EUMETSAT Satellite Application Facility on Climate Monitoring

Validation Report

CM SAF Cloud, Albedo, Radiation data record, AVHRR-based, Edition 3 (CLARA-A3)

Surface Radiation

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	TCDR	ICDR
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Surface Downward Longwave Radiation	CM-11262	CM-6261
Surface Radiation Budget	CM-11272	CM-6271
Surface Net Shortwave Radiation	CM-11281	CM-6281
Surface Net Longwave Radiation	CM-11291	CM-6291

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Applicable documents

Reference	Title	Code
AD 1	CM SAF Product Requirement Document	SAF/CM/DWD/PRD/4.0

Reference Documents

Reference	Title	Code
RD 1	Algorithm Theoretical Basis Document Surface Radiation Products CLARA-A3	SAF/CM/DWD/ATBD/CLARA/RAD/3.2

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Executive Summary

This CM SAF report provides information on the validation of the surface radiation products from the CM SAF CLARA Edition 3 (CLARA-A3) data sets derived from AVHRR sensors onboard the series of NOAA satellites and the METOP satellite. All climate data sets (SIS, SDL, SNS, SNL, SRB) are validated against available reference data sets from surface measurements. The accuracy is defined based on the absolute bias derived from the validation with the reference data and evaluated against the accuracy requirements as given on in the product requirements document (PRD) [AD 1]. The quality of the data from the Interim Climate Data Record (ICDR) is based on the comparison between the data generated with the ICDR processing environment and the data generated as part of the CDR for 2020. No direct comparison to surface reference data is performed for the ICDR data.

All data sets fulfil the accuracy requirements as specified in the Product Requirements Document (PRD) [AD 1].

Table 1: Summary of the accuracy of the CM SAF CLARA-A3 surface radiation data sets based on the mean absolute bias compared to surface reference measurements.

Data Set	Threshold / Target / Optimal Accuracies in W/m^2	Dataset Accuracy in W/m^2
SIS	9 / 5 / 3 18 / 15 / 10 (daily averages)	7 17
SDL	8 / 5 / 3	7
SNS	8 / 5 / 3	10
SNL	8 / 5 / 3	7
SRB	8 / 5 / 3	10

The basic accuracy requirements are defined in the product requirements document (PRD) AD 1], and the algorithm theoretical basis document (ATBD) describes the individual parameter algorithms [RD 1].

1 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, variabilities 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, https://www.cmsaf.eu/. Here, detailed information about product ordering, add-on tools, sample programs and documentation is provided.

2 Introduction

The surface radiation data sets derived from the AVHRR GAC satellite data contain information on the shortwave and longwave radiation. The shortwave surface radiation data sets (SIS) are based on the retrieval of the surface irradiance using information from the Nowcasting SAF cloud detection algorithm PPSv2021 and the satellite-derived radiances in the visible and near-infrared AVHRR satellite channels [RD 1]. The longwave surface radiation data sets rely on information obtained from the ERA-5 reanalysis and the monthly averaged cloud fraction obtained from the CM SAF CLARA-A3 data set [RD 1].

All products are globally available as monthly averages (SIS is also available as daily averages) between January 1979 and December 2020 on a 0.25°-regular longitude-latitude grid.

3 Validation Data Sets

The validation of the surface radiation data sets is conducted against surface measurements from the Baseline Surface Radiation Network (BSRN) [Ohmura et al., 1998]. The BSRN provides quality-controlled surface radiation measurements at more than 60 stations worldwide, with some stations providing data since 1992.The provided data coverage of BSRN differs between few months and more than 20 years of data. The data is distributed via the World Radiation Monitoring Center (WRMC) hosted by the Alfred Wegener Institute (AWI) in Bremerhaven, Germany (http://www.bsrn.awi.de/). The BSRN data are available at a high temporal resolution. For validation of the CLARA-A3 surface radiation products, daily and monthly averages were calculated following the quality-control and averaging methods presented in Roesch et al. [2011]. The list of BSRN stations used for the validation can be found in Section 7.

Recent work identified a problem with the primary reference calibration of surface radiation instruments [Nyeki et al., 2017], requiring a recalibration of instruments and a revision of the current data, including the data in the BSRN archive. The impact on the shortwave radiation data is expected to be small; the monthly downward longwave radiation data might increase by up to about 3 W/m^2 [Nyeki et al., 2017].

The validation thresholds as defined in the CM SAF CDOP Product Requirements Document [AD 1] for SIS, SDL, SNS, SNS, and SRB are listed in Table 1 The threshold requirement defines the minimum requirement for the product release, the target requirement defines the target for the current product release, and the optimal requirement is defined as the requirement that could be achieved with an optimal observing system.

As outlined above, in the assessment of these thresholds additional uncertainties arising from the surface measurements and their comparison with the gridded data need to be considered. The uncertainty of the individual (1-min) BSRN measurements can be estimated from the documentation of the instruments. The estimation of temporal averages (daily, monthly) introduces additional uncertainty, e.g., due to missing 1-min data. For the comparison between local reference measurements (BSRN) and gridded data results additional uncertainties needs to be considered, including those due to the representativeness of the location of the surface measurement. The representativeness depends on the station location, the size of the grid boxes of the gridded data, the temporal resolution of the data, and can also temporally vary, e.g,, with season.

Addressing and considering these individual uncertainties in the validation of satellite products is an ongoing, active international research topic, e.g., Urraca et al., 2022 a, b. At this stage, however, no easily applicable solutions are available and we assume additional uncertainties that are meant to account for all the different aspects of 5 W/m^2 for all monthly data and 10 W/m^2 for daily-averaged data. For some stations with a very low repesentativeness these assumed uncertainties are too low and these stations will be discarded from the overall quality assessment.The coverage factor, k, as introduced by Immler et al., 2010, describes an interval around the mean value of an observable as a multitude of the standard uncertainty, u. Strictly speaking, every uncertainty provided should be accompanied with the corresponding coverage factor. If the coverage factor cannot be (easily) determined, setting the coverage factor to k = 1 is a conservative choice. According to this concept and assuming k = 1 two independent measurements, m_1 and m_2, can be considered 'consistent' (at a 32 % significance level, see Table 1 of Immler et al., 2010) if $|m_1 - m_2| < \sqrt{u_1{}^2 + u_2{}^2}$, with u_1 and u_2 representing the uncertainty of the two measurements. In the case of the evaluation of the CLARA-A3 climate data record, the accuracy requirement can replace the uncertainty of the SARAH data records in the above formula. In this case, assuming an uncertainty of 5 W/m^2 (and k = 1) of the surface measurements and a threshold accuracy requirements of 9 W/m^2 (i.e, for the monthly mean surface irradiance) the CLARA-A3 SIS data record is considered "consistent" with the BSRN measurement if the absolute difference is less than 10.3 W/m^2. Assuming a coverage factor of k = 2 results in a threshold of the absolute difference of 20.6 W/m^2 below which the measurements can be considered to be 'in agreement' (Table 1 of Immler et al., 2010). Note that for the present validation report the coverage factor has not been included due to the unavailability of the coverage factor for the uncertainty of the BSRN measurements. Future research, by the CM SAF team as well as by the scientific community, will help to further establish scientifically sound uncertainties and coverage factors for the BSRN and CLARA-A3 measurements, which will subsequently be used in future CM SAF validation activities.

4 Validation

The strategy for the validation of the CM SAF CLARA-A3 surface radiation data sets follows the CM SAF Product Requirements Document [AD 1], i.e. the data are compared to surface reference measurements from the BSRN. The accuracy requirements applicable for this validation report are mainly derived from GCOS in 2004, which have been updated in December 2011. All products in the CLARA-A3 surface radiation dataset fulfil the updated GCOS requirements regarding the horizontal resolution (100 km).

4.1 Methodology

According to the PRD [AD 1] the validation of the CM SAF CLARA-A3 SIS, SDL, SNS, SNL, and SRB data sets is based on the comparison with available surface measurements. The CLARA-A3 data are extracted at each BSRN station site using a nearest-neighbour technique. The measures for the verification with surface measurements are the bias, the absolute bias, the bias-corrected variance, the correlation coefficient of the anomalies and the fraction of months (resp. days), which exceed the target accuracy (see details below). To account for uncertainties in the surface measurements and possible errors introduced by calculating the temporal averages from the BSRN observations, uncertainties of 5 W/m^2 and 10 W/m^2 are assumed for the monthly and daily averages, respectively, derived from the surface observations [Ohmura et al., 1998]. Only those stations are considered in the stationwise validation, which have more than 24 months of data between 1979 and 2020. The quality of the data sets is assessed by comparisons with the specified accuracy in the PRD [AD 1].

Bias

The bias or (also called mean error) is simply the mean difference between the average of two datasets, resulting from the arithmetic mean of the difference over the members of the data sets. It indicates whether the dataset on average over- or underestimates the reference dataset.

$$\text{Bias} = \frac{1}{n}\sum_{\text{k}=1}^{n}(y_k - o_k) = \bar{y} - \bar{o} \tag{1}$$

Mean absolute difference

In contrast to the bias, the mean absolute difference (herinafter reffered to as absolute bias) is the arithmetic average of the absolute values of the differences between each member (all pairs) of the time series. It is therefore a good measure for the mean “error” of a dataset.

$$\text{MAD} = \frac{1}{n}\sum_{\text{k}=1}^{n}\left|y_k - o_k\right| \tag{2}$$

Standard deviation

The standard deviation SD is a measure for the spread around the mean value of the distribution formed by the differences between the generated and the reference dataset.

$$\mathrm{SD} = \sqrt{\frac{1}{n-1}\sum_{\mathrm{k}=1}^{n}\left((y_k - o_k)-(\bar{y}-\bar{o})\right)^2} \tag{3}$$

Anomaly correlation

The anomaly correlation describes to which extend the anomalies of the two considered time series correspond to each other without the influence of a possibly existing bias. The correlation of anomalies retrieved from satellite data and derived from surface measurements allows the estimation of the potential to determine anomalies from satellite observations.

$$AC = \frac{\sum_{k=1}^{n}(y_k-\bar{y})(o_k-\bar{o})}{\sqrt{\sum_{k=1}^{n}(y_k-\bar{y})^2}\sqrt{\sum_{k=1}^{n}(o_k-\bar{o})^2}} \tag{4}$$

Here, for each station the mean annual cycle and were derived separately from the satellite and surface data, respectively. The monthly/daily anomalies were then calculated using the corresponding mean annual cycle as the reference.

Fraction of time steps above the validation target values

A measure for the uncertainty of the derived dataset is the fraction of the time steps that are outside the requested target value'T'. The target values is given by the target accuracy of the respective CM SAF product, plus the non-systematic error (uncertainty) of the BSRN measurements (Ohmura et al. 1998).

$$\mathrm{Frac} = 100\cdot\frac{\sum_{k=1}^{n} f_k}{n} \text{ with } \begin{cases} f_k = 1 & \text{if } y_k > T \\ f_k = 0 & \text{otherwise} \end{cases} \tag{5}$$

Thereby, the variable 'y' describes the dataset to be validated (e.g., CM SAF) and 'o' denotes the reference dataset (i.e., BSRN). The individual time step is marked with 'k' and 'n' is the total number of time steps.

4.2 SIS Validation

The surface incoming solar radiation data set from the CM SAF CLARA-A3 is validated against surface measurements obtained within the global Baseline Surface Radiation Network (BSRN). As described in Section 3 daily and monthly averages are calculated from the high-resolution BSRN data.

In addition to the validation results presented in the following it should be noted that in the CM SAF CLARA-A3 SIS data set selected grid boxes are set to missing values. During the generation of this data set it has been found that grid boxes with less than 20 observations per day do not fulfil the accuracy requirements. These grid boxes are set to missing data and should not be considered in the analysis of the data set.

4.2.1 Monthly Averages

4.2.1.1 Accuracy

The validation results for the monthly averaged CM SAF CLARA-A3 SIS data set are shown in Table 2.

Table 2: Validation results for the monthly averaged CM SAF CLARA-A3 SIS data set compared to BSRN surface measurements; the second row provides the mean validation results averaged over each station; also included are the corresponding results from the CLARA-A1 and CLARA-A2.1 + ICDR SIS data record

Data set	Analyzed Months / Stations	Bias (W/m^2)	Abs. bias (W/m^2)	Std.Dev (W/m^2)	Corr. Ano	Frac. Month > target
SIS, A3	9369	1.9	7.3	10.3	0.91	24.8 (10 W/m^2)
	55	2.2	7.5	8.2		
SIS, A2.1 + ICDR	8827	-2.2	8.3	11.8	0.90	20.3 (13 W/m^2)
	55	-1.2	8.5	9.8		
SIS, A2	6420	-1.6	8.8	13.1	0.87	17.6
SIS, A1	3105	-3.3	10.4	14.4	0.88	23.6

In total, 9369 monthly mean data values of the surface incoming solar radiation from 55 stations[1] between 1992 and 2020 were used for the global validation of the monthly mean CM SAF CLARA-A3 SIS data set. The bias of the data set compared to the BSRN reference data is 1.85 W/m2, the absolute bias is 7.3 W/m^2. The bias is well below the optimal accuracy of 8 W/m^2 as specified in the PRD [AD 1], showing the excellent quality of the data set. The absolute bias is slightly lower than the predefined threshold accuracy of 9 W/m^2 [AD 1], also providing evidence of the high quality of the monthly mean CM SAF CLARA-A2.1 SIS data set.

Considering the uncertainty of the surface observations of 5 W/m^2, about only 25 % of the available monthly-averaged data values are outside the target accuracy (Table 2). The

[1]The measurements from Sonnblick, Izana, Ny Alesund, Syowa, Georg von Neumayer, Concordia Station, South Pole have not been considered for the general assessment of the CLARA-A3 SIS data record due to their limited representativeness for the scale of a CLARA-A3 gridbox. The validation results from these stations, however, are provided in the stationwise validation, see e.g.,Figure 4-3

temporal correlation of the anomalies is 0.91, i.e., the data set is well suited for the detection and quantification of climate anomalies.

