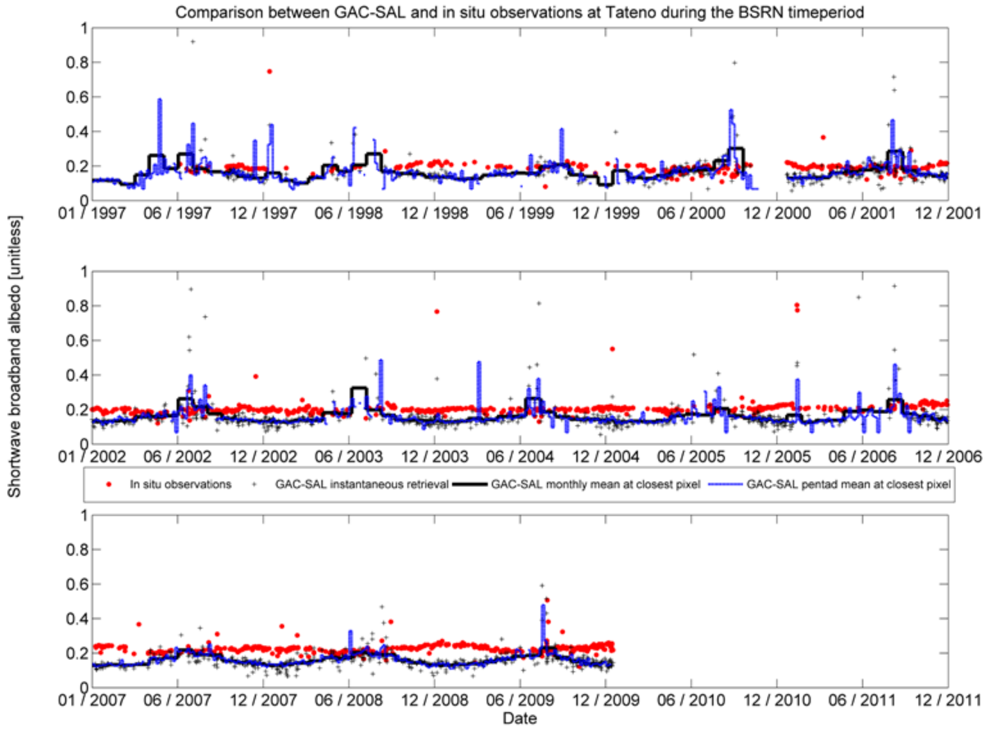

Figure 15: CLARA-SAL and in situ albedo over Tateno. Red circles indicate instantaneous in situ observations, black crosses indicate instantaneous CLARA-SAL retrievals, and the black and blue lines indicate the CLARA-SAL monthly and pentad mean albedo.

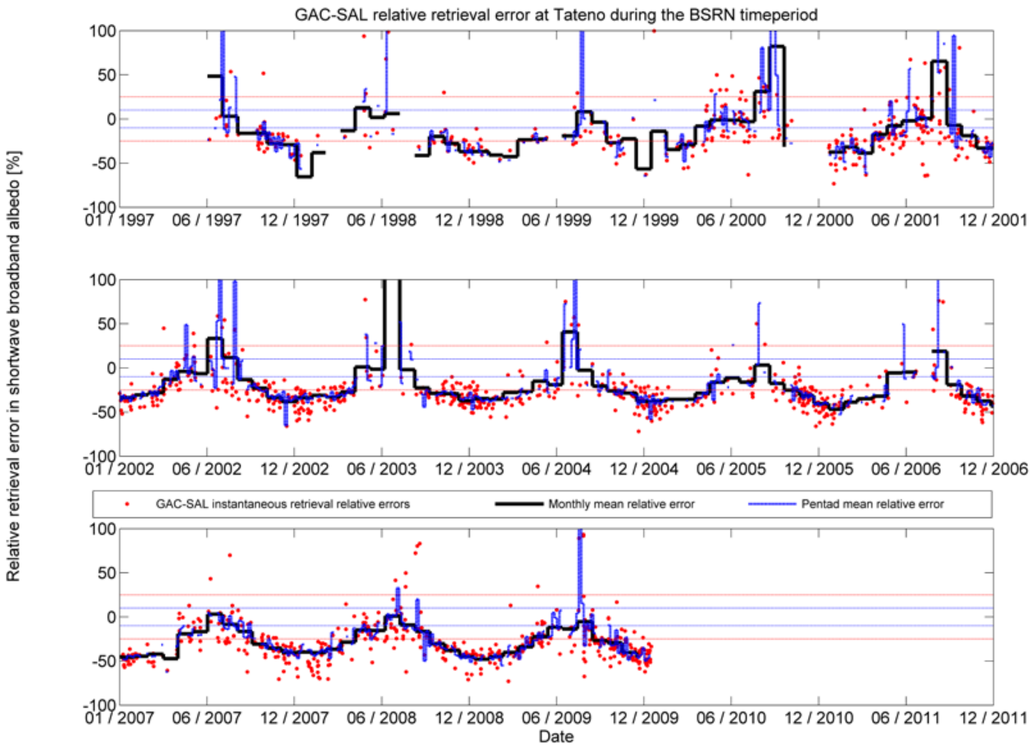

Figure 16: CLARA-SAL relative retrieval error over Tateno. Red circles indicate retrieval errors at instantaneous level; the black and blue lines indicates the retrieval error of the monthly and pentad mean. Red dashed line shows 25% and the blue dashed line 10% relative error levels.

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

Dataset / period	RMSE	Mean rel. error [%]	Notes
Instantaneous	0.098	-20.77	N=1517
Monthly means	0.070	-19.71	N=144 (valid months)
DJF	0.100	-38.96	N=36 (valid months)
MAM	0.057	-22.90	N=35 (valid months)
JJA	0.047	6.46	N=35 (valid months)
SON	0.062	-22.64	N=38 (valid months)

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

Dataset / period	RMSE	Mean rel. error [%]	Notes
Pentad means	0.078	-18.73	N=618 (valid pentads)
DJF	0.099	-38.07	N=163 (valid pentads)
MAM	0.061	-21.56	N=148 (valid pentads)
JJA	0.072	10.57	N=139 (valid pentads)
SON	0.073	-21.70	N=168 (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 error, 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-SAL & station albedo retrievals and the relative retrieval errors are shown in Figure 17 and Figure 18, respectively. Year 2006 has 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. Excepting 2001, CLARA-SAL appears to slightly overestimate the site albedo. This is understandable, since the dry and relatively small-grained snow around Summit camp has a very high reflectance and exhibits strong BRDF effects. The CLARA-SAL algorithm becomes saturated on occasion when observing such a bright target. Regardless, as the quality indicators in Table 16 and Table 17 show, CLARA-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 errors are on average under 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 error, CLARA-SAL would still perform at a comparable level to previous AVHRR-based snow albedo products.

The pentad and monthly CLARA-SAL means behave in an identical fashion. This is to be expected as the target is stable in time as well as spatially homogenous. The few exceptions where pentad means show a large discrepancy to in situ data likely result from corrupted in situ observations, as snow albedo at this site should not ever reach values of 0.2-0.3 (years 1999 & 2000).

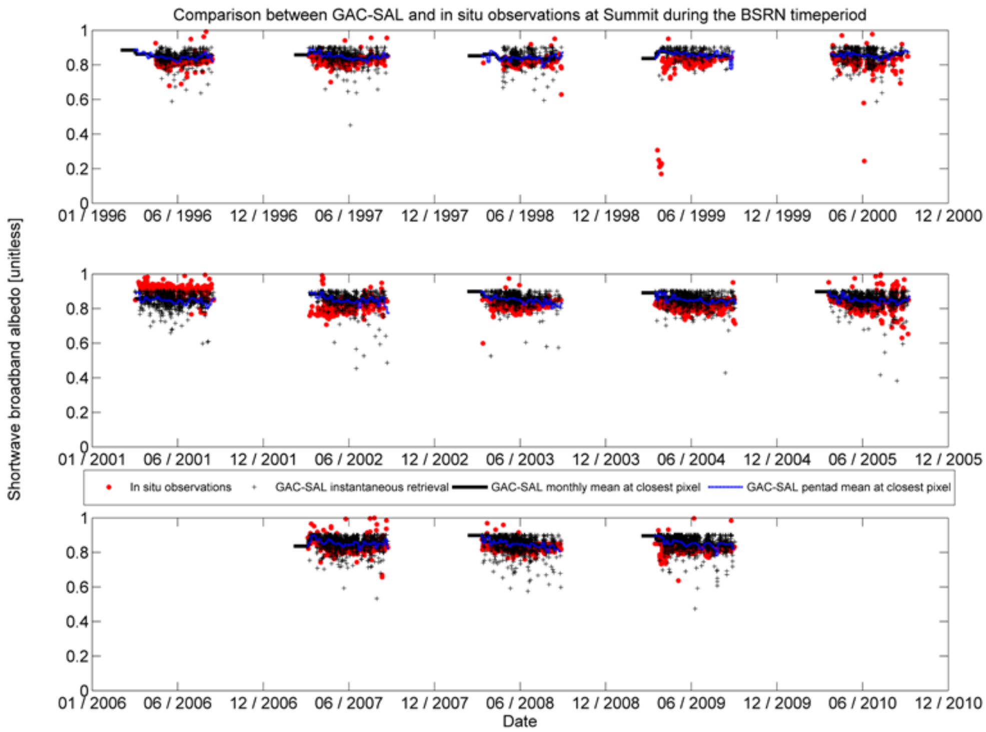

Figure 17: CLARA-SAL and in situ albedo over Summit camp. Red circles indicate instantaneous in situ observations, black crosses indicate instantaneous CLARA-SAL retrievals, and the black and blue lines indicate the CLARA-SAL monthly and pentad mean albedo.

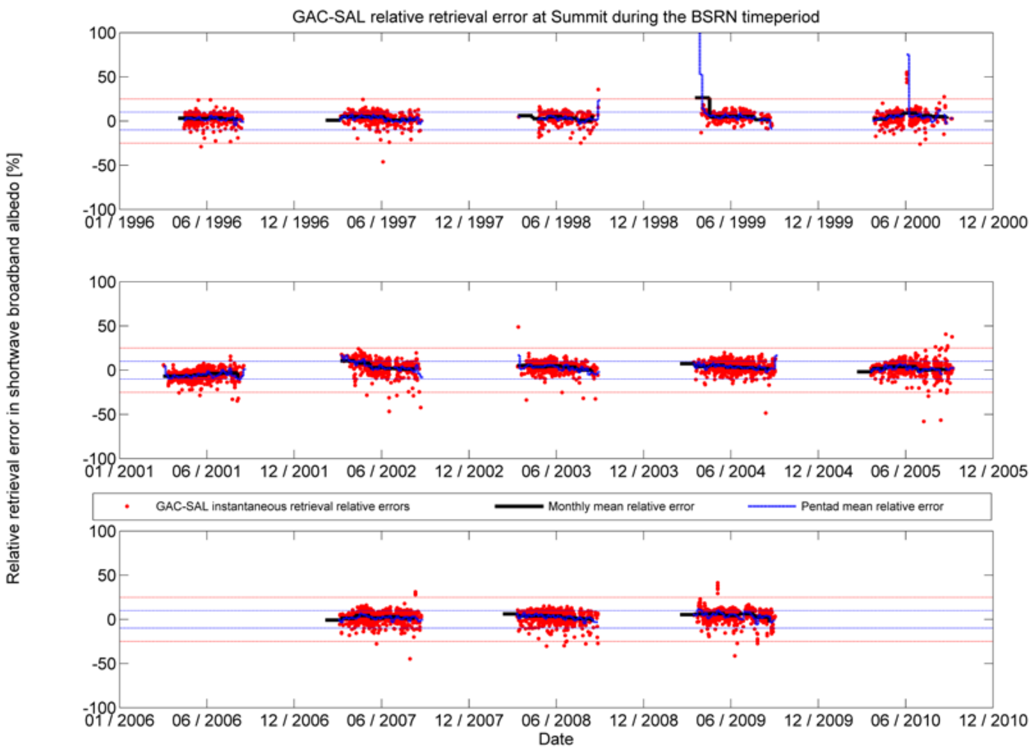

Figure 18: CLARA-SAL relative retrieval error over Summit camp. Red circles indicate retrieval errors at instantaneous level; the black and blue lines indicate the retrieval error of the monthly and pentad mean. Red dashed line shows 25% and the blue dashed line 10% relative error levels.

Table 16: CLARA-SAL product quality indicators at the monthly mean level over Summit camp.

Dataset / period	RMSE	Mean rel. error [%]	Notes
Instantaneous	0.069	4.01	N=7868 (albedo vs. hemispherical-directional reflectance)
Monthly means	0.042	2.80	N=83 (valid months)
DJF	-	-	N=0 (valid months)
MAM	0.054	4.37	N=31 (valid months)
JJA	0.030	2.54	N=39 (valid months)
SON	0.032	-0.20	N=13 (valid months)

Table 17: CLARA-SAL product quality indicators at the pentad mean level over Summit camp.

Dataset / period	RMSE	Mean rel. error [%]	Notes
Pentad means	0.062	3.76	N=420 (valid pentads)
DJF	-	-	N=0 (valid pentads)
MAM	0.086	6.94	N=160 (valid pentads)
JJA	0.039	2.05	N=228 (valid pentads)
SON	0.049	0.05	N=32 (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 (GIS) (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. However, the coarse resolution of CLARA-SAL acts to prevent the satellite data from becoming affected by the low reflectance of man-made structures.

The retrieved albedos and associated retrieval errors are shown in Figure 19 and Figure 20, respectively. The in situ albedo shows more variability than at Summit camp, as expected. Summers 2006-2008 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. CLARA-SAL monthly means successfully track this phenomenon. The quality indicators are listed in Table 18 and Table 19. 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 highest monthly mean retrieval error at DYE-2 was 10.11% (relative). Thus the algorithm clearly meets its specifications.

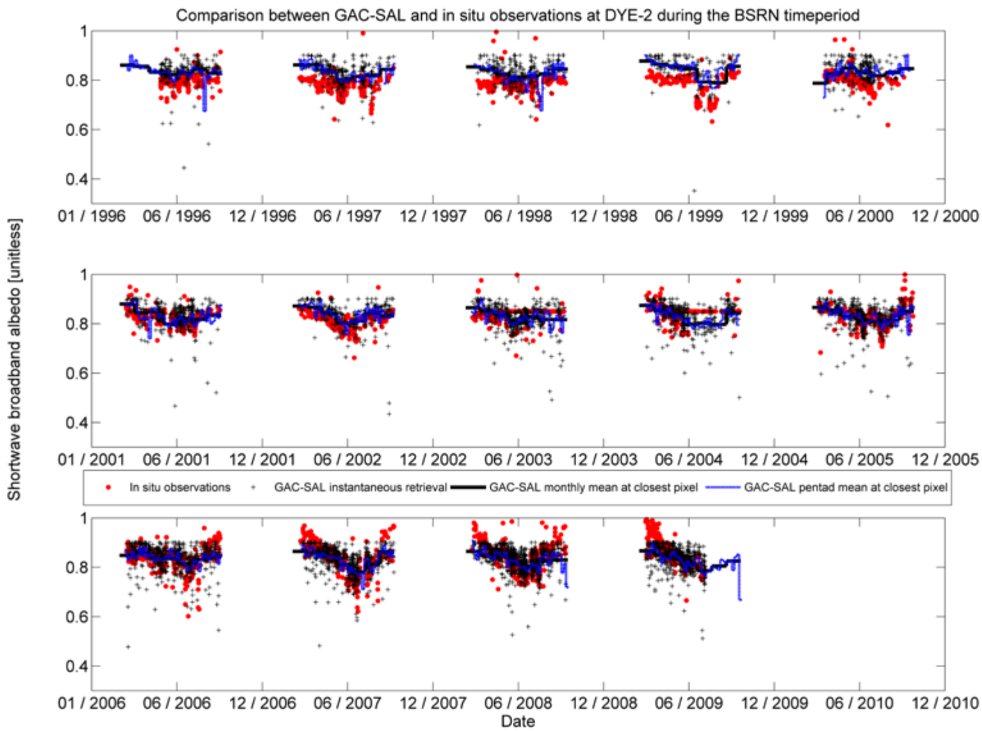

Figure 19: CLARA-SAL and in situ albedo over DYE-2. Red circles indicate instantaneous in situ observations, black crosses indicate instantaneous CLARA-SAL retrievals, and the black and blue lines indicate the CLARA-SAL monthly and pentad mean albedo.

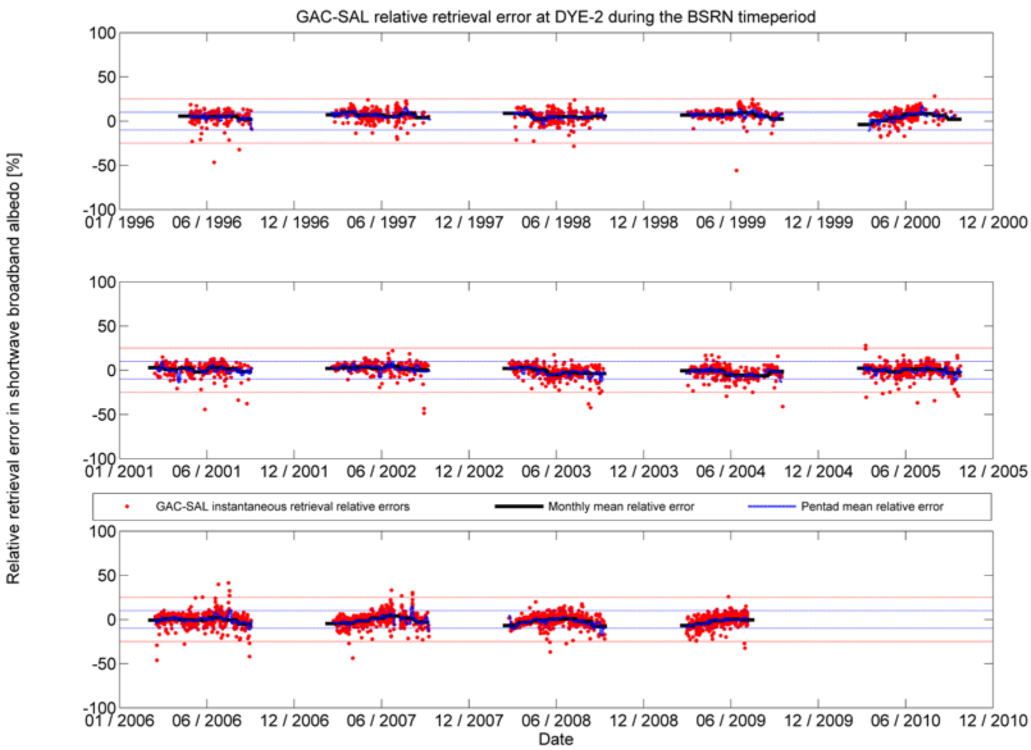

Figure 20: CLARA-SAL relative retrieval error over DYE-2. Red circles indicate retrieval errors at instantaneous level; the black and blue lines indicate the retrieval error of the monthly and pentad mean. Red dashed line shows 25% and the blue line 10% relative error levels.

Table 18: CLARA-SAL product quality indicators at the monthly mean level over DYE-2.

Dataset / period	RMSE	Mean rel. error [%]	Notes
Instantaneous	0.059	1.24	N=5783
Monthly means	0.036	1.45	N=94 (valid months)
DJF	-	-	N=0 (valid months)
MAM	0.036	1.40	N=40 (valid months)
JJA	0.036	2.17	N=41 (valid months)
SON	0.033	-0.71	N=13 (valid months)

Table 19: CLARA-SAL product quality indicators at the pentad mean level over DYE-2.

Dataset / period	RMSE	Mean rel. error [%]	Notes
Pentad means	0.041	1.11	N=511 (valid pentads)
DJF	-	-	N=0 (valid pentads)
MAM	0.04	1.12	N=216 (valid pentads)
JJA	0.04	1.82	N=230 (valid pentads)
SON	0.051	-1.46	N=65 (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. Years 2007 and 2008 have been excluded from the analysis as there was no in situ data available.

The albedo retrievals and associated retrieval errors are shown in Figure 21 and Figure 22. At the instantaneous 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 monthly mean CLARA-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.

The CLARA-SAL quality indicators for JAR-2 are listed in Table 20 and Table 21. Again, mean monthly and pentad accuracies improve as a result of mutually cancelling over- and underestimations, although RMSE is still typically under 0.08. The maximum monthly mean relative retrieval error is 25.2%, very near to being within specifications. Individual relative overpass errors may reach over 100% (in 1.2% of all 3987 matched cases, therefore not shown in figures to maintain clarity).

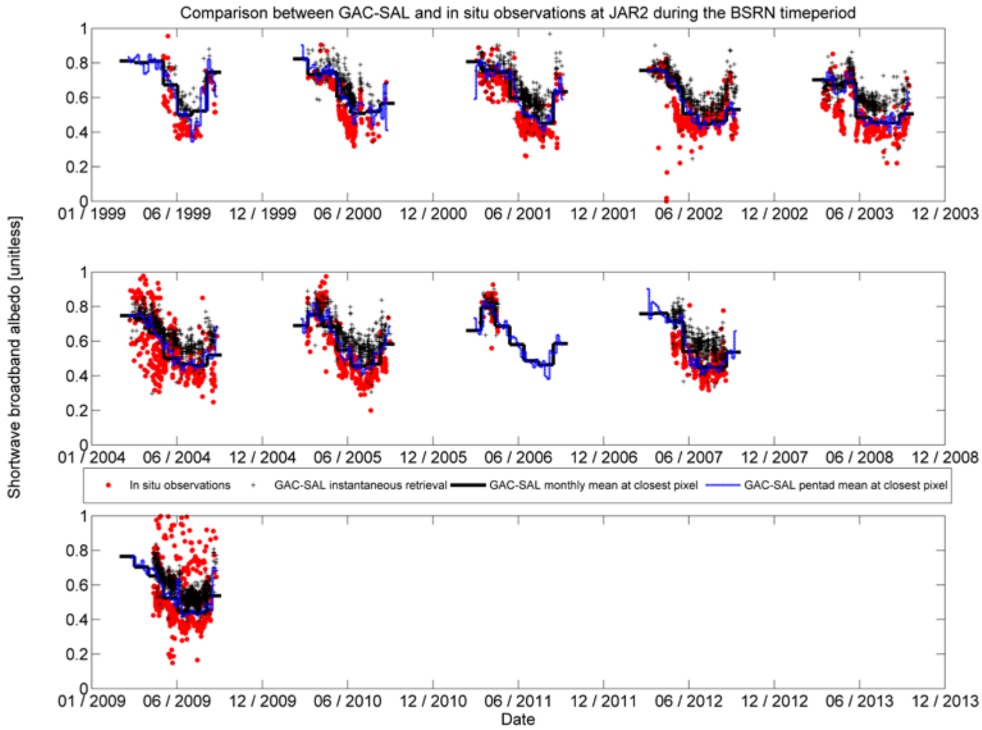

Figure 21: CLARA-SAL and in situ albedo at JAR-2. Red circles indicate instantaneous in situ observations, black crosses indicate instantaneous CLARA-SAL retrievals, and the black and blue lines indicate the CLARA-SAL monthly and pentad mean albedo.