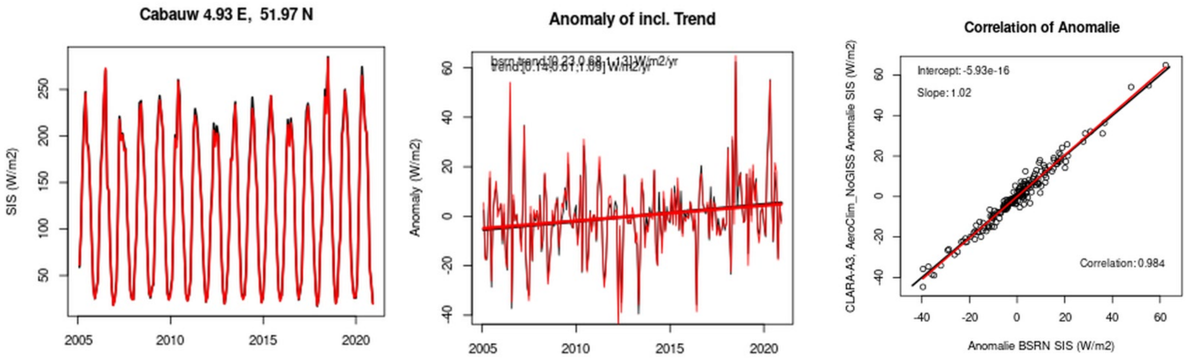

Figure 4-1: Analysis of the monthly time series of the CM SAF CLARA-A3 SIS data set compared to monthly averaged data from BSRN for Cabauw, Netherlands. Shown are (left) the time series of the monthly mean data sets, (center) the time series of the anomalies relative to the multi-year monthly averages, and (right) the correlation of the monthly anomalies derived from the BSRN and the CM SAF CLARA-A3 SIS data set.

To document the performance of the CLARA-A3 SIS data record and the analysis Figure 4-1 presents an example of analysed time series. The CM SAF CLARA-A3 SIS data set is compared to monthly averaged data from BSRN for Cabauw, Netherlands. The annual cycle is dominating the variability of the surface solar radiation. The inter-annual variability is depicted by the time series of the anomalies, calculated by subtracting the mean value of the corresponding months, and mainly governed by the variability in cloud coverage. The high quality of the CM SAF CLARA-A3 SIS data set is shown by the high correlation of the anomalies.

The spatial distribution of the 64 surface stations used for the validation are shown in

Figure 4-2 together with the multi-year mean surface solar irradiance for the month of September (chosen to provide the highest data coverage) from the CM SAF CLARA-A3 SIS data set.

Figure 4-3 presents the results from the validation of the CM SAF CLARA-A3 SIS data set for each of the used BSRN surface stations in more detail. 50 stations are within the target accuracy, while the data record exceeds the target accuracy at 14 of the 64 surface stations. 6 of these surface stations are located in the polar regions (Ny Alesund, Alert, Syowa, Georg von Neumayer, Concordia, South Pole) documenting the challenges involved in accurately deriving the surface solar radiation over polar regions. Izana (Canary Islands, Spain) and Sonnblick (Alps, Austria) are located in highly topographically-structured terrain and the representativity of these measurements for comparison with remote-sensing data is questionable. The enhanced bias in Tamanrasset, Ilorin (both stations are located in Africa), and Tiruvallur (India) might be explained by local aerosol loadings and/or properties, which are not correctly described in the satellite retrieval scheme. Possible explanations for the enhanced differences at Lanyu Island (Taiwan), Howrah (India) and Yushan (Taiwan) will be further investigated in the future; incl. their possible reduced spatial representativeness, e.g., due to their location close to the coast in the case of Lanyu Island and Yushan, as well as the higher levels of surface irradiance in low latitude regions resulting in comparably high absolute deviations.

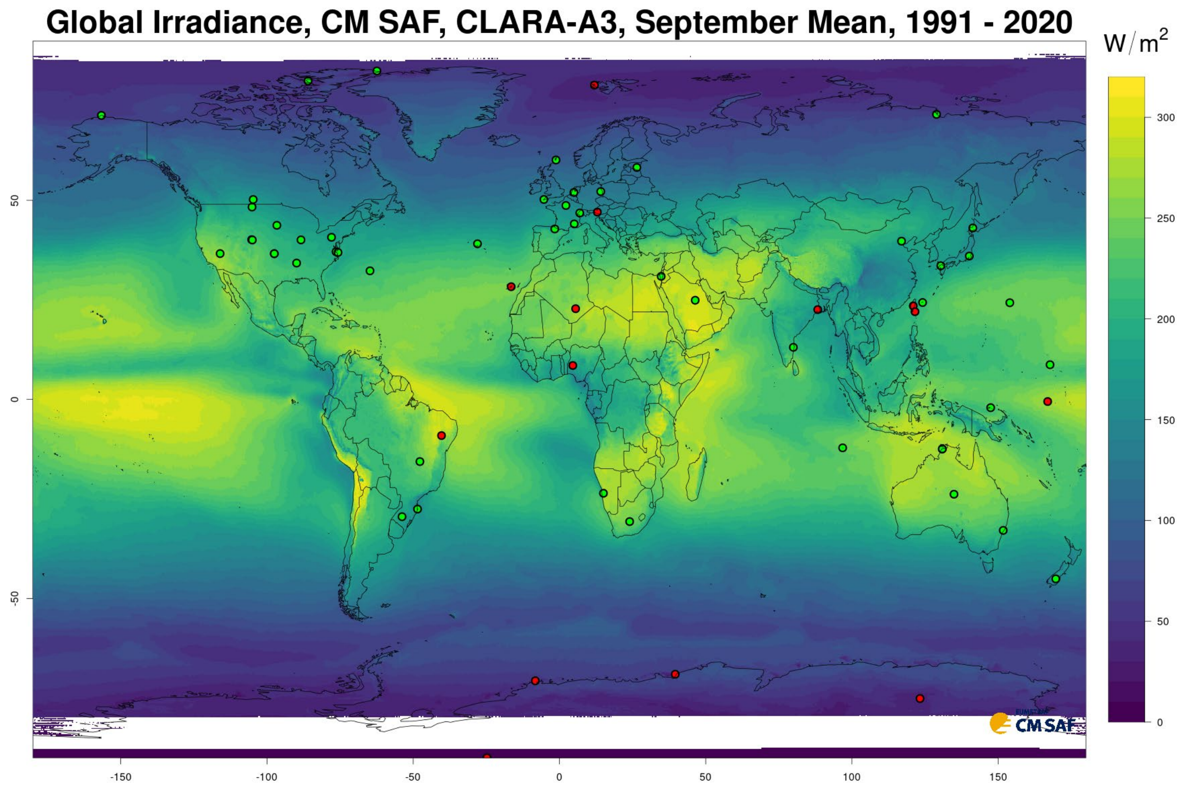

Figure 4-2: Multi-year average of the CM SAF CLARA-A3 surface solar irradiance data set for the month of September (chosen to provide the highest data coverage) and validation results obtained by comparison with available BSRN surface measurements. Green dots represent surface stations where the CLARA-A3 SIS data set is within the target accuracy, red dots correspond to surface stations, where the CLARA-A3 SIS data set does not meet the target accuracy.

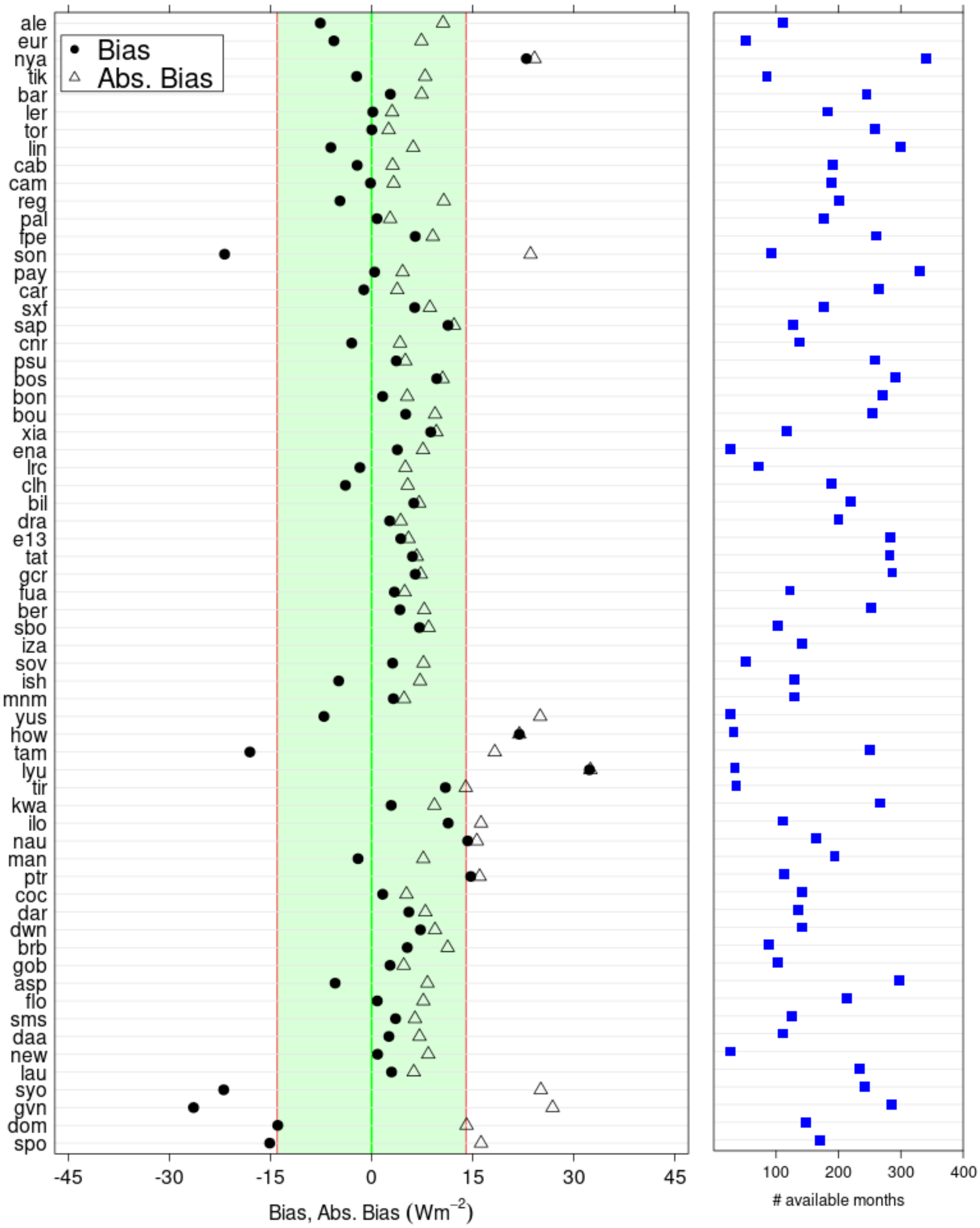

Figure 4-3: Stationwise validation results for the CMSAF CLARA-A3 SIS data set. Shown are the bias (filled dots) and the absolute bias (triangle) of the monthly mean SIS data from the CM SAF CLARA-A3 data set compared to the BSRN surface measurements. The station names are listed north-to-south and named according to their BSRN-label (see http://www.bsrn.awi.de/). The area between the red lines marks the threshold accuracy including the uncertainty of the surface observations. The number of available monthly data for the evaluation is shown in the right part of the Figure.

Based on the results presented here, we conclude that the monthly-averaged CM SAF CLARA-A3 SIS data set is within the target accuracy as defined in the PRD [AD 1].

4.2.1.2 Stability

The stability of the CM SAF CLARA-A3 SIS data record is documented by comparison with BSRN surface reference measurements. The temporal evolution of the difference between the CLARA-A3 data record and the surface measurements is used to quantify the decadal stability of the CLARA-A3 SIS data record.

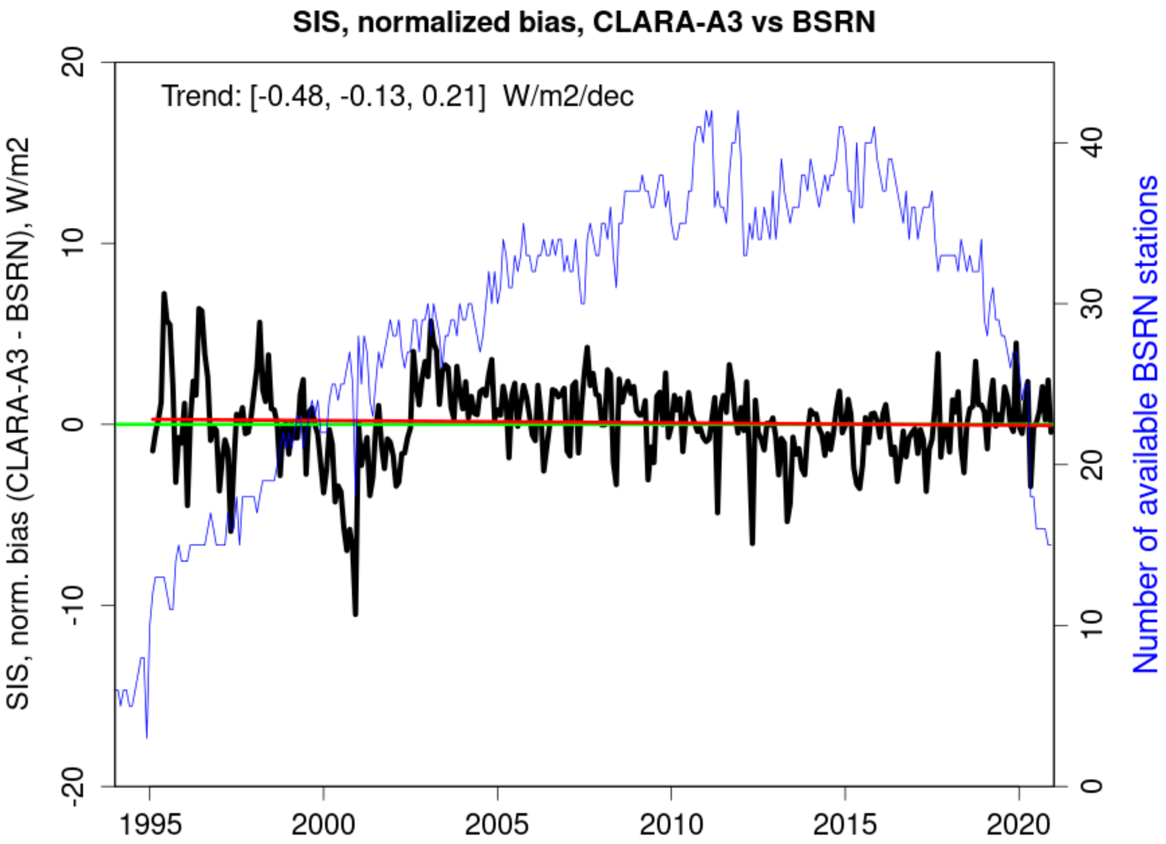

Figure 4-4: Temporal evolution of the normalized bias between the CM SAF CLARA-A3 SIS climate data record and the BSRN surface measurements. The decadal linear trend as well as the 95%-confidence levels are also provided. Basis for this figure are BSRN stations used for the general assessment of the CLARA-A3 SIS data record in Table 2. The blue line represents the number of available monthly data in the calculation of the normalized bias (right scale).