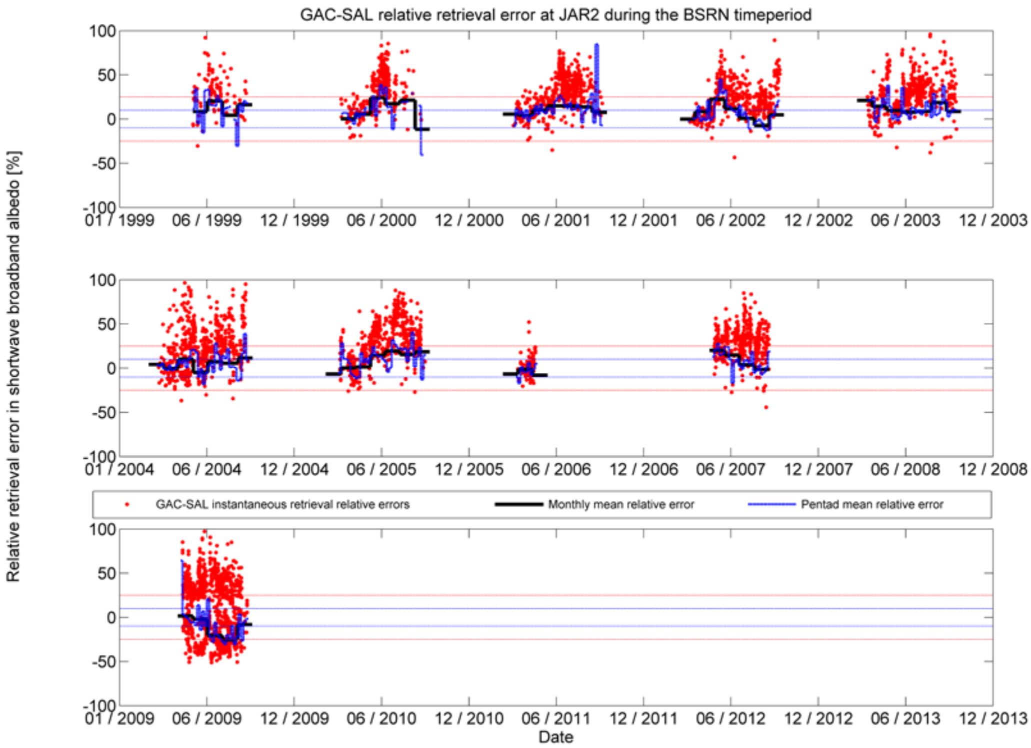

Figure 22: CLARA-SAL relative retrieval error over JAR-2. Red circles indicate retrieval errors at instantaneous level; the black and blue lines indicate the retrieval error of the monthly and pentad mean. Red dashed line shows 25% and the blue dashed line shows 10% relative error levels.

Table 20: CLARA-SAL product quality indicators at the monthly mean level over JAR-2.

Dataset / period	RMSE	Mean rel. error [%]	Notes
Instantaneous	0.166	24.22	N=4455
Monthly means	0.064	6.55	N=57 (valid months)
DJF	-	-	N=0 (valid months)
MAM	0.061	5.34	N=22 (valid months)
JJA	0.067	7.68	N=27 (valid months)
SON	0.065	6.01	N=8 (valid months)

Table 21: CLARA-SAL product quality indicators at the pentad mean level over JAR-2.

Dataset / period	RMSE	Mean rel. error [%]	Notes
Pentad means	0.082	7.62	N=295 (valid pentads)
DJF	-	-	N=0 (valid pentads)
MAM	0.08	7.86	N=109 (valid pentads)
JJA	0.08	7.32	N=156 (valid pentads)
SON	0.104	8.32	N=30 (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.

Quality control on the data revealed an orientation flaw in April 2004. The instruments were realigned to level during routine maintenance in June 2004. As a precaution, all data between January-July 2004 have been excluded from this analysis.

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 and contributes to the 0.25 degree area of the temporal means products, although the land cover fraction of urban and sub-urban areas is small.

The monthly and pentad mean retrievals and the associated retrieval uncertainties are shown in Figure 24 and Figure 25. The results clearly show how CLARA-SAL tracks the snow melt during spring and is fairly stable over the summer period. To illustrate the seasonal cycle, the retrievals from year 2006 are shown in detail in Figure 23. There is a clear underestimation of the in situ albedo during winter; this results from 1) the different fractions of forest cover in the CLARA-SAL albedo relative to the in situ measurement, and 2) imperfect knowledge of the BRDF behavior of boreal forest. The results of the SNORTEX campaign are being studied to address the second issue in future reprocessing.

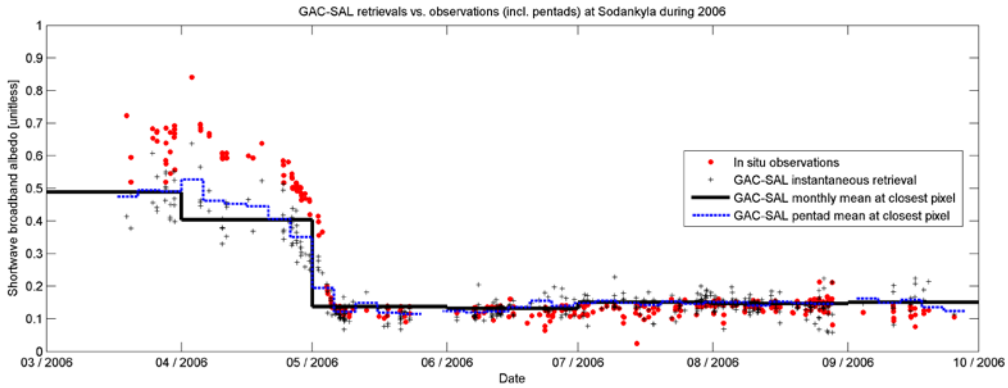

Figure 23: CLARA-SAL retrievals over Sodankylä for year 2006.

Table 22 and Table 23 show the retrieval quality of CLARA-SAL over the Sodankylä site. The product meets its specifications, although site representability issues are evident. Along the previously mentioned undesestimation during winter/spring, there is a notable overestimation during autumn. However, the SON period data at Sodankylä latitude is sparse; practically speaking only September provides valid comparisons. CLARA-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" 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.

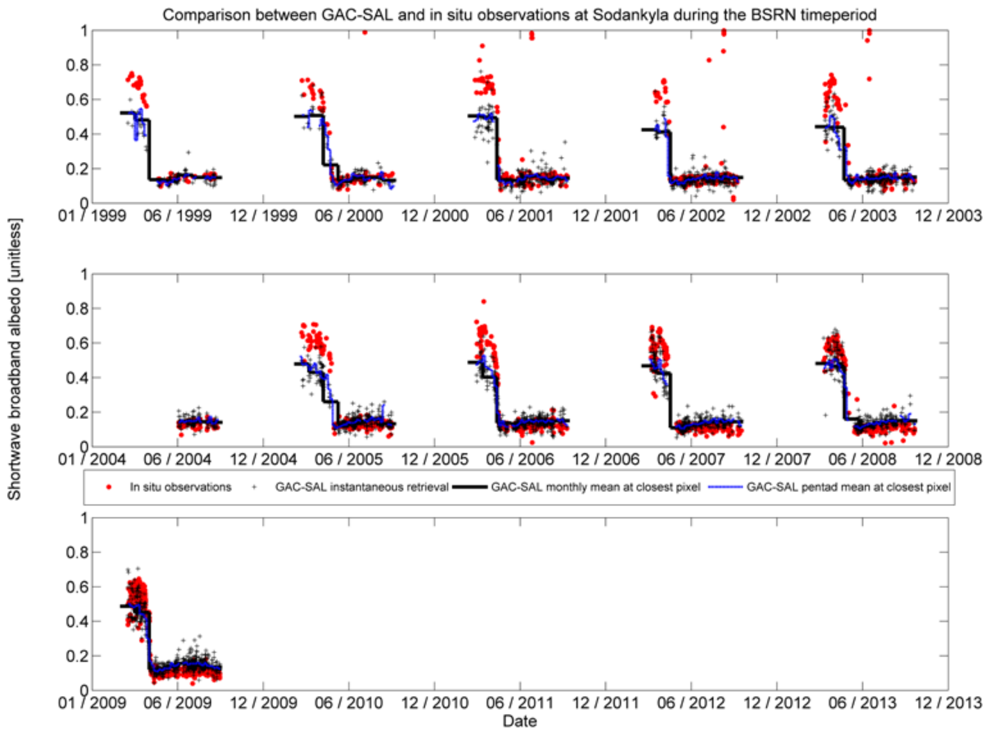

Figure 24: CLARA-SAL and in situ albedo over Sodankylä. Red circles indicate instantaneous in situ observations, black crosses indicate instantaneous CLARA-SAL retrievals, and the black and blue lines indicate the CLARA-SAL monthly and pentad mean albedo.

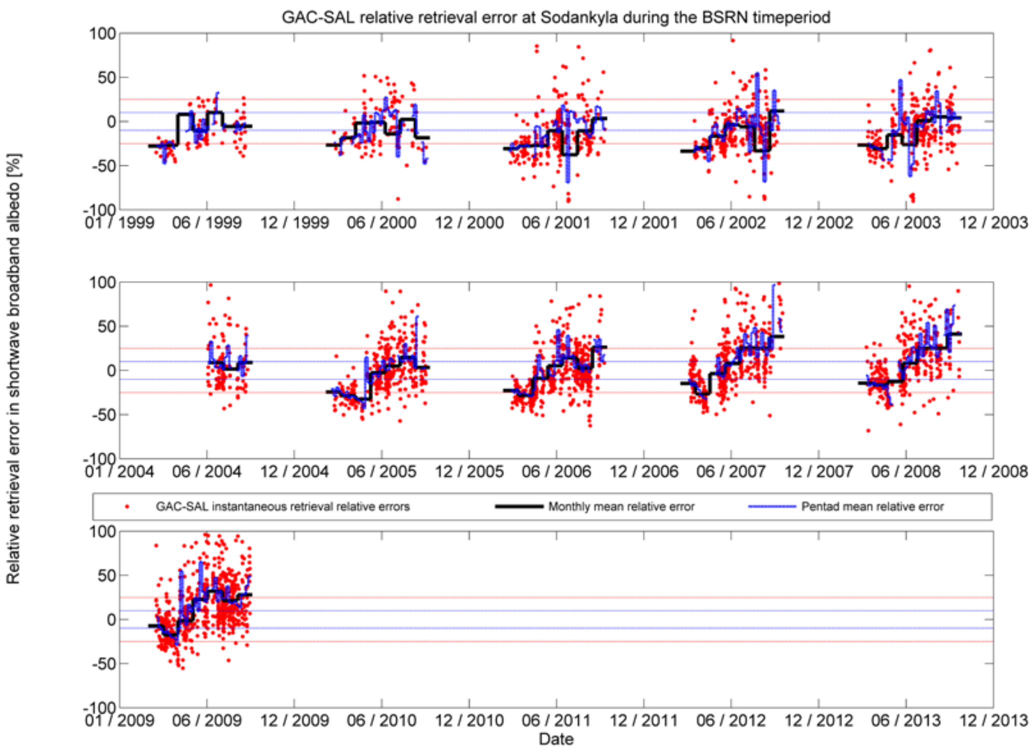

Figure 25: CLARA-SAL relative retrieval error over Sodankylä. Red circles indicate retrieval errors at instantaneous level; the black and blue lines indicate the retrieval error of the monthly and pentad mean. Red dashed line shows 25% and the blue dashed line shows 10% relative error levels.