Figure 4-4 shows the temporal evolution of the normalized bias difference between the CM SAF CLARA-A3 SIS climate data record and the BSRN surface references measurements. Only months with more than 10 valid data points are considered for the estimation of the mean bias; the normalized bias has no significant temporal trend documenting the high stability of the CLARA-A3 SIS data record.

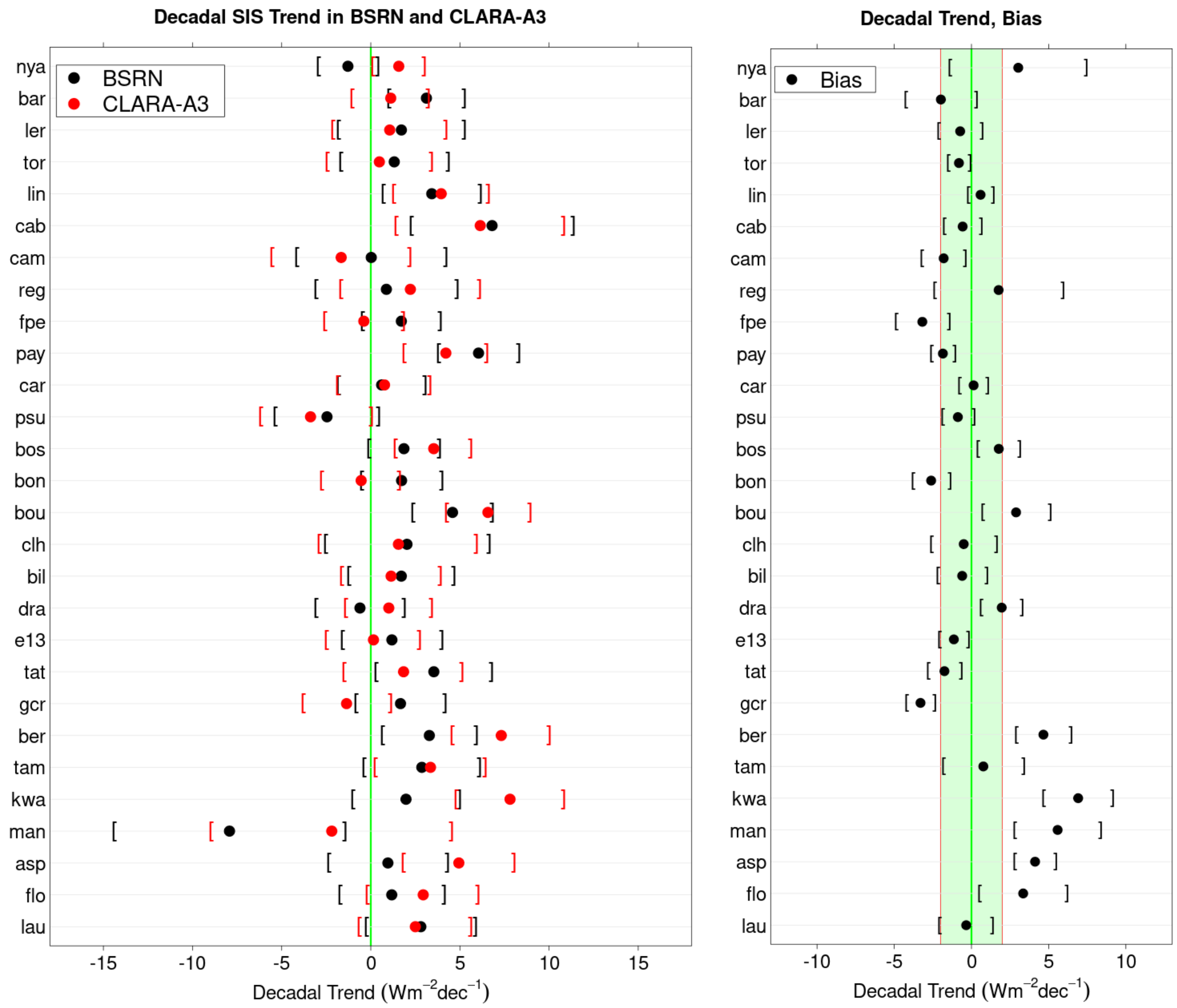

Figure 4-5: (left) Comparison of decadal trends incl. their statistical uncertainty of the CM SAF CLARA-A3 SIS climate data record and BSRN surface measurements at BSRN sites with at least 10 years of overlapping data. The brackets indicate the 95%-confidence level of the linear decadal trend. (right) Decadal trend of the bias between CLARA-A3 SIS and the BSRN data. The brackets indicate the 95%-confidence level of the linear decadal trend. The green region indicates the threshold requirement.

Figure 4-5 shows the decadal trends incl. their statistical uncertainty for the BSRN stations with more than 15 years of common data from the CM SAF CLARA-A3 SIS data record and the surface measurements as well as the decadal trends of the corresponding bias time series. There is a tendency of the CLARA-A3 SIS data record to show smaller trends than the BSRN measurements; at some stations the trend in the CLARA-A3 SIS data largely exceeds the trend estimated from BSRN (e.g., kwa, man). Within the range of uncertainty the CLARA-A3 SIS data record agrees with the surface reference data at all locations. For both data records there are positive trends at most locations, some of these trends are statistically significant. No significant negative trend in the surface irradiance is detected in both data records. The threshold requirement for stability is met at almost all reference stations considering the uncertainty of the trend estimation, only at 5 from 28 stations the trend in the bias exceeds this requirement.

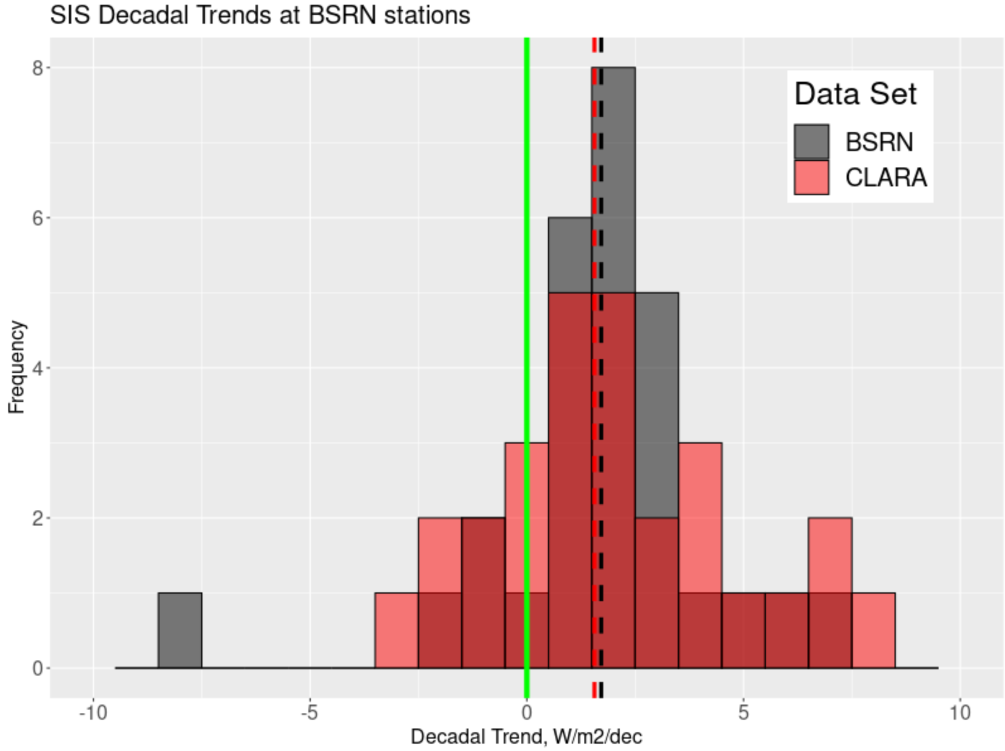

Figure 4-6: Histogram of the decadal trends of surface irradiance derived from the BSRN measurements at the selected locations (see Figure 4-5) and the CM SAF CLARA-A3 SIS data record. The dashed lines indicate the median trend of the distributions; the green line indicates the zero trend.

Figure 4-6 presents the histograms of the decadal trends derived from the BSRN measurements and the CM SAF CLARA-A3 SIS data record at the selected locations. Both data records yield positive decadal trends for most stations with median trends of 1.72 W/m^2/dec and 1.56 W/m^2/dec for the surface measurements and the CLARA-A3 data record, respectively. The variability of the trends is slightly larger for the CLARA-A3 data record.

Overall, we conclude that the CM SAF CLARA-A3 SIS climate data record fulfils the requirement on decadal stability.

4.2.2 Daily Averages

For the surface incoming solar radiation also daily-averaged data are provided by CM SAF as part of the CMSAF CLARA-A3 surface radiation climate data record. The validation of the daily mean CM SAF CLARA-A3 SIS data set is also conducted by comparison with the surface measurements from the BSRN surface network. The threshold accuracy defined for the daily-averaged data is 18 W/m^2 [AD 1]. The results of the validation of the CM SAF CLARA-A3 data set of the daily mean surface incoming solar radiation are provided in Table 3.

Table 3: Validation results for the daily averaged CM SAF CLARA-A3 SIS data set compared to BSRN surface measurements; the second row provides the mean validation results averaged over each station; also included are the corresponding results from the previous versions of the CLARA SIS data record.

Data set	Analyzed Days / Stations	Bias (W/m²)	Abs. bias (W/m²)	Std.Dev (W/m²)	Corr. Ano	Frac. Month > target	Frac. Month > threshold
SIS, A3	263,,280	1.6	16.9	25.0	0.91	22.1 (25 W/m²)	18.7 (28 W/m²)
	55	2.9	17.7	24.0			
SIS, A2.1 + ICDR	248,998	-2.4	18.4	27.1	0.91	24.6 (25 W/m²)	21.2 (30 W/m²)
	55	-0.3	19.5	26.4			
SIS, A2	181,649	-1.7	18.6	27.7	0.90	25.0	19.5
SIS, A1	96,237	-4.7	22.9	34.3	0.85	25.5	20.8

More than 260,000 daily-averaged data values from 55 BSRN stations are considered for the validation of the daily mean CM SAF CLARA-A3 SIS data set. The bias is slightly positive consistent with the result from the monthly mean analysis. The absolute bias is below the threshold of 18 W/m². Less than 20 % of the daily mean values deviate to more than 28 W/m² (corresponding to the threshold accuracy plus uncertainty of the surface measurements) from the reference data set. Figure 4-5 presents more detailed results from the validation of the daily-averaged CM SAF SIS CLARA-A3 data set for each of the 64 BSRN surface stations. The results of the station-by-station daily validation analysis correspond to analysis of the monthly accuracy of the CLARA-A3 SIS data record.

Overall the accuracy of the daily mean CM SAF CLARA-A3 SIS data set fulfils the accuracy requirement as stated in the PRD [AD 1].