Table 22: CLARA-SAL product quality indicators at the monthly mean level over Sodankylä.

Dataset / period	RMSE	Mean rel. error [%]	Notes
Instantaneous	0.097	2.43	N=3310
Monthly means	0.087	-4.7	N=73 (valid months)
DJF	-	-	N=0 (valid months)
MAM	0.131	-19.64	N=30 (valid months)
JJA	0.029	3.26	N=32 (valid months)
SON	0.025	12.92	N=11 (valid months)

Table 23: CLARA-SAL product quality indicators at the pentad mean level over Sodankylä.

Dataset / period	RMSE	Mean rel. error [%]	Notes
Pentad means	0,089	-0,35	N=367 (valid pentads)
DJF	-	-	N=0 (valid pentads)
MAM	0,13	-17,75	N=143 (valid pentads)
JJA	0,049	9,28	N=178 (valid pentads)
SON	0,036	16,43	N=46 (valid pentads)

9. Summary of land-based validation site results

The validation results for all land-based sites are summarized in Table 24. Only monthly mean validation results are shown as the pentad mean results are highly similar.

Table 24: Validation results summary for monthly means over all land-based sites.

Site	RMSE	Mean relative retrieval error [%]
Barrow, USA	0.102	-15.24
Neumayer, Antarctica	0.173	-12.37
Payerne, Switzerland	0.11	-43.44
Southern Great Plains, USA	0.038	-10.77
Syowa, Antarctica	0.188	-7.24
Tateno, Japan	0.070	-19.71
Summit Camp, Greenland	0.042	2.80
DYE-2, Greenland	0.036	1.45
JAR-2, Greenland	0.064	6.55
Sodankylä, Finland	0.087	-4.7

10. Validation Against Tara Expedition Observations

To assess the performance of CLARA-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 based on the 39 confirmed clear-sky matches between Tara observations and AVHRR surface reflectance retrievals that were utilized in Riihelä et al. (2010) in the validation of the operational Arctic LAC SAL product. CLARA-SAL pentads matching the timestamps of the 39 cases were processed and the albedo at Tara location during each of cases recorded for comparison. The results are shown in Figure 26. CLARA-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. 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-SAL pentad means is **0.073**. The study by Riihelä et al. found and RMSE of 0.045 between weekly SAL and weekly Tara means. The increase in RMSE is to be expected since the comparability between the ice camp observations and the satellite product is bound to worsen as the spatial resolution is coarsened. Otherwise, the behavior of CLARA-SAL is very similar to the operational LAC-SAL.

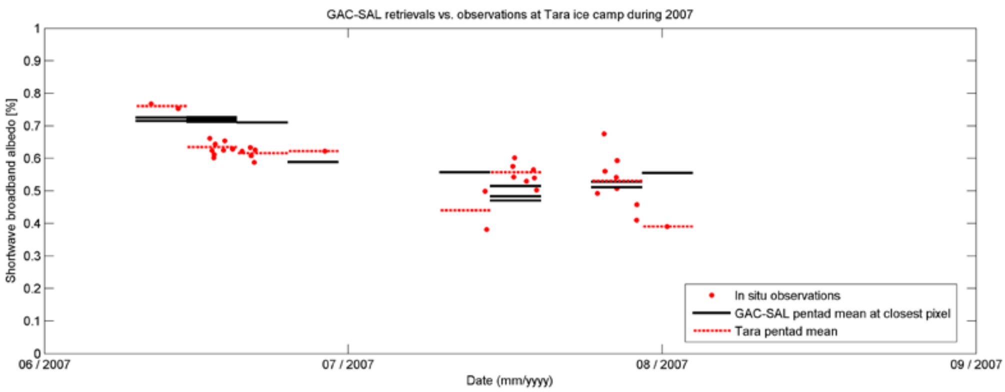

Figure 26: CLARA-SAL pentad retrievals (black lines) versus confirmed clear-sky albedo observations at Tara ice camp (red circles) and CLARA-SAL-equivalent pentad means at Tara (red dashed lines). Different CLARA-SAL pentad retrievals appear during the same time period since the ice camp drifts across the Arctic Ocean and its location changes from one CLARA-SAL pixel to another.

11. Comparison Against CERES FSW And MODIS products

The previous validation results show the CLARA-SAL product accuracy against ground truth over small scales. It is, however, equally valuable to know how CLARA-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). Of these, APP-X is not a fully global dataset. Therefore we shall focus in this study to compare CLARA-SAL with the CERES FSW black-sky albedo product first, and MODIS MCD43C3 second.

11.1. CERES FSW

The Clouds and the Earth's Radiant Energy System (CERES) instruments on board Aqua and Terra satellites instruments perform measurements of the Earth's atmosphere and surface on three broadband channels. Its Flux and Clouds Regional Swath (FSW) products provided by the NASA CERES/ARM Validation Experiment (CAVE) team offer the black-sky shortwave surface albedo on a regular lat/lon grid similar to the CLARA-SAL grid. There are also other similarities between the products which simplify the comparison; 1) The data are available as clear-sky monthly mean albedo products like CLARA-SAL, 2) both products represent the albedo corresponding to satellite observation times, normalized into a fixed Sun Zenith Angle, and 3) the FSW products apply the same SZA normalization algorithm as CLARA-SAL. Ocean albedo is based on the same LUT in both products, but the current Edition of CLARA-SAL is based on static input variables everywhere.

There are also some notable differences in the products; CLARA-SAL implements a topography correction of reflectances in steep terrain. This typically increases the CLARA-SAL albedo in mountainous regions.

Like CLARA-SAL, CERES FSW also offers coverage of the sea ice albedo on both Hemispheres as well as snow/ice albedo over land surfaces. CERES FSW is provided at 1-degree spatial resolution, therefore we resampled CLARA-SAL to match its resolution. The resampling was performed by averaging 4x4 pixel groups in the CLARA-SAL monthly mean data (NOT a moving averaging window). The FSW data is available from March 2000 to May 2005. Examples of the CERES FSW and resampled CLARA-SAL product are shown in Figure 27 and Figure 28, respectively.

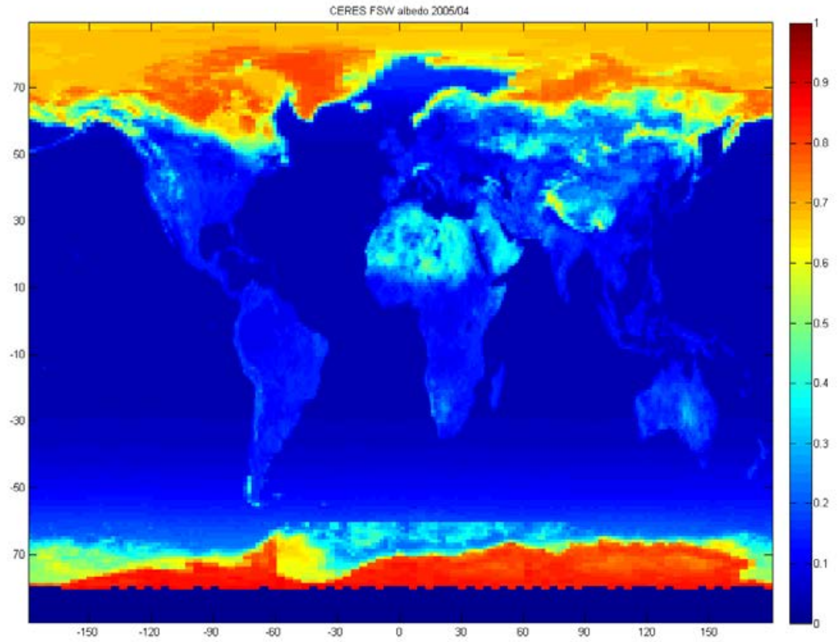

Figure 27: CERES FSW monthly mean albedo product for April 2005.

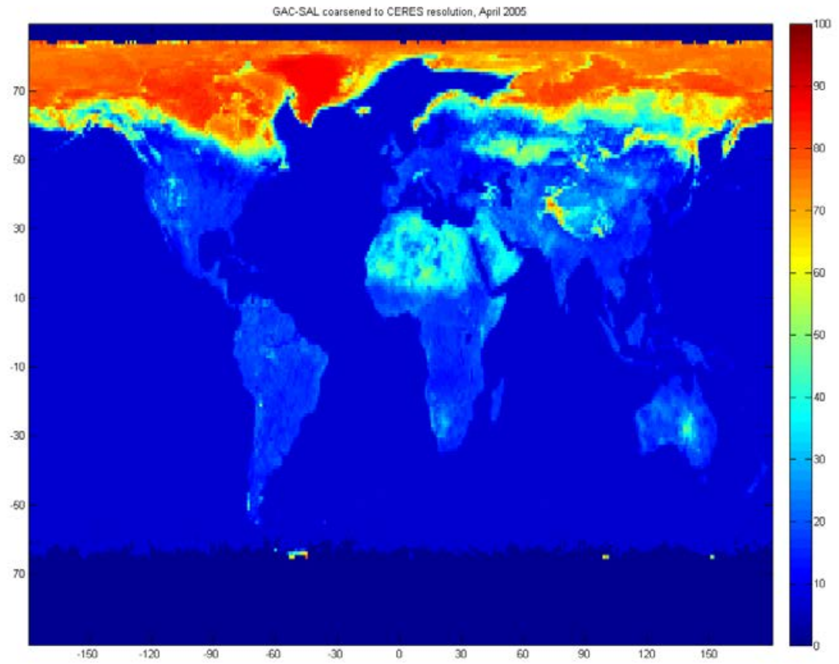

Figure 28: CLARA-SAL product resampled to 1-degree CERES FSW resolution, April 2005.

We begin the comparison by computing the global mean albedo for land surfaces throughout the study period, month by month. The different data coverage in the products (resulting from different SZA cutoff angles and cloudiness identification) is compensated by calculating the mean only from the 1-degree pixels that are valid in both products per month. The resulting graph is shown in Figure 29.

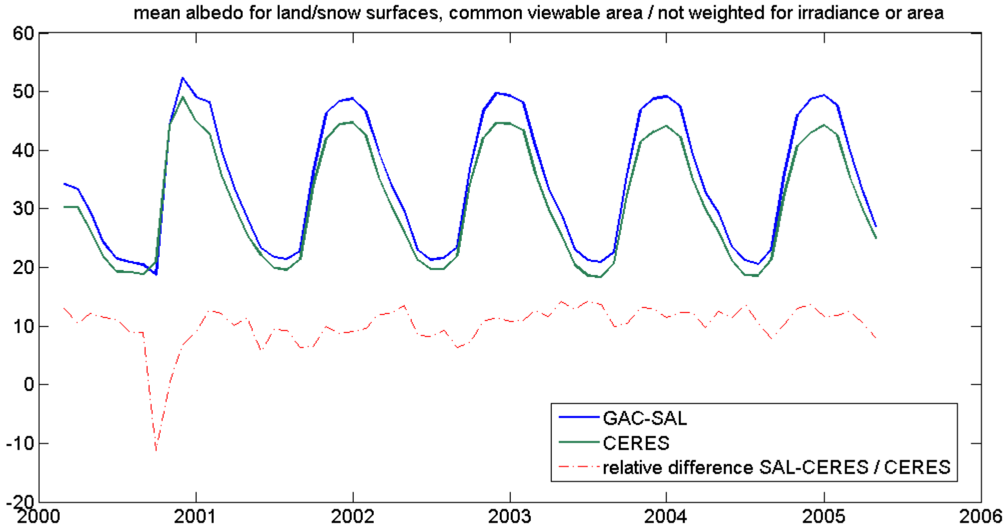

Figure 29: CERES FSW and CLARA-SAL land surface monthly mean albedos during 2000 - 2005. Blue line denotes CLARA-SAL data, green line denotes CERES FSW data. Means are composed only of those 1-degree pixels that are valid in both products during a particular month. Albedo is not weighted for irradiance or pixel area. Red dashed line indicates relative difference between CLARA-SAL and CERES.

As expected, the products are broadly similar. Differences during year 2000 may result from NOAA-15 processing problems in CLARA-SAL. From 2001 onwards, the relative difference between the products is quite stable at 10%. The source regions of the difference vary somewhat from month to month, but there are some constant features as well. An example of the relative difference maps for land regions only in shown in Figure 30. CLARA-SAL typically has a higher albedo in the tropics and South/Southeast Asia, as well as in eastern US. CERES often has a higher albedo in the northern parts of Eurasia and North America, but CLARA-SAL typically has a somewhat higher albedo in the permanently snow-covered Antarctica (not shown) and Greenland.

Another way of studying the differences is to look at the latitudinal means of the products. Figure 31 illustrates the latitudinal means calculated for all available data per latitude. Figure 32 shows a similar calculation of latitudinal means, but only for land and snow-covered pixels. Figure 33 displays the relative difference of CLARA-SAL and CERES from the data of Figure 32.

We see a number of features in the data (which are very typical of all five years studied); 1) CERES has a markedly lower sea ice albedo in the Arctic Ocean, 2) CLARA-SAL has a markedly higher albedo over the tropical latitudes, 3) the seemingly large difference in land/snow albedo around -55 N consists of but a few pixels over Patagonia, thus its significance is minor. The difference is likely caused by the topography correction that is included in CLARA-SAL but not in CERES FSW albedo.

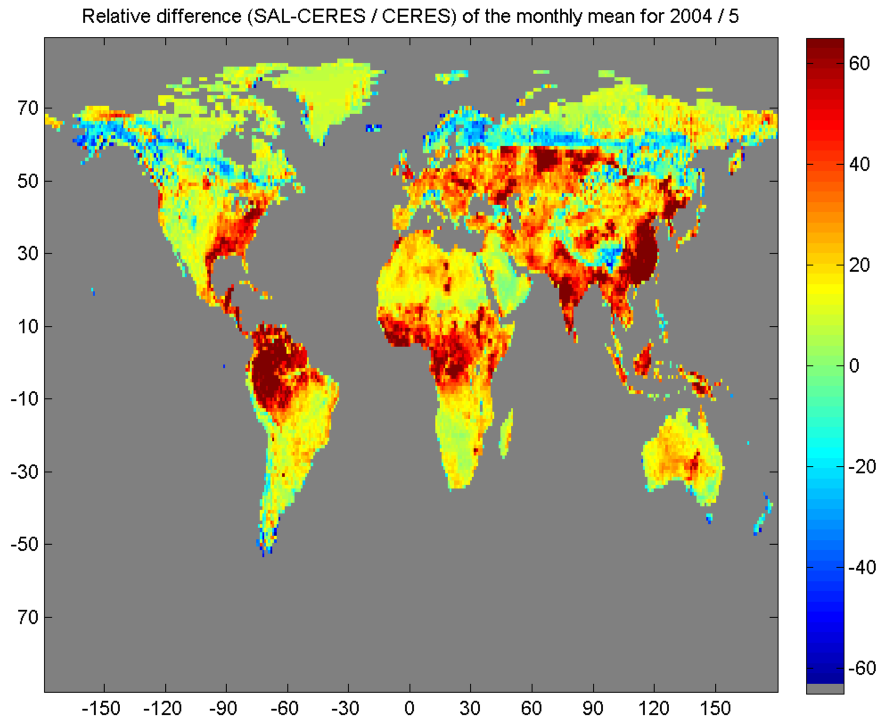

*Figure 30: An example of the **relative** differences between CLARA-SAL and CERES, monthly means from May 2004. Land and snow covered land areas considered, ocean and sea ice excluded.*

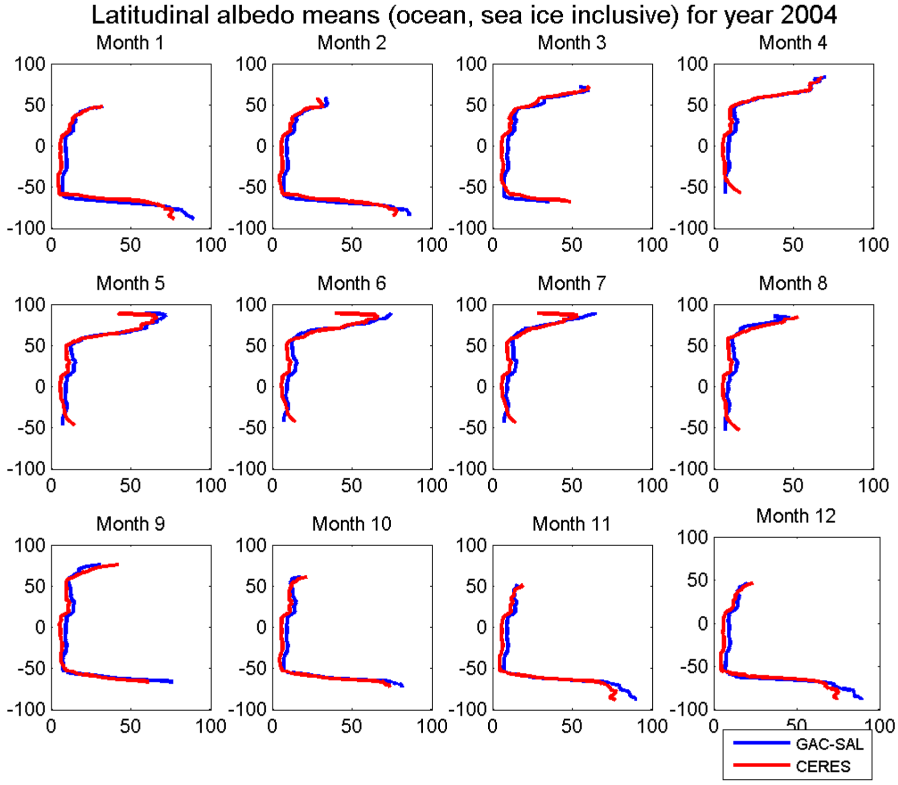

Figure 31: Latitudinal albedo means of CLARA-SAL and CERES FSW, monthly means for year 2004. Blue line denotes CLARA-SAL mean albedo, Red line denotes CERES FSW.

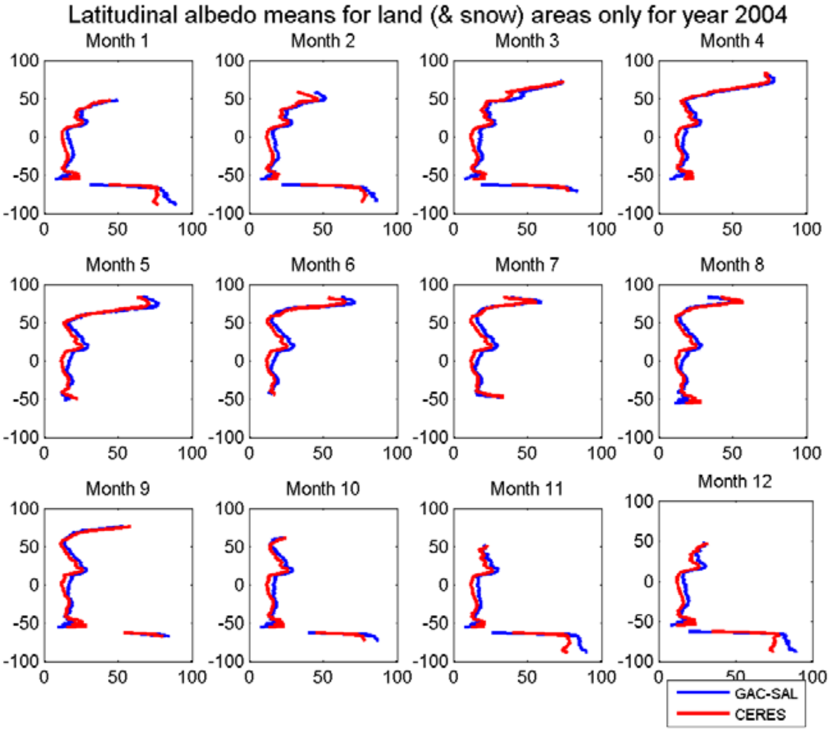

Figure 32: Latitudinal albedo means of CLARA-SAL and CERES FSW for land and snow-covered land only, monthly means for year 2004. Blue line denotes CLARA-SAL mean albedo, Red line denotes CERES FSW.

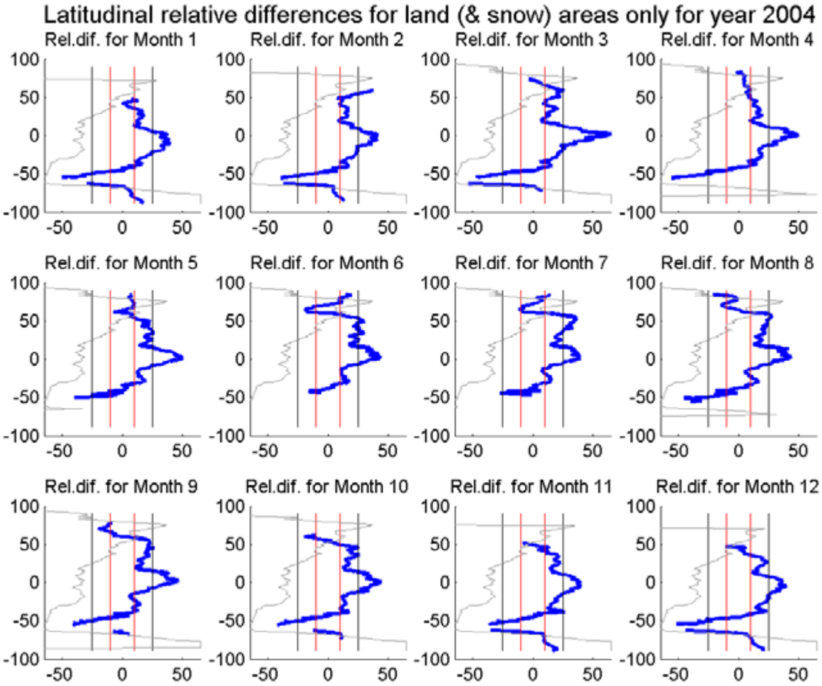

Figure 33: Relative difference between CLARA-SAL and CERES (CERES as baseline), land and snow on land-areas only. The year is 2004. The blue line indicates the difference (on x-axis). The grey line illustrates the amount of data pixels per latitude from which the means are calculated (out of 360). Vertical red and grey lines mark 10% and 25% difference.