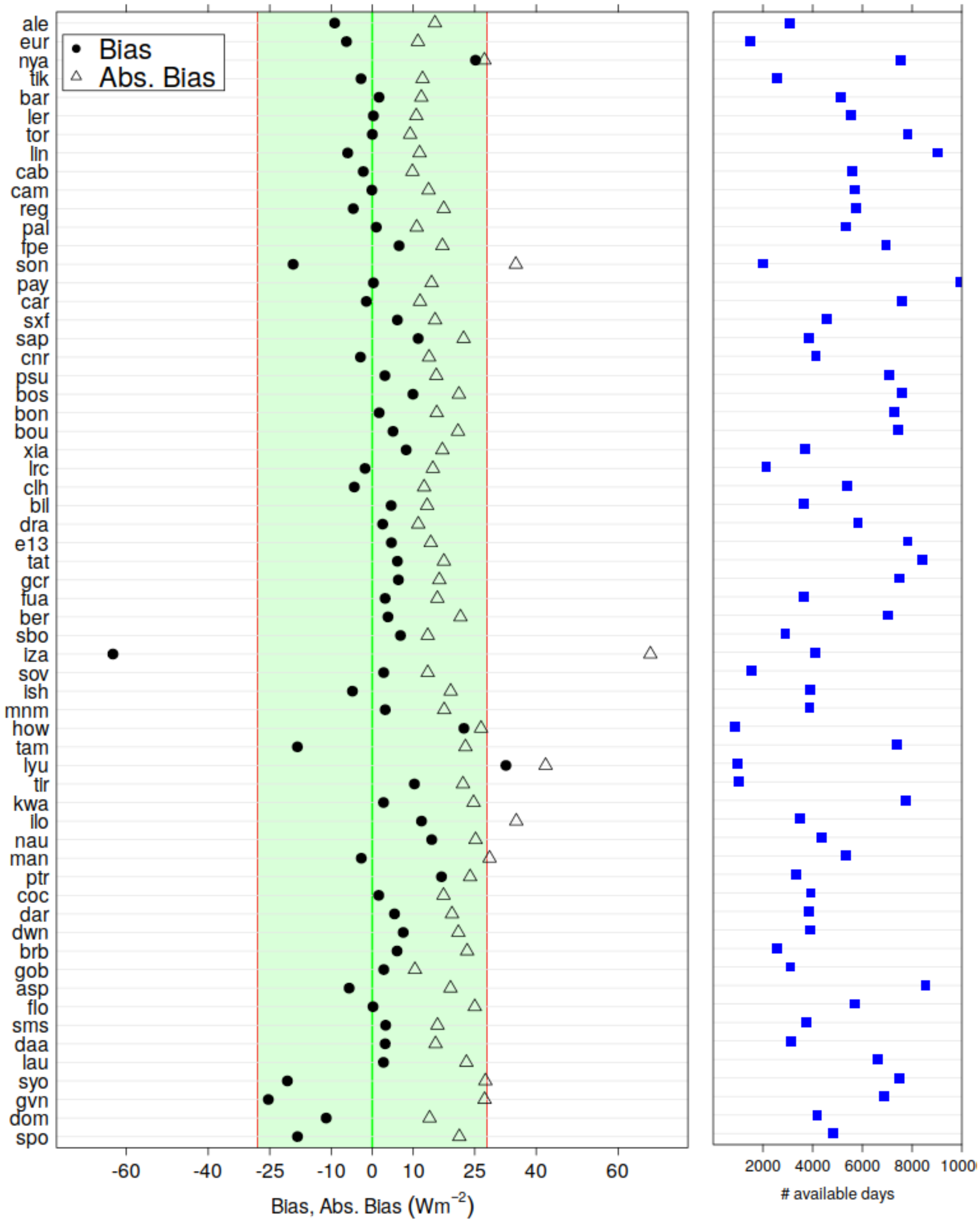

Figure 4-7: Stationwise validation results for the daily mean CMSAF CLARA-A3 SIS data set. Shown are the bias (filled dots) and the absolute bias (triangle) of the daily mean SIS data from the CM SAF CLARA-A3 data set compared to the BSRN surface measurements. The station names are listed north-to-south and named according to their BSRN-label (see http://www.bsrn.awi.de/). The area between the red lines marks the threshold accuracy including the uncertainty of the surface observations. The number of available daily data for the evaluation is shown in the right part of the Figure.

4.3 SDL Validation

The validation of the monthly mean surface downwelling longwave radiation is done by comparison with surface measurements obtained within the BSRN network. In total, data from 65 stations are used for the validation. An altitudinal correction of has been applied to account for differences in elevation between the satellite data set and the reference data. The validation results are shown in Table 4.

Table 4: Validation results for the monthly averaged CM SAF CLARA-A3 SDL data set compared to BSRN surface measurements; the second row provides the mean validation results averaged over each station; also included are the results from the CLARA-A1 (predecessor of CLARA-A2.1) SDL data record and from the ERA-Interim reanalysis.

Data set	Analyzed Months / Stations	Bias (W/m^2)	Abs. bias (W/m^2)	Std.Dev (W/m^2)	Corr. Ano	Frac. Month > target	Frac. Month > threshold
SDL, A3	9530	-5.8	7.2	7.1	0.9	24.6 (10 W/m^2)	13.3 (13 W/m^2)
	55	-7.0	8.6	5.3			
SDL, A2.1	10.653	-4.1	7.9	10.1	0.84	13.8 (15 W/m^2)	6.7 (20 W/m^2)
SDL, A2	7302	-4.7	7.9	9.4	0.84	13.7	6.1
SDL, A1	5314	-3.7	8.3	10.4	0.82	16.5	7.4

The bias of the CM SAF CLARA-A3 SDL data set is slightly negative (−5.8 W/m^2), the absolute bias is within the threshold accuracy of 8 W/m2 [AD 1], showing the high quality of the CM SAF CLARA-A3 SDL data set. Less than 25 % of the available monthly mean values exceed the target accuracy, considering an uncertainty of the monthly-averages derived from the surface observations of 5 W/m^2. The comparison with the previous versions of the CM SAF SDL CLARA data record show substantial improvements in the absolute bias and the correlation of the anomalies, while the bias of the CLARA-A3 SDL data record is slightly more negative than previous versions of the CLARA SDL data record. This enhanced underestimation likely is associated with the use of ERA-5 in the generation of CLARA-A3, which had been found to underestimate surface measurements [Tang et al., 2021]. The climatological average (1991 – 2020) of the surface downwelling longwave radiation derived from CLARA-A3 is about 1 W/m^2 larger than the corresponding average estimated directly from ERA5 (340.8 W/m^2 vs 339.8 W/m^2), indicating that the CLARA-A3 data record has a slightly less negative bias than the ERA5 data record.

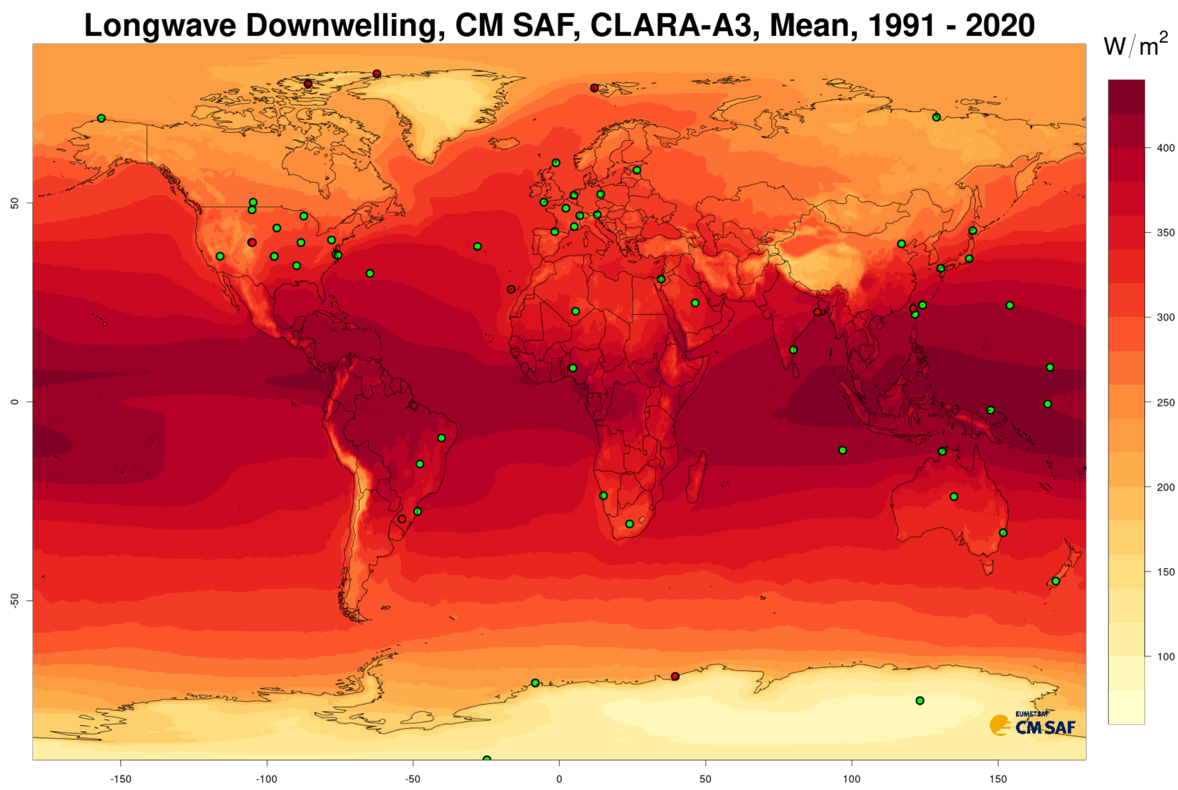

Figure 4-8: Multi-year mean of the CMSAF CLARA-A3 SDL data set. Green dots correspond to BSRN surface stations, where the CM SAF CLARA-A3 SDL data set fulfils the accuracy requirements.

The spatial distribution of the surface stations used for the validation are shown in

Figure 4-8 together with the multi-year mean of the CM SAF CLARA-A3 SDL data set. For 55 out of the 65 stations the quality of the CM SAF CLARA-A3 SDL data set is within the target accuracy; only at 10 stations the threshold accuracy is not reached.

Figure 4-9 presents more detailed results from the validation (bias and absolute bias) of the CM SAF SDL CLARA-A3 data set for each of the 65 BSRN surface stations. Based on the results presented here, we conclude that the monthly mean CM SAF CLARA A3 SDL data record is within the target accuracy as defined in the PRD [AD 1]

The stability of the CLARA-A3 SDL climate data record is demonstrated by a low trend (- 0.17 W/m^2/decade, i.e., well below the threshold requirement) in the normalized bias between CLARA-A3 SDL and corresponding BSRN station data (see

Figure 4-10). Only months with more than 10 valid data points are considered for the estimation of the mean normalized bias.

Figure 4-11 shows that the decadal trends of the CM SAF CLARA-A3 SDL data are very comparable to the trends derived from the data collected at the individual BSRN stations with the range of uncertainty. Only at 4 stations the trend in the bias between the CLARA-A3 SDL data and the BSRN measurements exceeds the threshold requirement.

Figure 4-12 presents the histograms of the decadal trends derived from the BSRN measurements and the CM SAF CLARA-A3 SDL data record at the selected locations. Both data records yield positive decadal trends for most stations with median trends of 1.52 W/m^2/dec and 1.87 W/m^2/dec for the surface measurements and the CLARA-A3 data record, respectively. The variability of the trends is slightly smaller for the CLARA-A3 data record.

Overall, we conclude that the CM SAF CLARA-A3 SDL data record fulfils the accuracy and stability requirements.

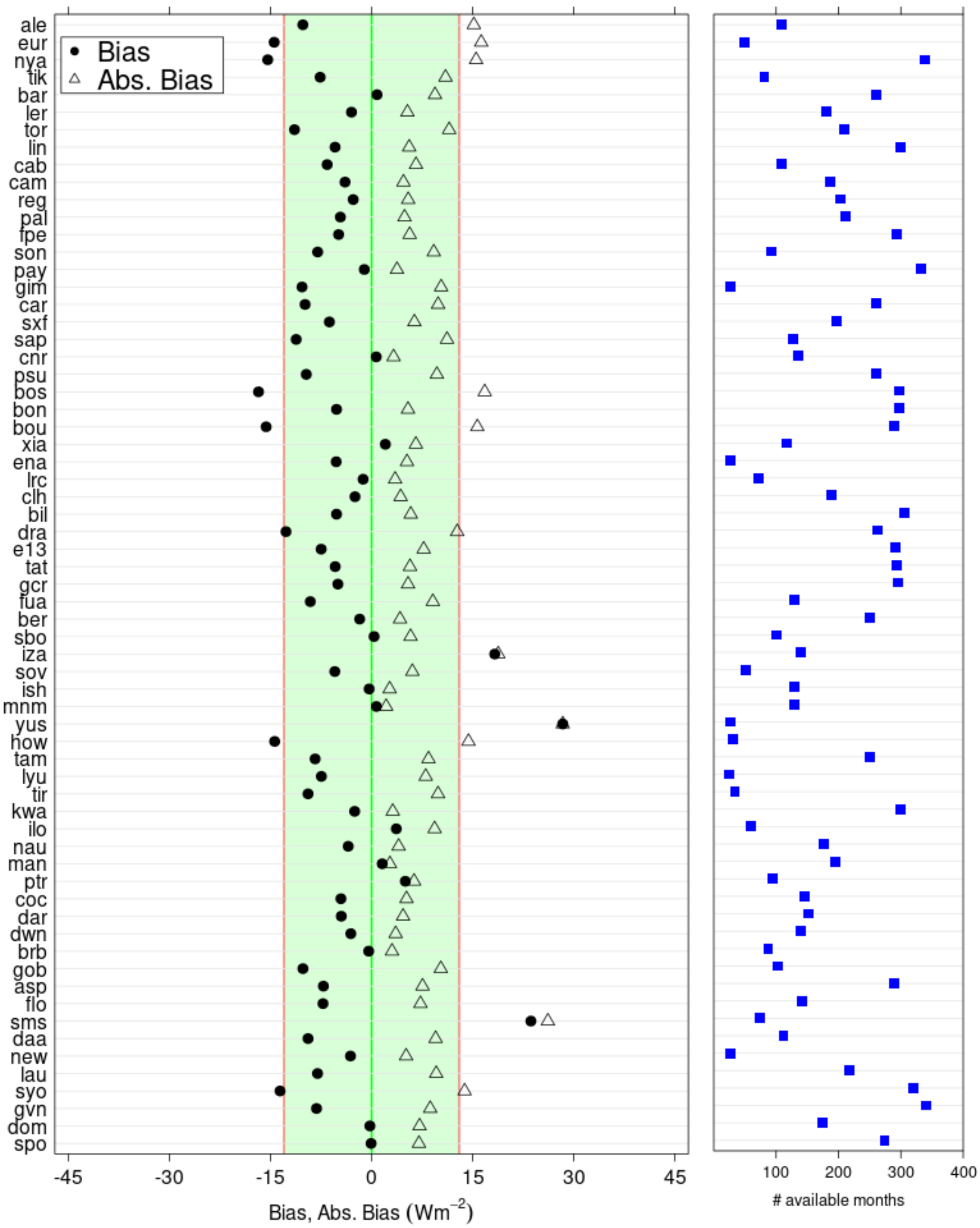

Figure 4-9: Stationwise validation results for the monthly mean CMSAF CLARA-A3 SDL data set. Shown are the bias (filled dots) and the absolute bias (triangle) of the monthly mean SDL data from the CM SAF CLARA A3 data set compared to the BSRN surface measurements. The station names are

listed north-to-south and named according to their BSRN-label (see http://www.bsrn.awi.de/). The green area marks the threshold accuracy including the uncertainty of the surface observations. The number of available monthly data for the evaluation is shown in the right part of the Figure.

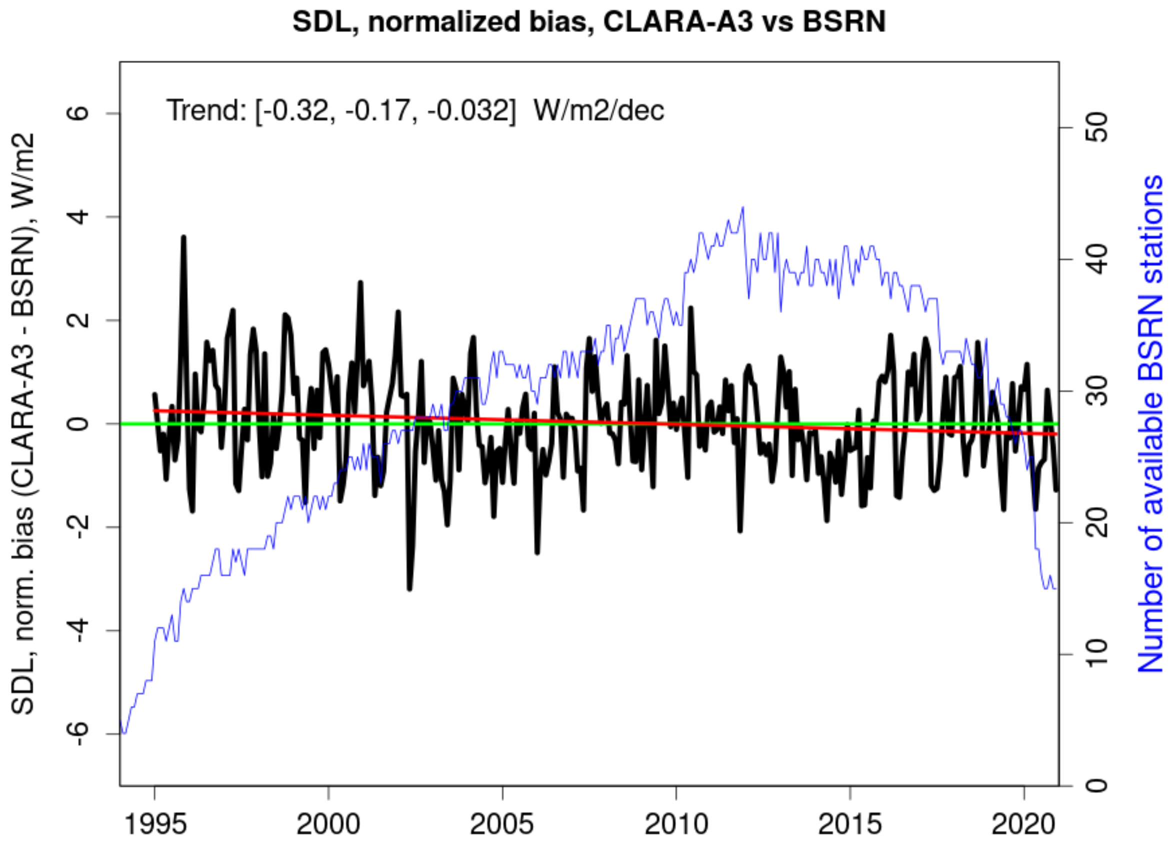

Figure 4-10: Temporal evolution of the normalized bias between the CM SAF CLARA-A3 SDL climate data record and the BSRN surface measurements. The decadal linear trend as well as the 95%-confidence levels are also provided. The blue line represents the number of available monthly data in the calculation of the bias (right scale).

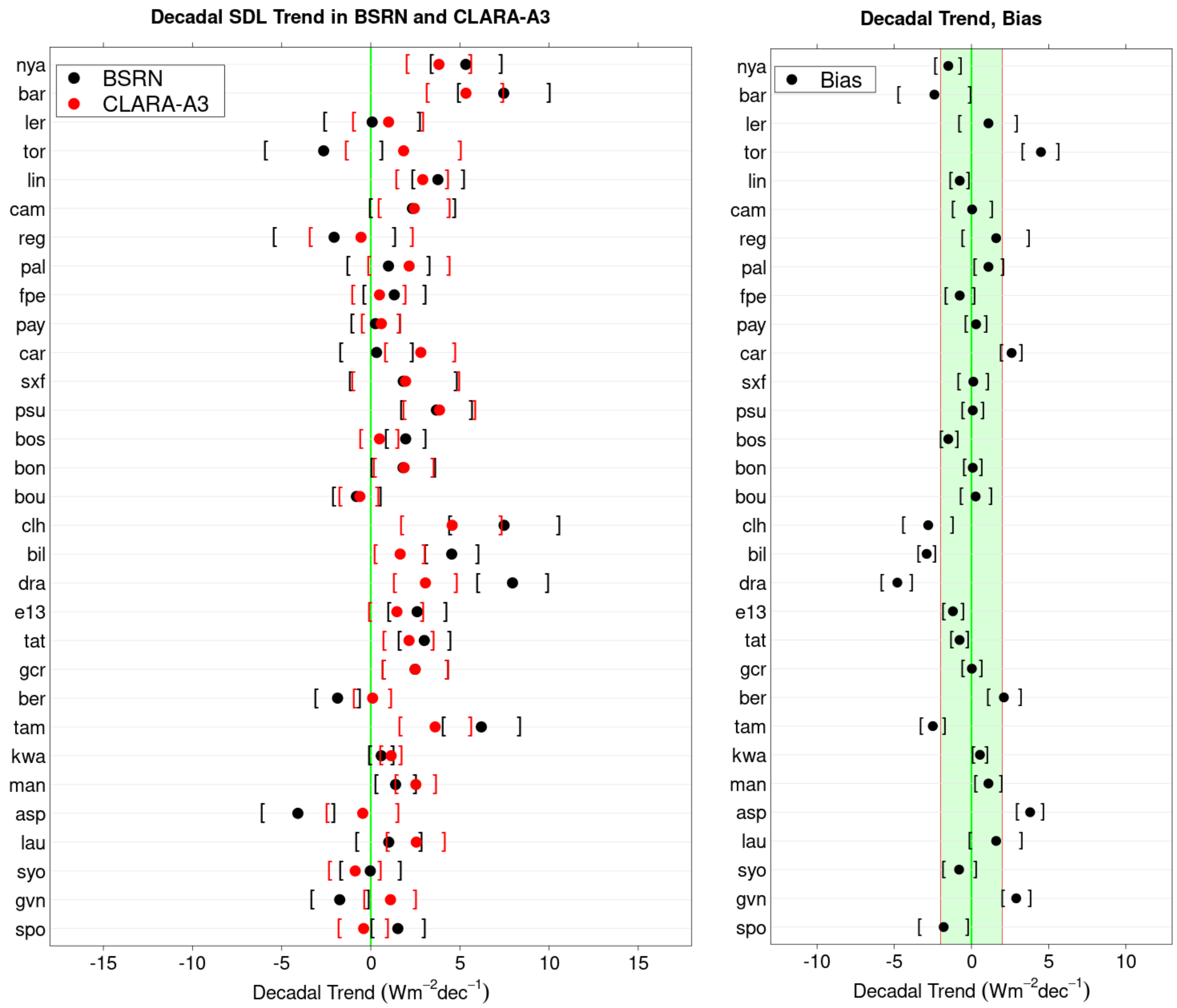

Figure 4-11: (left) Comparison of decadal trends of CM SAF CLARA-A3 SDL climate data record and BSRN surface measurements at BSRN sites with at least 15 years of data. The brackets indicate the 95%-confidence level of the linear decadal trend. . (right) Decadal trend of the bias between CLARA-A3 SIS and the BSRN data. The brackets indicate the 95%-confidence level of the linear decadal trend. The green region indicates the threshold requirement.

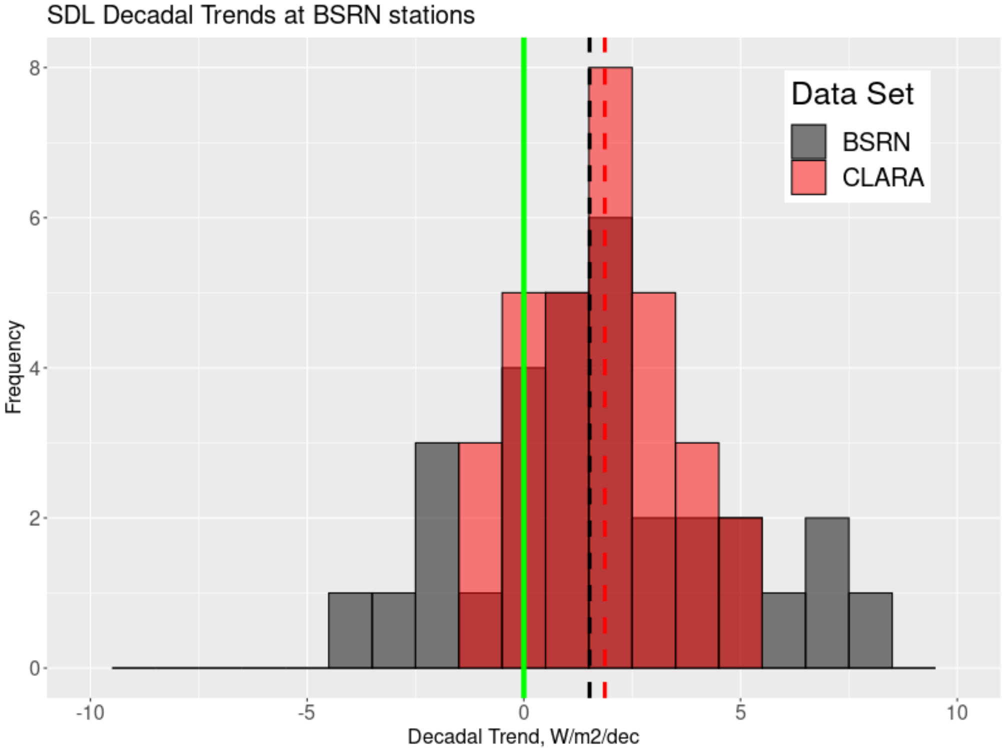

Figure 4-12: Histogram of the decadal trends of surface downwelling longwave radiation derived from the BSRN measurements at the selected locations (see Figure 4-11) and the CM SAF CLARA-A3 SDL data record. The dashed lines indicate the median trend of the distributions; the green line indicates the zero trend.

4.4 SNS Validation

The validation of the monthly mean surface net shortwave radiation is performed by comparison with surface measurements obtained within the BSRN network. In total, data from 27 stations are used for the validation. The validation results are shown in Table 5.

Table 5: Validation results for the monthly averaged CM SAF CLARA-A3 SNS data set compared to BSRN surface measurements; the second row provides the mean validation results averaged over each station.

Data set	Analyzed Months / Stations	Bias (W/m²)	Abs. bias (W/m²)	Std.Dev (W/m²)	Corr. Ano	Frac. Month > target	Frac. Month > threshold
SNS, A3	2165	9.5	10.8	9.2	0.89	48.3 (10 W/m²)	33.9 (13 W/m²)
	13	8,5	10.0	8,1			

The bias of the CM SAF CLARA-A3 SNS data set is positive (9.5 W/m²), the absolute bias (10.8 W/m²) is a bit larger than the threshold accuracy of 8 W/m2 [AD 1], but still appears reasonable, also considering the difficulty in comparing spatially-averaged and locally-measured reflected solar radiation. About 1/3 of the available monthly mean values exceed the threshold accuracy, considering an uncertainty of 5 W/m^2 for the monthly-averages data derived from surface observations.

The spatial distribution of the surface stations used for the validation are shown in

Figure 4-13 together with the multi-year mean of the CM SAF CLARA-A3 SNS data set. For 13 out of the 23 stations the quality of the CM SAF CLARA-A3 SNS data set is within the threshold accuracy; at 10 stations the threshold accuracy is not reached. Figure 4-14 presents more detailed results from the validation (bias and absolute bias) of the CM SAF SNS CLARA-A3 data set for each of the 23 BSRN surface station.

The positive bias between the CLARA-A3 SNS data record and the surface reference measurements is unlikely to be explained alone by the spatial mismatch of reflected (and, subsequently, net) solar radiation from gridded data and local measurements. Additional, possibly systematic, errors may be introduced by using the 5-day mean albedo based on derived instantaneous albedo estimates, which do not cover the full diurnal cycle of solar zenith angles.

Overall, we conclude that, despite the deviations that partly exceed the predefined threshold accuracy, the monthly mean CM SAF CLARA-A3 SNS data record can be considered to be in line with the requirements as defined in the PRD [AD 1]

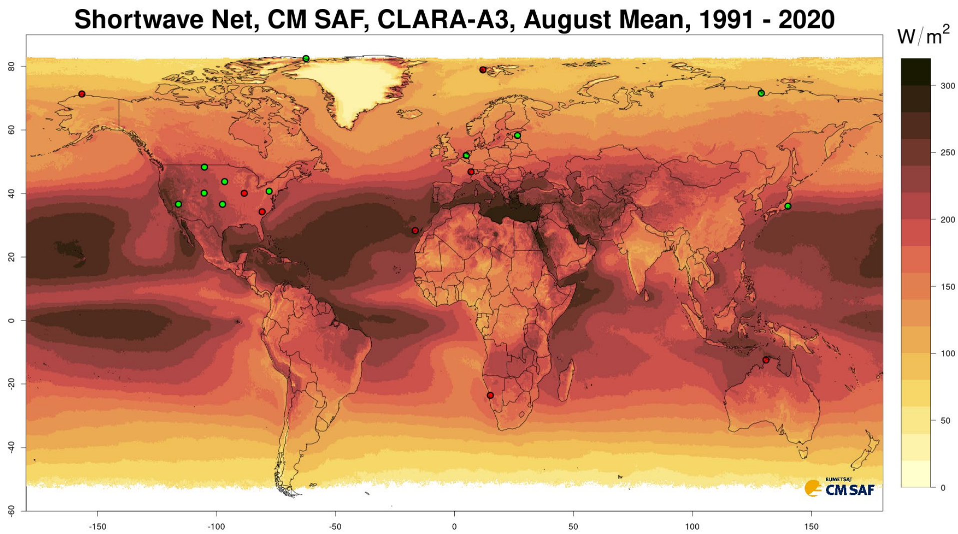

Figure 4-13: Multi-year mean of the CM SAF CLARA-A3 SNS data set for August. Green dots correspond to BSRN surface stations, where the CM SAF CLARA-A3 SNS data set fulfils the threshold accuracy requirements. Only stations with at least 24 months of valid data are shown.