To sum up the comparative study on CLARA-SAL and CERES FSW, we find that;

- Considering the land and snow-covered land surfaces, CLARA-SAL albedo is on average 10% higher (relative).
- CERES sea-ice albedo over the Arctic Ocean is considerably lower than CLARA-SAL.
- CLARA-SAL albedo is considerably higher than CERES over the tropics.
- Both products detect similar latitudinal mean characteristics in the global albedo.

11.2. MODIS 16-day BSA shortwave albedo product (MCD43C3)

We have also carried out a comparison to the MCD43C3 black-sky shortwave albedo product from MODIS. The chosen study year was 2009. To match the CLARA-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-SAL products are pentads and monthly means. For simplicity, it was decided to create a MODIS-equivalent CLARA-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-SAL or MODIS had no data-values were excluded.

Figure 34, Figure 35 and Figure 36 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-SAL pentads, and the two are then studied for relative differences. The example results are from May 2009 and they tell a similar story to the CERES - CLARA-SAL comparison. CLARA-SAL produces a higher albedo over the tropics and Southeast Asia, although the difference between CLARA-SAL and MODIS is often smaller than between CLARA-SAL and CERES. Over snow-covered surfaces, the products usually agree within 10% relative.

We also calculated the global land/snow surface mean albedo per MODIS product period as in the CERES comparison. The result for 2009 is shown in Figure 37. The global albedo means are remarkably similar; the difference being that CLARA-SAL tends to be 10-20% higher. The reader should note that these albedos have not been weighed for irradiance or area, as in the CLARA-SAL – CERES-comparison.

It should be noted that the MCD43C3 product corresponds to the mean solar zenith angle (SZA) for each location and timeperiod considered, unlike CLARA-SAL which is set to a fixed SZA everywhere (except snow-covered surfaces). This will cause a natural difference in the products, but its magnitude is very difficult to determine in a comparative analysis. 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-SAL. However, as solar energy on the SWIR spectrum is minimal, the expected impact on the comparability is also deemed very small.

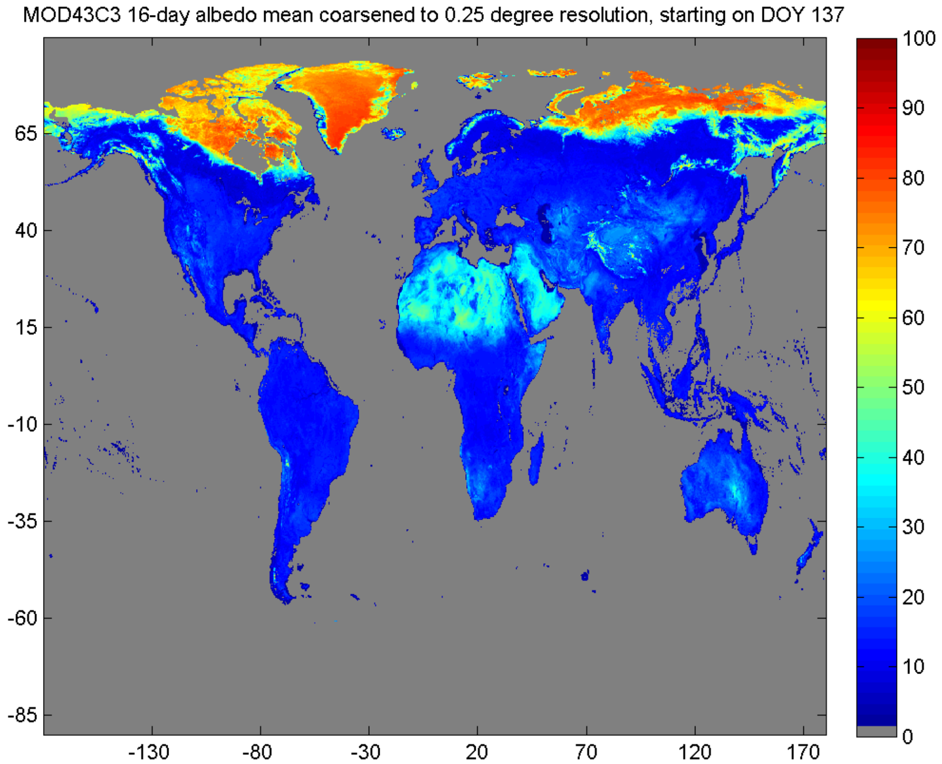

Figure 34: MCD43C3 16-day BSA shortwave albedo product starting from DOY 137 of 2009. Product has been resampled to 0.25 degree spatial resolution.

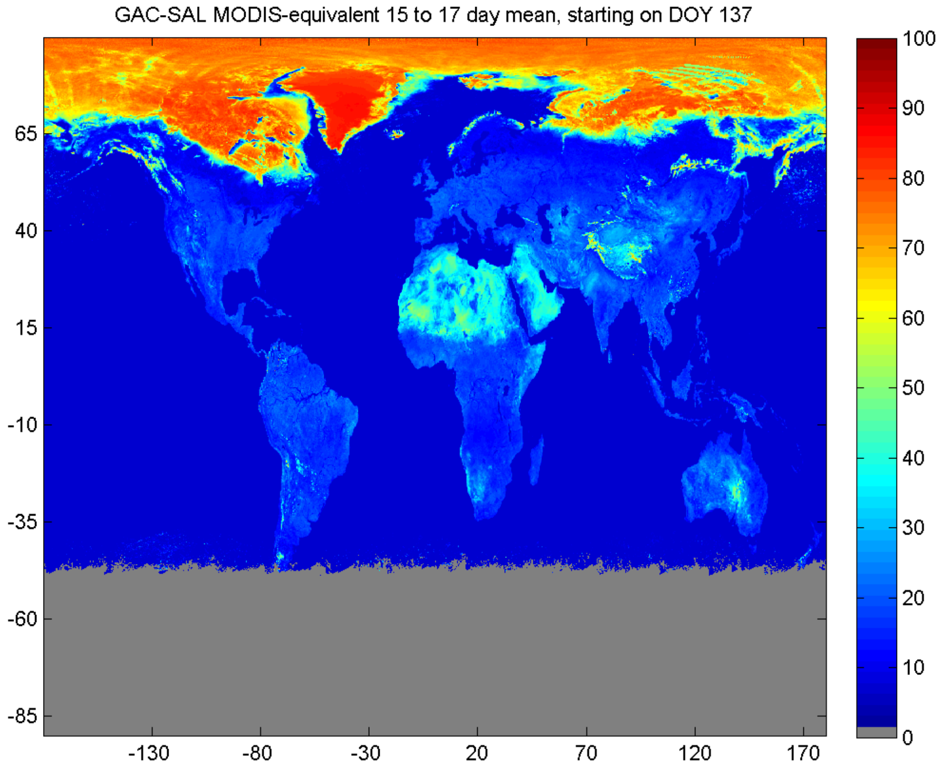

Figure 35: A composite of three CLARA-SAL pentads fitting within (±1 day) the 16-day MCD43C3 period starting on DOY 137 of 2009.

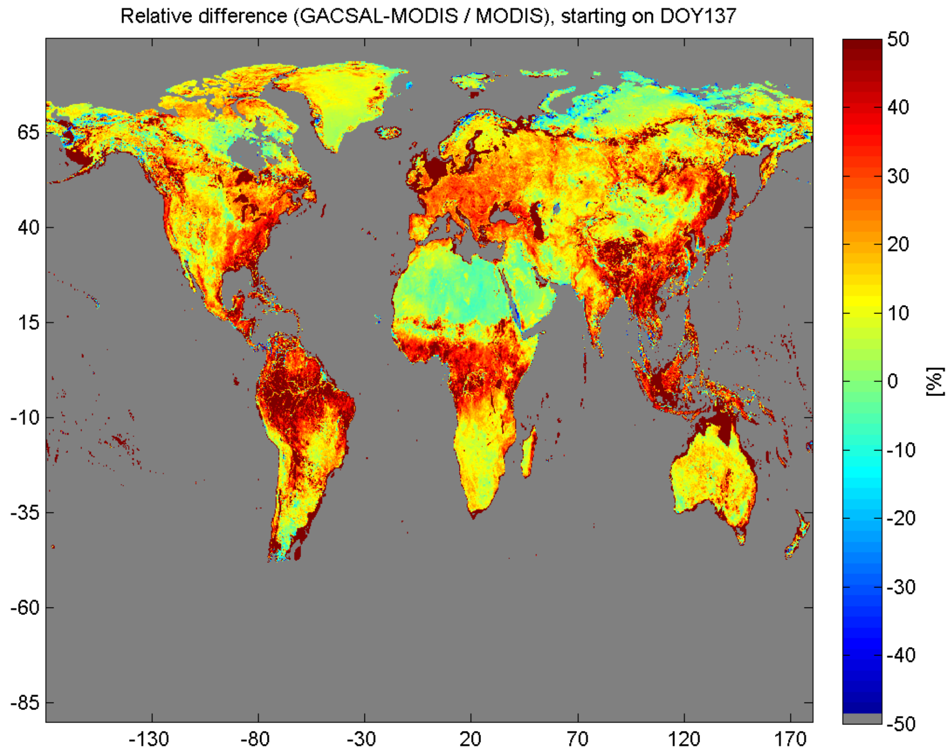

*Figure 36: **Relative** difference (in %) between CLARA-SAL and MCD43C3 over the 16-day MODIS product period starting on DOY 137 of 2009.*

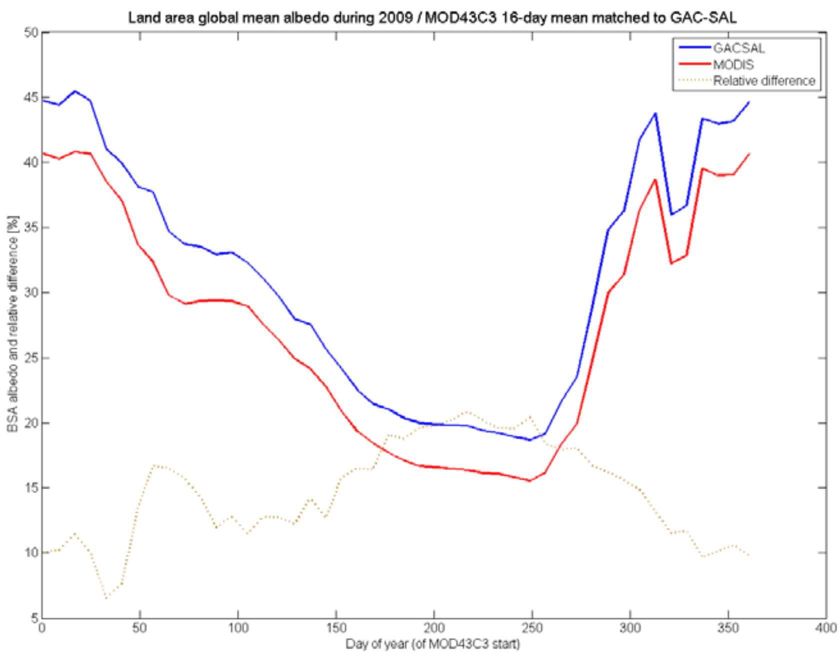

Figure 37:Land/snow surface global black-sky albedo mean for 2009 from the MCD43C3 and CLARA-SAL pentad composites. Red and blue lines indicate MODIS and CLARA-SAL albedo, respectively, and the dashed brown line shows the relative difference (in % using left y-axis) between the products. The albedo has not been weighted for irradiance or area. CLARA-SAL is normalized to 60 degrees SZA; MCD43C3 is not fixed to any common SZA.