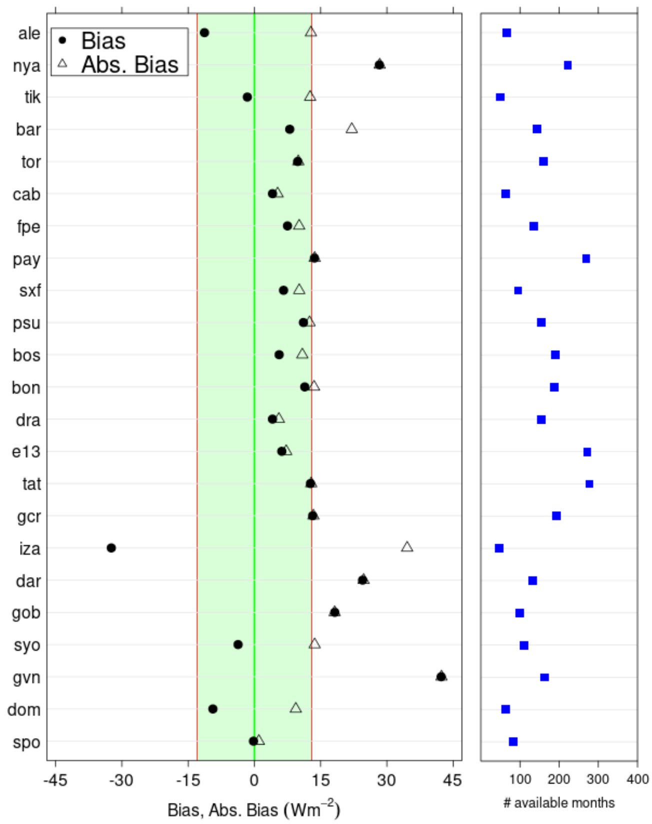

Figure 4-14: Stationwise validation results for the monthly mean CMSAF CLARA-A3 SNS data set. Shown are the bias (filled dots) and the absolute bias (triangle) of the monthly mean SNS data from the CM SAF CLARA A3 data set compared to the BSRN surface measurements. The green area marks the threshold accuracy including the uncertainty of the surface observations. The number of available monthly data for the evaluation is shown in the right part of the Figure. Note that for some stations the bias and the absolute bias are (almost) identical; for these stations the triangle, representing the absolute bias, is difficult to identify in the figure.

4.5 SNL Validation

The validation of the monthly mean surface net longwave radiation is performed by comparison with surface measurements obtained within the BSRN network. In total, data from 26 stations are used for the validation. The validation results are shown in Table 6.

Table 6: Validation results for the monthly averaged CM SAF CLARA-A3 SNS data set compared to BSRN surface measurements.; the second row provides the mean validation results averaged over each station.

Data set	Analyzed Months / Stations	Bias (W/m^2)	Abs. bias (W/m^2)	Std.Dev (W/m^2)	Corr. Ano	Frac. Month > target	Frac. Month > threshold
SNL, A3	2363	-4.3	6.8	7.1	0.84	23.5 (10 W/m^2)	10.5 (13 W/m^2)
	13	-4.3	6.9	5.6			

The bias of the CM SAF CLARA-A3 SNL data set is negative (-4.3 W/m^2), the absolute bias (6.8 W/m^2) is below the threshold accuracy of 8 W/m2 [AD 1]. Less than 25% of the available monthly mean values exceed the target accuracy, considering an uncertainty of 5 W/m^2 for the monthly-averages data derived from surface observations.

The spatial distribution of the surface stations used for the validation are shown in Figure 4-15 together with the multi-year August mean of the CM SAF CLARA-A3 SNL data set. For 19 out of the 23 stations the quality of the CM SAF CLARA-A3 SNL data set is within the threshold accuracy; only at 4 stations the threshold accuracy is not reached. Figure 4-16 presents more detailed results from the validation (bias and absolute bias) of the CM SAF SNL CLARA-A3 data set for each of the 23 BSRN surface station.

Despite the fundamental limitations when comparing upward (and, subsequently, net) radiation from gridded data and local measurements, e.g., due to the reduced spatial representativity of the surface emissivity, this evaluation results in an agreement between the CM SAF CLARA-A3 SNL data record and the surface measurements within the threshold requirements. Thus, we conclude that the monthly mean CM SAF CLARA A3 SNL data record can be considered to be in line with the requirements as defined in the PRD [AD 1]

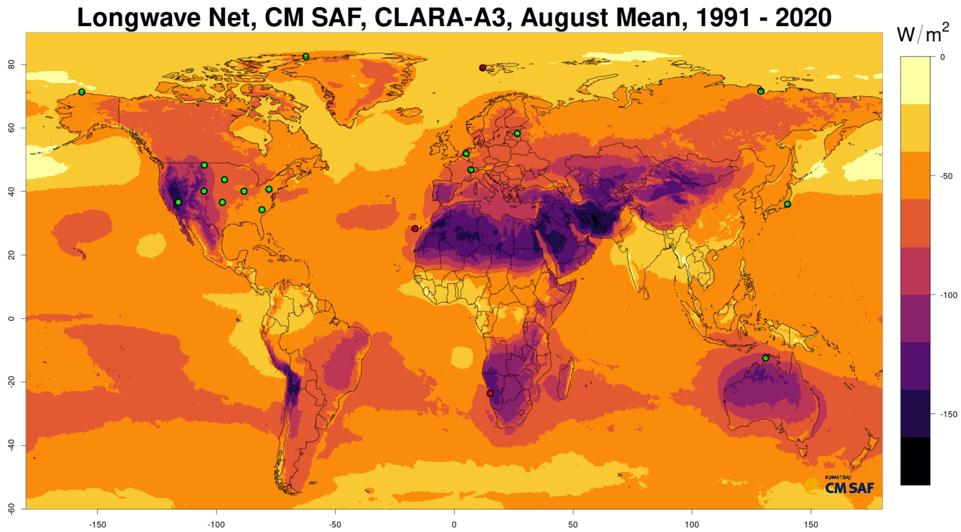

Figure 4-15: Multi-year mean of the CM SAF CLARA-A3 SNL data set for August. Green dots correspond to BSRN surface stations, where the CM SAF CLARA-A3 SNL data set fulfils the threshold accuracy requirements. Only stations with at least 24 months of valid data are shown.

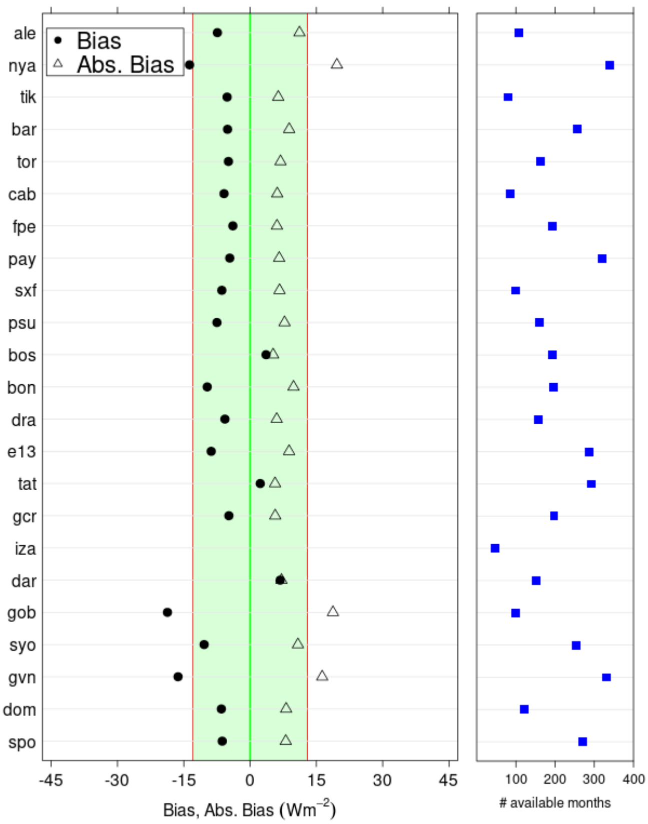

Figure 4-16: Stationwise validation results for the monthly mean CMSAF CLARA-A3 SNL data set. Shown are the bias (filled dots) and the absolute bias (triangle) of the monthly mean SNL data from the CM SAF CLARA A3 data set compared to the BSRN surface measurements. The green area marks the threshold accuracy including the uncertainty of the surface observations. The number of available monthly data for the evaluation is shown in the right part of the Figure.

4.6 SRB Validation

The validation of the monthly mean surface radiation budget is performed by comparison with surface measurements obtained within the BSRN network. In total, data from 26 stations are used for the validation. The validation results are shown in Table 7.

Table 7: Validation results for the monthly averaged CM SAF CLARA-A3 SRB data set compared to BSRN surface measurements; the second row provides the mean validation results averaged over each station.

Data set	Analyzed Months / Stations	Bias (W/m^2)	Abs. bias (W/m^2)	Std.Dev (W/m^2)	Corr. Ano	Frac. Month > target	Frac. Month > threshold
SRB, A3	2072	5.4	9.7	11.3	0.64	39.1 (10 W/m^2)	28.3 (13 W/m^2)
	13	4.6	8.9	9.3			

The bias of the CM SAF CLARA-A3 SRB data set is positive (5.4 W/m^2), the absolute bias (9.7 W/m^2) is larger than the threshold accuracy of 8 W/m^2 [AD 1], still appears reasonable, considering the difficulty in comparing spatially-averaged and locally-measured reflected / emitted radiation. Less than 30 % of the available monthly mean values exceed the threshold accuracy, considering an uncertainty of 5 W/m^2 for the monthly-averages data derived from surface observations.

The spatial distribution of the surface stations used for the validation are shown in Figure 4-17 together with the multi-year August mean of the CM SAF CLARA-A3 SRB data set. For 13 out of the 23 stations the quality of the CM SAF CLARA-A3 SRB data set is within the threshold accuracy; at 10 stations the threshold accuracy is not reached. Figure 4-18 presents more detailed results from the validation (bias and absolute bias) of the CM SAF SRB CLARA-A3 data set for each of the 23 BSRN surface station.

Considering the fundamental limitations when comparing reflected (and, subsequently, net) radiation from gridded data and local measurements (e.g, limitations in the spatial representativeness of surface albedo and emissivity) we conclude that, despite the deviations that partly exceed the predefined threshold accuracy, the monthly mean CM SAF CLARA A3 SRB data record can be considered to be in line with the requirements as defined in the PRD [AD 1]

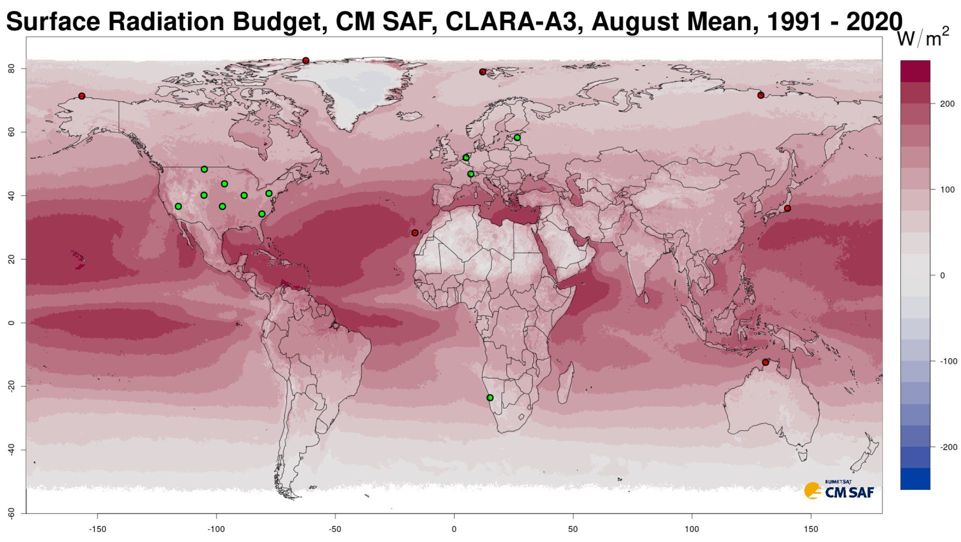

Figure 4-17: Multi-year mean of the CM SAF CLARA-A3 SRB data set for August. Green dots correspond to BSRN surface stations, where the CM SAF CLARA-A3 SRB data set fulfils the threshold accuracy requirements. Only stations with at least 24 months of valid data are shown.