Yet another way of comparing the products is to look at the latitudinal albedo means, as we did with CERES and CLARA-SAL. This calculation was performed on the 2009 products, and the results for the land/snow areas are shown in Figure 38.

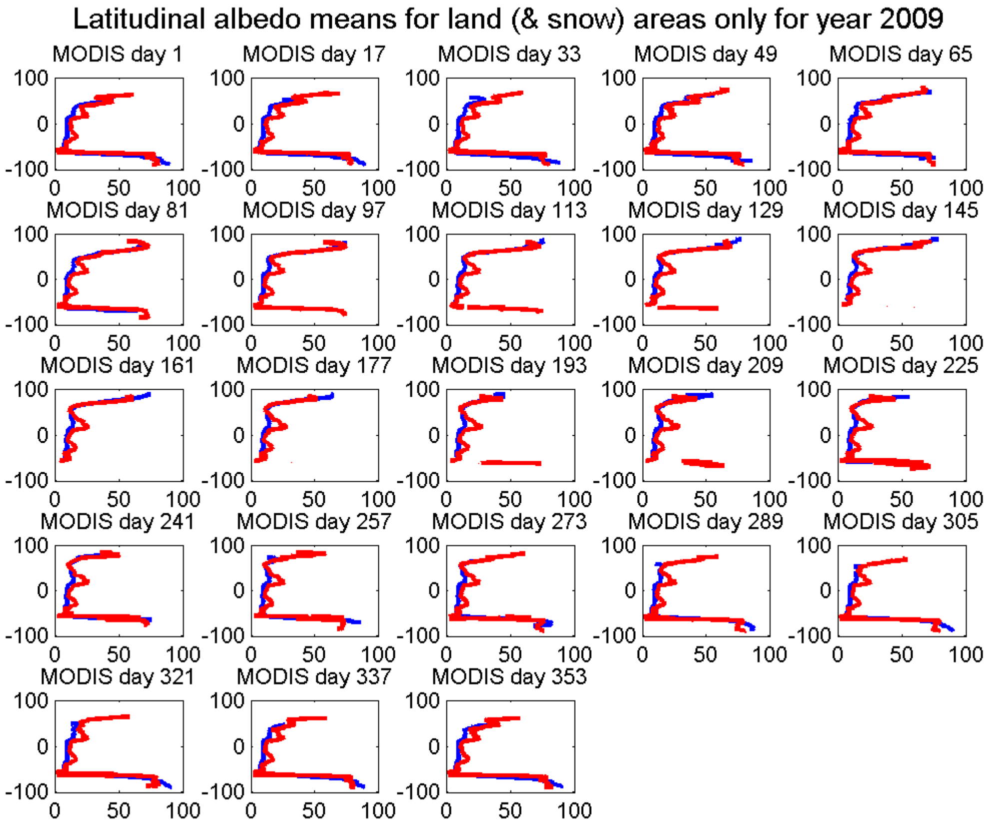

Figure 38:MCD43C3 (red) and CLARA-SAL (blue) latitudinal BSA albedo means for 2009. Only every second MODIS 16-day product is compared here for clarity. Y-axis indicates latitude (degrees) and the x-axis indicates BSA albedo (in %)

The comparison shows that MODIS has a clearly higher albedo over the subtropical regions (20-30N and 20-30S). The mean latitudinal albedo is similar over the large Northern Hemisphere landmasses, especially over NH spring and summer. The means are somewhat different over Antarctica. Overall, CLARA-SAL has a larger snow albedo over Greenland and Antarctica than either MODIS or CERES.

Relative differences in the latitudinal means are shown in Figure 39. Over most of the northern hemisphere, the relative difference between MODIS and CLARA-SAL is between 10 and 20%. The large difference “spike” occurring often between 50S and 60S is, again, 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.

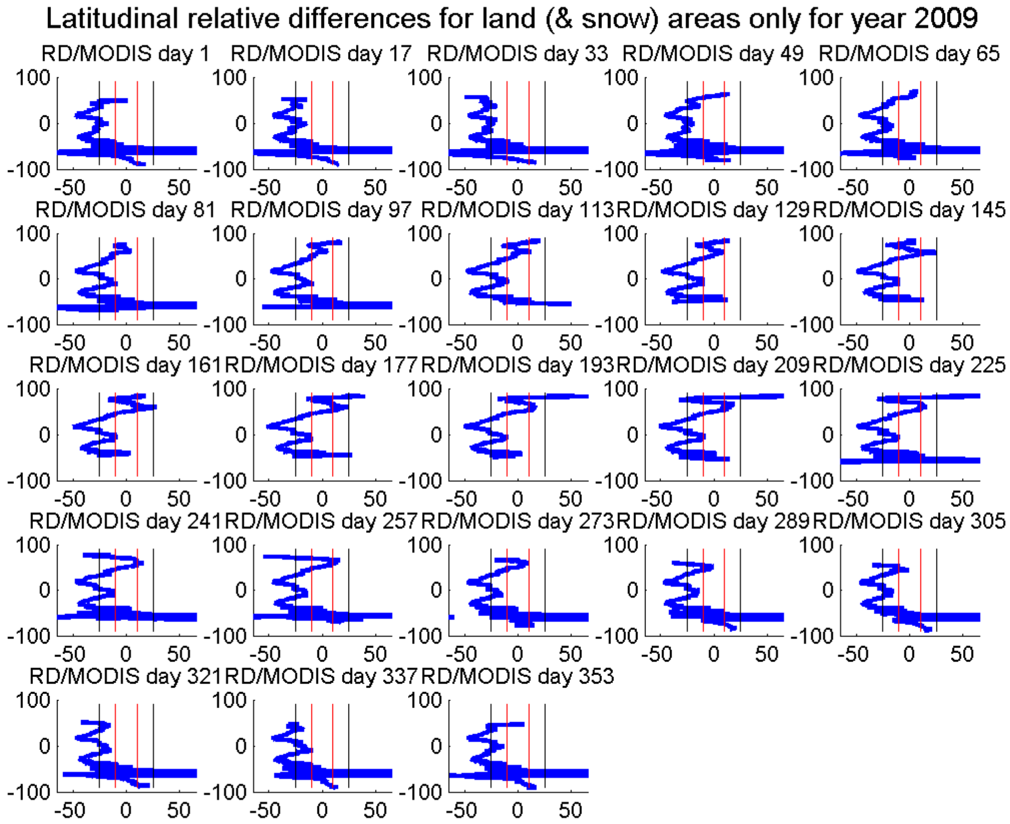

Figure 39: Relative difference between MODIS and CLARA-SAL ((GACSAL-MCD43C3)/MCD43C3) as a latitudinal mean. Study period is the year 2009. Y-axis indicates latitude (degrees), X-axis indicates relative difference (in %).

12. Discussion On Product Stability

The results thus far shown in this report have illustrated the retrieval quality of CLARA-SAL over certain validation sites and a comparison to other well-known satellite albedo products. Our last remaining task is to study the temporal stability of CLARA-SAL over regions known to exhibit stable albedo over long time-periods. To do this, we have chosen two study sites; one over the Sahara desert and another over the Greenland Ice Sheet. To ensure a representative view on product stability, we average the CLARA-SAL monthly means over large areas of the two study sites and show the evolution (if any) of the regional mean albedo over the validation period of 1989-2009. The study sites and regions of CLARA-SAL averaging are shown in Figure 40.

The stability results of the Sahara region are shown in Figure 41. Anomalies from the long-term mean occur mostly during the early 1990's, as well as 1999-2000. It is notable that the periods of highest anomalies coincide with the periods when the least satellite data was available for the GACSAL monthly means. The mid-1990s and 1999-2000 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.

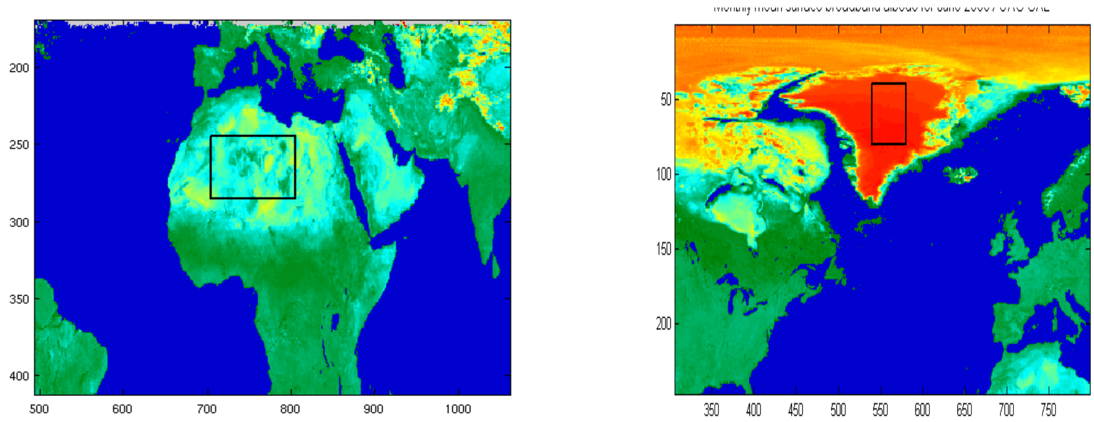

Figure 40: The Sahara (left) and Greenland Ice Sheet (right) study regions for temporal stability.

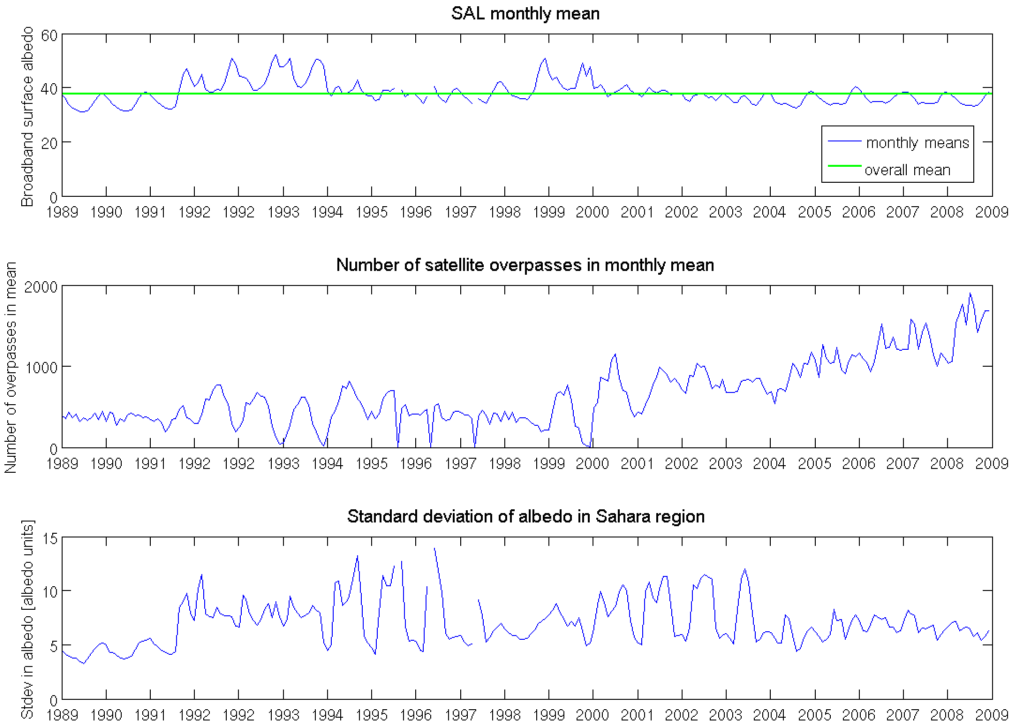

Figure 41:Stability analysis of the Sahara region.

We also calculated the stability for an area in the Libyan desert at 29.1 N, 24.5 E, previously used by Govaerts and Lattanzio (2007) as a calibration study target. The study region was limited to ±2 pixels around the site, thus showing small-scale variation of CLARA-SAL over Sahara. The stability of CLARA-SAL over this site shows exactly the same features as the large-area study in Figure 41, but with somewhat larger variability. The maximum deviation from the interannual mean at this site was 48% (relative), illustrative of the large and variable aerosol loading over Sahara.

Over the Greenland Ice Sheet (GIS), the situation is better and variations from the 20-year mean are no more than 0.05 (5% absolute). Standard deviation of the monthly means is also always under 0.1 (10% absolute). The central part of the GIS 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-SAL atmospheric correction works well.

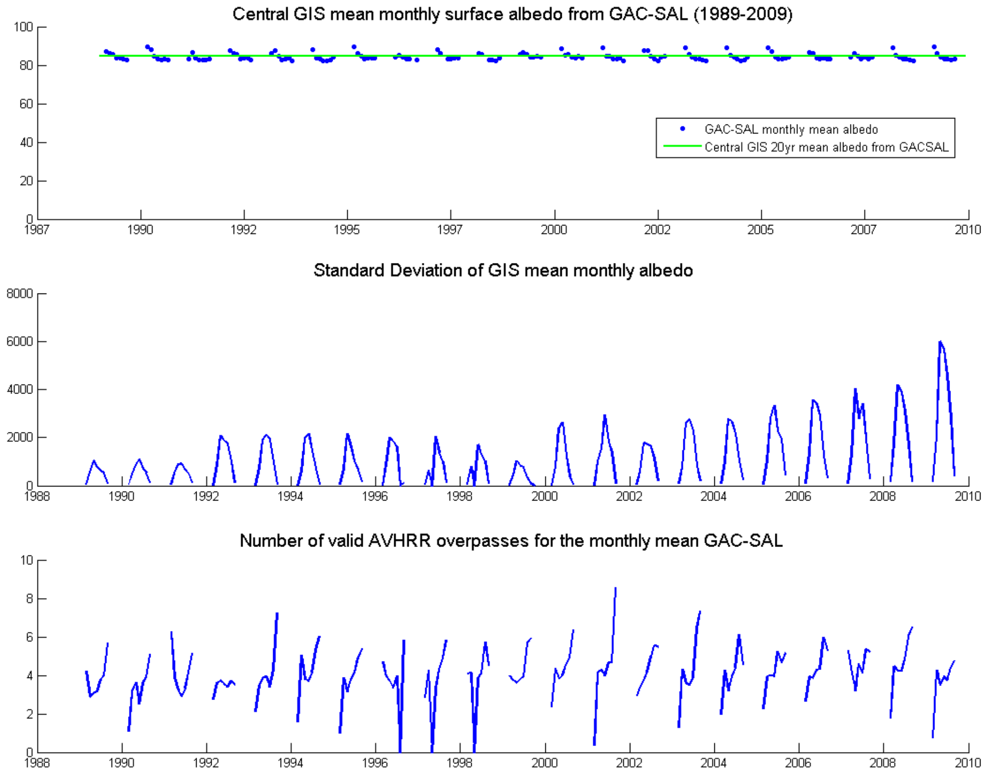

Figure 42:CLARA-SAL stability over the Central Greenland Ice Sheet region.

Apart from the desert and snow sites, we also investigated the stability of the CLARA-SAL over a temperate forest site in Central Europe. We chose the Schwarzwald forest (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 43 shows the results from investigating the single CLARA-SAL pixel closest to 48N, 8E between 1989-2009. The timeseries is quite stable over the 20-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-SAL products in Figure 44. Snow deposition events stand out clearer in the pentad timeseries. 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.

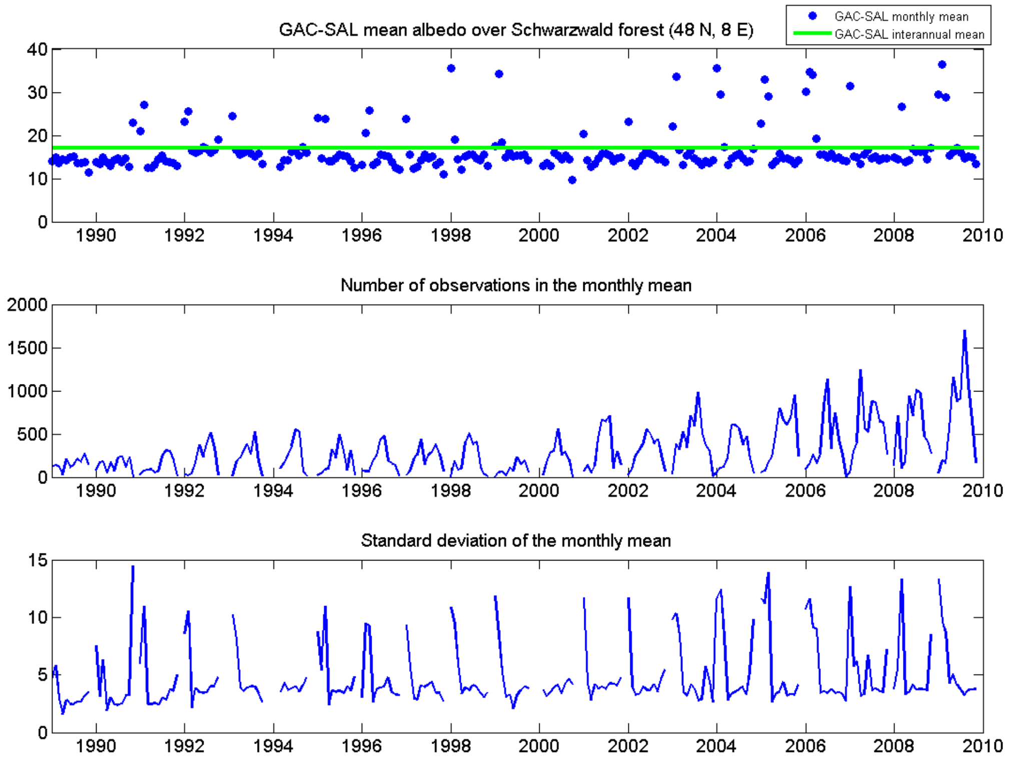

Figure 43:CLARA-SAL stability over Schwarzwald forest, Germany (48 N, 8 E). Monthly means.

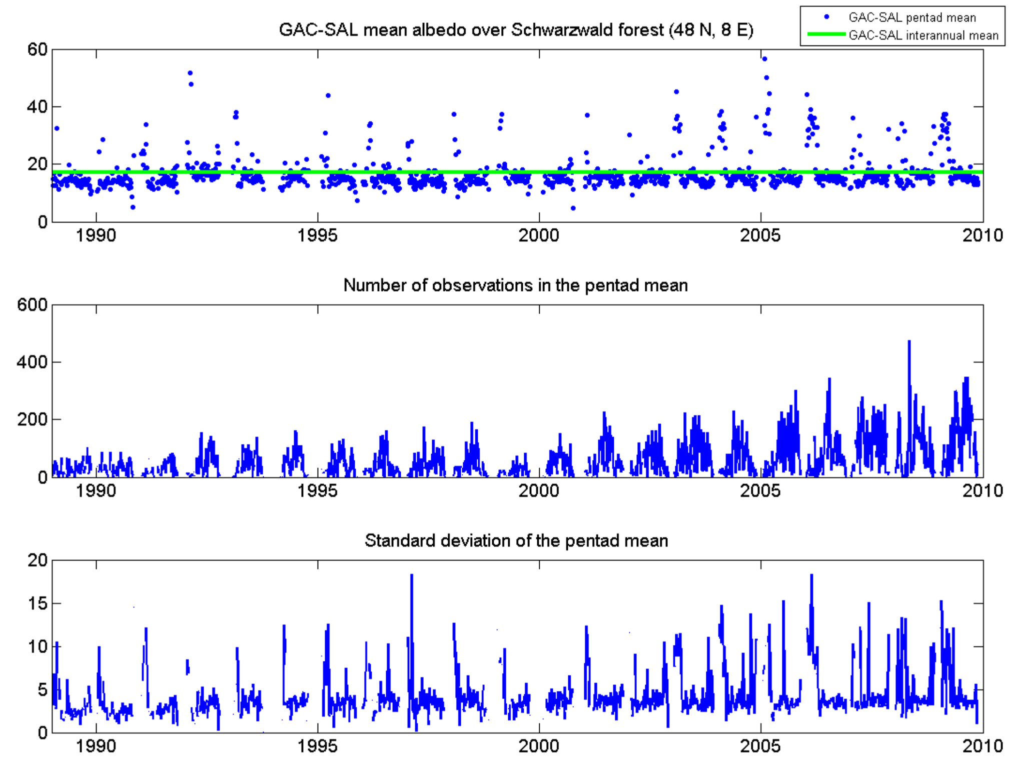

Figure 44: CLARA-SAL stability over Schwarzwald forest, Germany (48 N, 8 E). Pentad means.

13. Conclusions

This report has presented the findings of the validation study on the CLARA-SAL TCDR Edition 1. The CLARA-SAL products have 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 the CERES (FSW) and MODIS (MCD43C3) sensors.

The BSRN and GC-Net timeseries are limited in length; most validation sites have albedo records from the mid-1990s onwards. This means that the CLARA-SAL product quality between 1982 and 1994 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 dataset which forms one of the necessary inputs for CLARA-SAL processing 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-SAL products fulfil their target accuracy for 90% of 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-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 CERES and MODIS show that CLARA-SAL produces a 10-20% (relative) higher global mean albedo over land areas (snow included).. A study of latitudinal means shows that CLARA-SAL tracks latitudinal albedo features similarly to CERES and MODIS; differences to MODIS mostly occur over the tropical regions and Patagonia (where the topography correction in CLARA-SAL causes differences). The Arctic sea ice albedo in CLARA-SAL is markedly larger than in CERES. Regional larger differences between CLARA-SAL and MODIS/CERES also occur over Southeast Asia and the East coast of North America. The differences are likely a result of the atmospheric correction in SAL, which currently applies a standard AOD to all corrections. It is known that AOD concentrations over the urbanized eastern seaboard of the US, India, China, and Southeast Asia are typically larger than the pre-set AOD in CLARA-SAL.

Finally, we have studied CLARA-SAL stability over regions where we expect very little variation in surface albedo; the Sahara desert and the inner parts of the Greenland Ice Sheet. Over GIS, CLARA-SAL is very stable during the validation period, maximum deviation from the interannual mean being 5% (relative). The Sahara sites show a much larger variability, no doubt as a result of the constant aerosol input in this Edition. Inclusion of realistic and robust aerosol input data is a major target for the next CLARA-SAL Edition.

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

14. References

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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-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