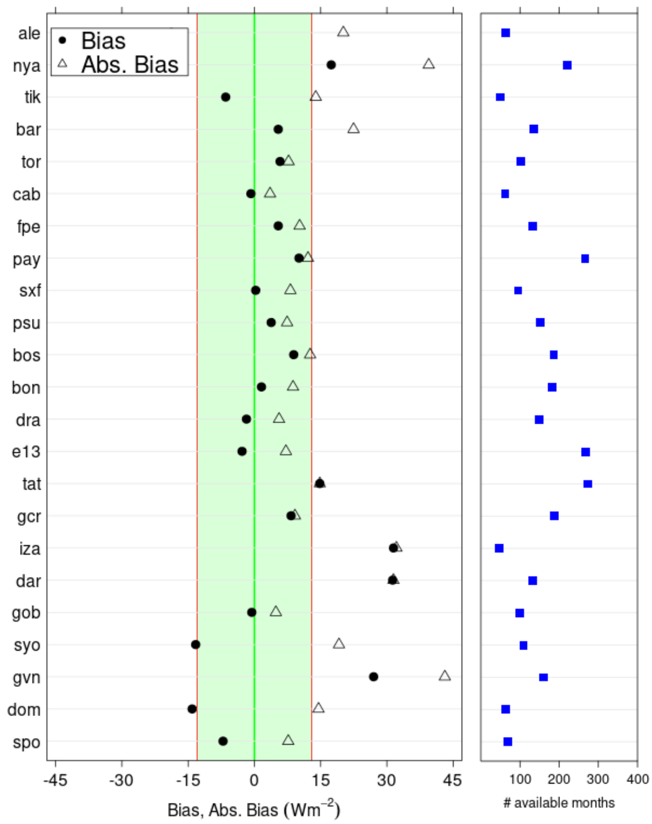

Figure 4-18: Stationwise validation results for the monthly mean CMSAF CLARA-A3 SRB data set. Shown are the bias (filled dots) and the absolute bias (triangle) of the monthly mean SRB data from the CM SAF CLARA A3 data set compared to the BSRN surface measurements. The green area marks the threshold accuracy including the uncertainty of the surface observations. The number of available monthly data for the evaluation is shown in the right part of the Figure.

4.7 Evaluation of ICDR products

The evaluation of the ICDR data records is performed by comparison of the data generated from the operational ICDR processing chain to corresponding data from the CDR. To establish such an intercomparison the ICDR processing chain was used to generate the ICDR data from July to December 2020. In contrast to the CDR data processing, data from the AVHRR instrument onboard the Metop-C satellite have not been used for the processing of the CLARA-A3 ICDR data record due to the large uncertainty of the time-dependent calibration coefficient of this instrument beyond 2020.

Figure 4-19 shows the bias between the monthly mean surface irradiance (SIS) data record as generated using the CLARA-A3 ICDR operational processing for July to December 2020 and the corresponding data from the CLARA-A3 CDR data record. In general the bias is small; the bias is largest in the Southern Hemisphere, in particular in Antarctica and the neighbouring sea ice areas, likely due to a slightly different sensitivity of cloud detection and assumed surface albedo as well as the exclusion of data from the Metop-C satellite. The bias of the daily mean SIS data is comparable and not shown here.

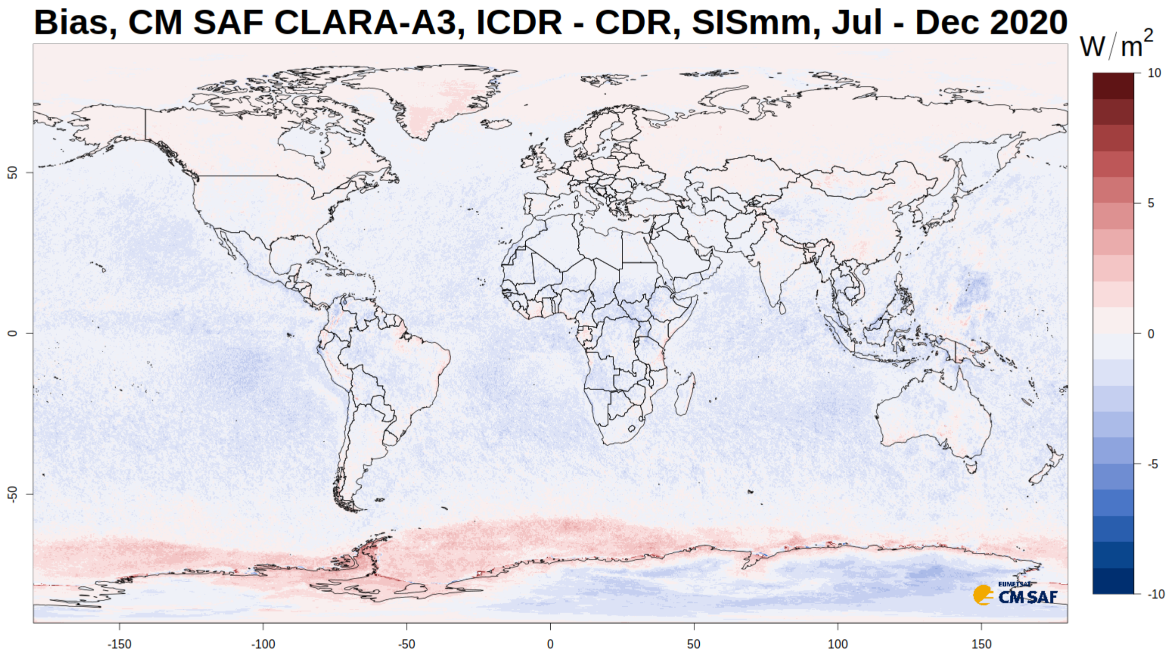

Figure 4-19: Bias of the monthly mean surface irradiance (SIS) data records from the CLARA-A3 CDR and the corresponding data generated using the CLARA-A3 ICDR operational processing environment from July to December 2020.

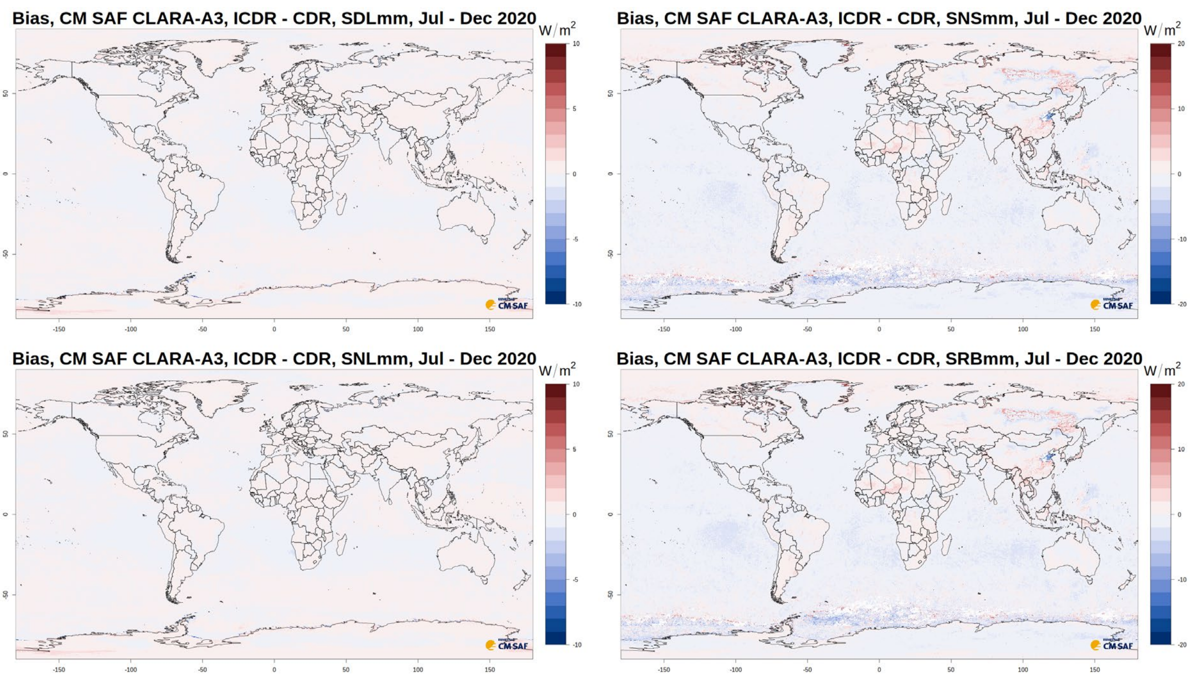

Figure 4-20: Bias of the monthly mean (top, left) surface downwelling radiation (SDL), (top, right) surface net shortwave, (bottom, left) surface net longwave, and (bottom, right) surface radiation budget data records from the data generated using the CLARA-A3 ICDR operational processing environment and the CLARA-A3 CDR from July to December 2020.

Figure 4-20 presents the biases of the monthly mean surface radiation parameters (SDL, SNS, SNL, and SRB) between the data generated with the operational processing chain used to generate the CLARA-A3 ICDR and the CLARA-A3 CDR data records between July and December 2020. For the longwave data (SDL, SNL) the bias is very small due to the excellent correspondence between ERA5 and the ERA5T data record used to estimate the CLARA-A3 ICDR longwave data record. Some differences can be seen for the net shortwave radiation along the polar Antarctic Ice Shield and in Siberia due to differences in the sea ice information and surface albedo retrieval, respectively. These differences translate into corresponding biases in the surface radiation budget. Overall, we consider the documented biases to be small.

Figure 4-21 shows the spatial distribution of the mean absolute bias of the differences between the surface radiation parameters as derived from the operational processing environment used to generate the CLARA-A3 ICDR and the corresponding data from the CLARA-A3 CDR from July to December 2020. As already documented in the analysis of the bias, the longwave radiation components are very similar in both data records, while the absolute bias of the shortwave radiation components shows some larger values (in the order of 10 W/m^2), in particular in Antarctica (SIS) and the Antarctic Ice Shield and Siberian (SNS), which transfer into corresponding values of the absolute bias in the surface radiation budget (SRB). Largest absolute biases can be seen in the daily mean surface irradiance, in particular in areas with large variability, e.g., the Western Pacific, where the exclusion of data from the Metop-C satellite in the ICDR data processing enhances the deviations between the CDR and the ICDR data records. For most grid boxes, however, the absolute bias is well below the threshold accuracy of the CDR (see Table 1).

Figure 4-22 shows the spatial distribution of the fraction of available time steps exceeding the corresponding threshold accuracy in the absolute difference between the data derived from the CLARA-A3 ICDR processing environment and the CDR data record between July and December 2020. Only in very few regions differences between the two data records exceeding the threshold accuracy for monthly data. The threshold accuracy is exceeded for more than 15 % of the daily surface irradiance data in areas with large daily variability, i.e, the Western Pacific, likely due to the reduced availability of data from excluding the data of the Metop-C satellite. Even in these regions, however, the monthly data of the surface irradiance are within the threshold accuracy. It is worth noting that the expected atmospheric anomalies in the shortwave and longwave surface radiation typically well exceed the corresponding threshold accuracy. Hence, such anomalies will still be detectable by comparison of the climatology based on the CLARA-A3 CDR and the ICDR data records.

Overall, we conclude that the CLARA-A3 ICDR data record is in line with the corresponding CM SAF requirements. It must be noted, however, that the calibration of the satellite data impacts the quality and the stability of CLARA-A3 ICDR data records. Current calibration coefficients for the AVHRR instruments are based on data until 2017; a degrade in the calibration quality is expected over time. New calibration coefficients are expected to be available and applied to the CLARA-A3 ICDR data records in late 2023, which are expected to also allow the use of AVHRR data from Metop-C for the generation of the CLARA-A3 data record; an impact on the accuracy and stability of the ICDR is expected. Regular assessments of the data quality of the CLARA-A3 ICDR data records are provided in the CM SAF Annual Quality Assessment Report (AQA)

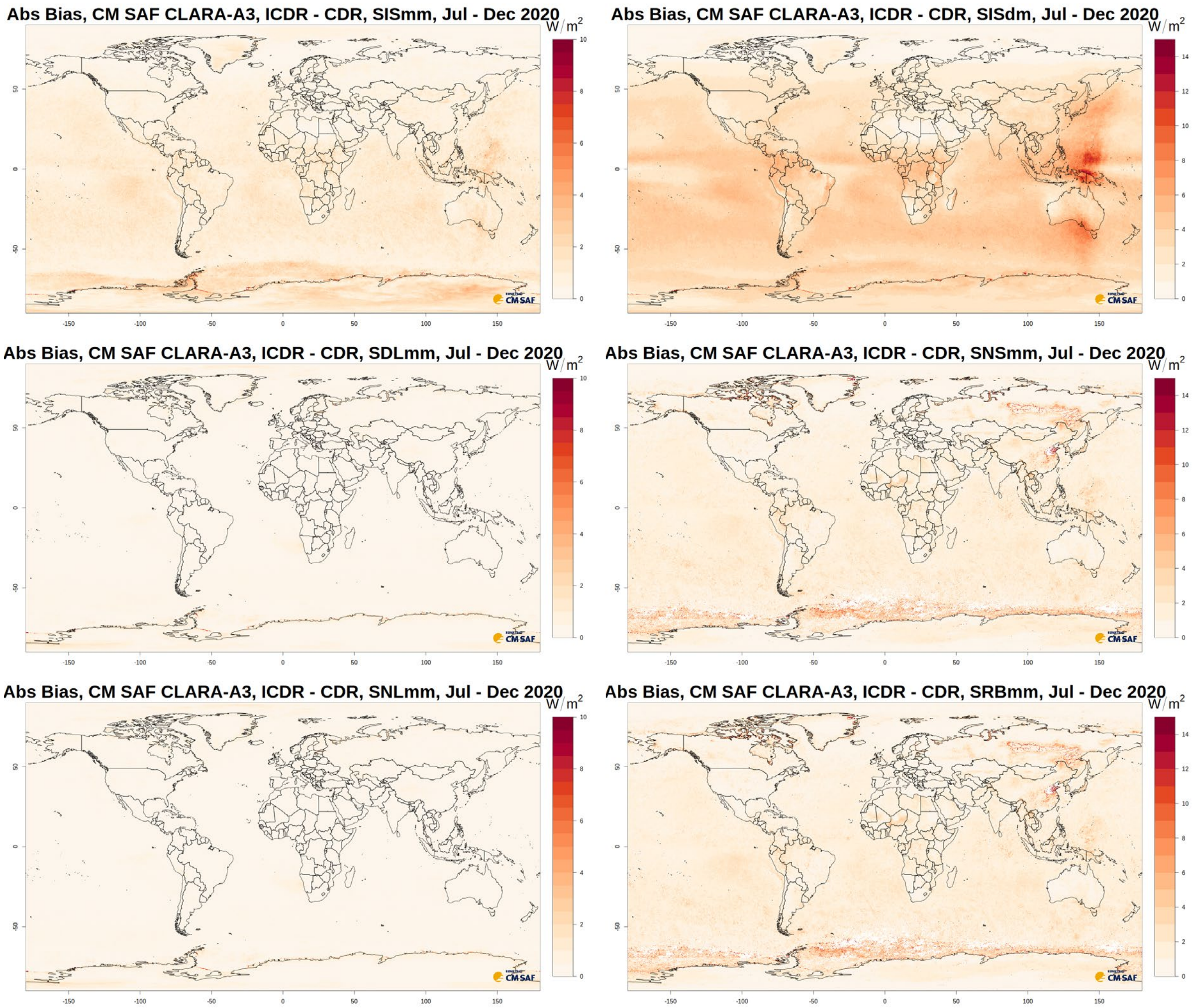

Figure 4-21: Mean absolute bias of (top, left) the monthly surface incoming shortwave (SIS), (top, right) the daily surface incoming shortwave (SISdm), (center, left) the surface downwelling longwave, (center, right) the surface net shortwave, (bottom, left) the surface net longwave, and (bottom, right) the surface radiation budget data records from the data generated using the CLARA-A3 ICDR operational processing environment and the CLARA-A3 CDR from July to December 2020.

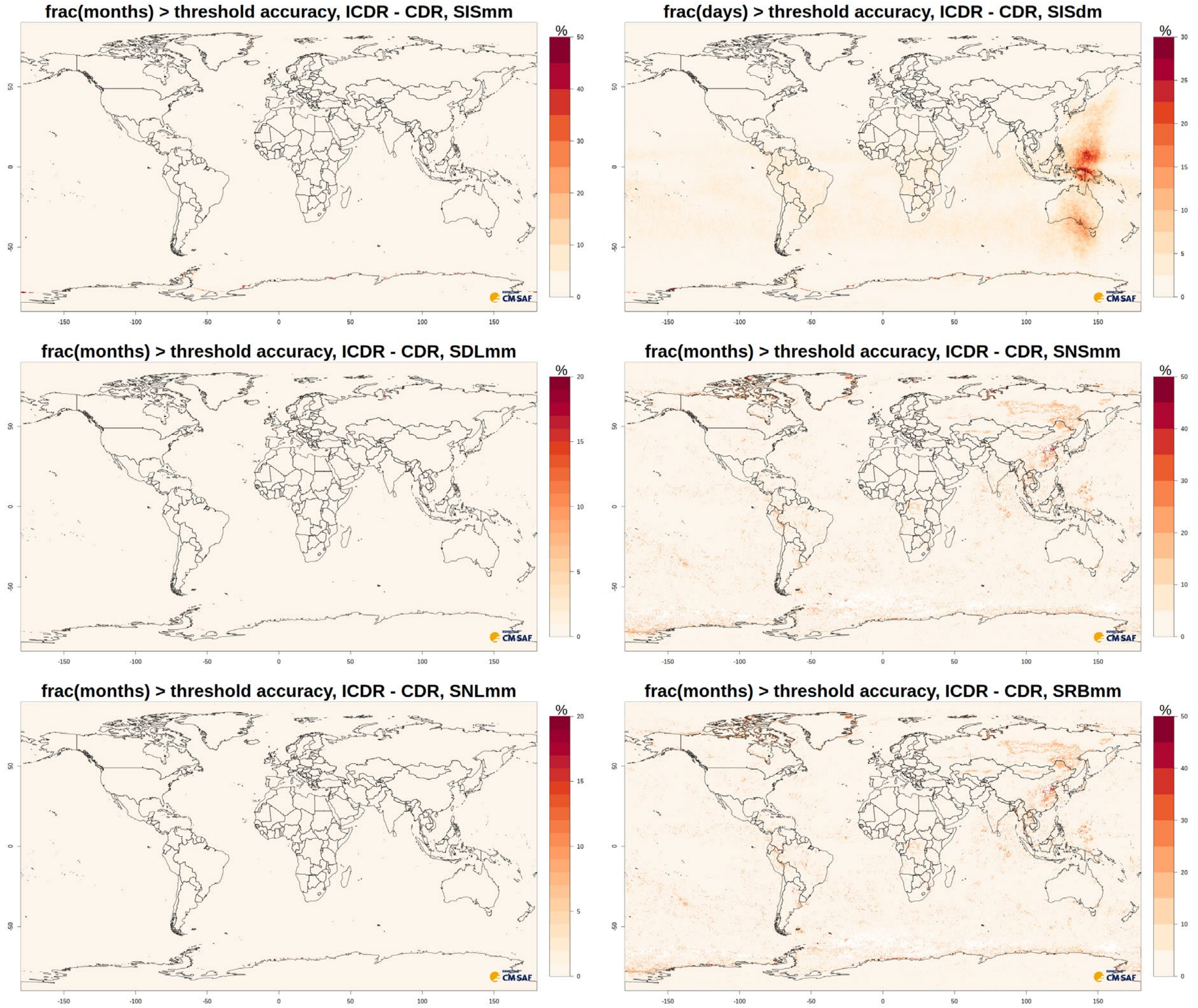

Figure 4-22: The fraction of available time steps (i.e., months / days) in which the absolute difference between the data from the CLARA-A3 ICDR processing and the CLARA-A3 CDR exceeds the threshold accuracy for (top, left) the monthly surface incoming shortwave, (top, right) the daily surface incoming shortwave, (center, left) the surface downwelling longwave, (center, right) the surface net shortwave, (bottom, left) the surface net longwave, and (bottom, right) the surface radiation budget data records.

5 Conclusions

We presented the validation of the CM SAF CLARA-A3 Surface Radiation data sets based on the requirements as defined in the CM SAF PRD [AD 1]. All data records fulfil or are in line at least with the threshold accuracy requirements.

The suitability of these data sets for climate applications depends strongly on the specific application. The general accuracy of the data sets has been shown by validation with reference measurements and by uncertainty assessments. The data record of the surface downwelling solar radiation (SIS) has been shown to have a high quality and is mainly derived from satellite observations. The quality assessment of the surface net shortwave data has identified larger deviations from the BSRN reference measurements, but this assessment is limited by the fundamental difficulty of comparing gridded data with local measurements. The quality of the longwave surface fluxes is in general within the expectations, however, these data sets use substantial information from reanalysis and should not be used for the validation of reanalysis and other model-derived data sets.

6 References

Immler, F. J., Dykema, J., Gardiner, T., Whiteman, D. N., Thorne, P. W., and Vömel, H. (2010), Reference Quality Upper-Air Measurements: guidance for developing GRUAN data products, Atmos. Meas. Tech., 3, 1217–1231, https://doi.org/10.5194/amt-3-1217-2010, 2010.

Nyeki, S., Wacker, S., Gröbner, J., Finsterle, W., and Wild, M. (2017), Revising shortwave and longwave radiation archives in view of possible revisions of the WSG and WISG reference scales: methods and implications, Atmos. Meas. Tech., 10, 3057–3071, https://doi.org/10.5194/amt-10-3057-2017

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

Roesch, A., M. Wild, A. Ohmura, E. G. Dutton, C. N. Long, and T. Zhang (2011), Assessment of BSRN radiation records for the computation of monthly means, Atmospheric Measurement Techniques, 4(2), 339-354.

Tang, W., J. Qin, K. Yang, F. Zhu, X. Zhou (2021), Does ERA5 outperform satellite products in estimating atmospheric downward longwave radiation at the surface?, Atmospheric Research (252), 105453, https://doi.org/10.1016/j.atmosres.2021.105453.

Urraca R, Lanconelli C, Cappucci F, Gobron N. (2022a) Comparison of Long-Term Albedo Products against Spatially Representative Stations over Snow. Remote Sensing. 14(15):3745. https://doi.org/10.3390/rs14153745

Urraca R, Lanconelli C, Gobron N (2022b) Closing the uncertainty budget in satellite product validation: a new method to quantify the spatial mismatch error in validations of shortwave incoming irradiance, Poster presented at Metrology for Climate Action Workshop, www.bipmwmo22.org, 26 – 30 September 2022

7 List of BSRN Stations

Short-name	Station	Location	Latitude	Longitude	Elevation (m)	Dwn	Up / meas. height
ALE	Alert	Canada, Lincoln Sea	82.490	-62.420	127	x	
ASP	Alice Springs	Australia, Northern Territory	-23.798	133.888	547	X	
BAR	Barrow	USA , Alaska	71.323	-156.661	8	X	
BER	Bermuda	USA, Bermuda	32.267	-64.667	8	X	
BIL	Billings	USA, Oklahoma	36.605	-97.516	317	X	
BON	Bondville	USA, Illinois	40.067	-88.367	213	x	X 2 m
BOS	Boulder	USA, Colorado	40.125	-105.237	1689	X	X 10 m
BOU	Boulder	USA, Colorado	40.050	-105.007	1577	x	
BRB	Brasilia	Brazil, Brasilia City	-15.601	-47.713	1023	x	
BUD	Budapest-Lorinc	Hungary, Budapest	47.429	19.182	139.1	x	X 2 m
CAB	Cabauw	Netherlands	51.971	4.927	0	x	X 2 m
CAM	Camborne	United Kingdom	50.217	-5.317	88	x	
CAR	Carpentras	France	44.083	5.059	100	x	
CLH	Chesapeake Light	USA, North Atlantic Ocean	36.905	-75.713	37	x	

Short-name	Station	Location	Latitude	Longitude	Elevation (m)	Dwn	Up / meas. height
CNR	Cener	Spain, Navarra	42.816	-1.601	471	x	
COC	Cocos Island	Australia, Cocos (Keeling) Islands	-12.193	96.835	6	x	
DAA	De Aar	South Africa	-30.667	23.993	1287	x	
DAR	Darwin	Australia	-12.425	130.891	30	x	
DOM	Concordia Station, Dome C	Antarctica	-75.100	123.383	3233		
DRA	Desert Rock	USA, Nevada	36.626	-116.018	1007	x	X 10 m
DWN	Darwin Met Office	Australia	-12.424	130.893	32	x	
E13	Southern Great Plains	USA, Oklahoma	36.605	-97.485	318	x	X 10 m
ENA	Eastern North Atlantic	Portugal, Azores	39.091	-28.029	15.2	x	
EUR	Eureka	Canada, Ellesmere Island	79.989	-85.940	85	x	
FLO	Florianopolis	Brazil, South Atlantic Ocean	-27.605	-48.523	11	x	
FPE	Fort Peck	USA, Montana	48.317	-105.100	634	x	X 10 m
FUA	Fukuoka	Japan	33.582	130.376	3	x	
GCR	Goodwin Creek	USA, Mississippi	34.255	-89.873	98	x	X 10 m

Short-name	Station	Location	Latitude	Longitude	Elevation (m)	Dwn	Up / meas. height
GOB	Gobabeb	Namibia, Namib Desert	-23.561	15.042	407	x	
GVN	Georg von Neumayer	Antarctica, Dronning Maud Land	-70.650	-8.250	42		
HOW	Howrah	India	22.554	88.306	51		
ILO	Ilorin	Nigeria	8.533	4.567	350		
ISH	Ishigakijima	Japan	24.337	124.164	5.7	x	
IZA	Izaña	Spain, Tenerife	28.309	-16.499	2372.9		
KWA	Kwajalein	Marshall Islands	8.720	167.731	10	x	
LAU	Lauder	New Zealand	-45.045	169.689	350	x	
LER	Lerwick	United Kingdom, Shetland Island	60.139	-1.185	80	x	
LIN	Lindenberg	Germany	52.210	14.122	125	x	
LRC	Langley Research Center	USA, Virginia	37.104	-76.387	3	x	
LYU	Lanyu Station	Taiwan	22.037	121.558	324		
MAN	Momote	Papua New Guinea	-2.058	147.425	6	x	
MNM	Minamitorishima	Japan, Minami-Torishima	24.288	153.983	7.1	x	
NAU	Nauru Island	Nauru	-0.521	166.917	7	x	
NEW	Newcastle	Australia	-32.884	151.729	18.5	x	

Short-name	Station	Location	Latitude	Longitude	Elevation (m)	Dwn	Up / meas. height
NYA	Ny-Ålesund	Norway, Spitsbergen	78.925	11.930	11		
OHY	Observatory of Huancayo	Peru	-12.050	-75.320	3314		
PAL	Palaiseau, SIRTA Observatory	France	48.713	2.208	156	x	
PAR	Paramaribo	Surinam	5.806	-55.215	4		
PAY	Payerne	Switzer-land	46.815	6.944	491	x	X 2 m
PSU	Rock Springs	USA, Pennsylvania	40.720	-77.933	376	x	X 10 m
PTR	Petrolina	Brazil	-9.068	-40.319	387	x	
REG	Regina	Canada	50.205	-104.713	578	x	
RLM	Rolim de Moura	Brazil	-11.582	-61.773	252	x	
RUN	Reunion Island, University	Reunion	-20.901	55.484	116		
SAP	Sapporo	Japan	43.060	141.329	17.2	x	
SBO	Sede Boqer	Israel	30.860	34.779	500	x	
SEL	Selegua, Mexico Solarimetric Station	Mexico	15.784	-91.990	602	x	
SMS	São Martinho da Serra	Brazil	-29.443	-53.823	489		
SON	Sonnblick	Austria	47.054	12.958	3108.9		
SOV	Solar Village	Saudi Arabia	24.910	46.410	650	x	

Short-name	Station	Location	Latitude	Longitude	Elevation (m)	Dwn	Up / meas. height
SPO	South Pole	Antarctica	-89.983	-24.799	2800		
SXF	Sioux Falls	USA, South Dakota	43.730	-96.620	473	x	X 10 m
SYO	Syowa	Antarctica	-69.005	39.589	18		
TAM	Tamanrasset	Algeria	22.790	5.529	1385	x	
TAT	Tateno	Japan	36.058	140.126	25	x	X 2 m
TIK	Tiksi	Russia, Siberia	71.586	128.919	48	x	
TIR	Tiruvallur	India	13.092	79.974	36	x	
TOR	Toravere	Estonia	58.254	26.462	70	x	X 2 m
XIA	Xianghe	China	39.754	116.962	32	x	
YUS	Yushan Station	Taiwan	23.488	120.960	3858		