EUMETSAT Satellite Application Facility on Climate Monitoring

Validation Report

Meteosat Solar Surface Radiation and Effective Cloud Albedo Climate Data Records

SARAH-3

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	CDR	ICDR
Effective Cloud Albedo (CAL):	**CM-23083**	**CM-5081**
Surface Incoming Shortwave Radiation (SIS):	**CM-23203**	**CM-5211**
Surface Direct Irradiance (SDI):	**CM-23293**	**CM-5291**
Sunshine Duration (SDU):	**CM-23283**	**CM-5281**
Photosynthetic Active Radiation (PAR):	**CM-23273**	**CM-5271**
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Applicable Documents

Reference	Title	Code
AD 1	CM SAF Product Requirement Document	SAF/CM/DWD/PRD/4.1

Reference Documents

Reference	Title	Code
RD 1	Algorithm Theoretical Baseline Document (ATBD) Meteosat Solar Surface Irradiance and effective Cloud Albedo Climate Data records SARAH-3	SAF/CM/DWD/ATBD/METEOSAT/HEL/3.2
RD 2	Product User Manual Meteosat Climate Data Records of Surface Radiation SARAH-3	SAF/CM/DWD/PUM/METEOSAT/HEL/3.0
RD 3	Requirements Review document	SAF/CM/CDOP3/DWD/RR38/1.2

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Executive Summary

The new Solar Radiation Data record – Heliosat Version 3 (SARAH-3) consists of the Solar Surface Irradiance (SIS), two Surface Direct Irradiance (SDI) parameters, the Photosynthetic Active Radiation (PAR), Daylight (DAL), the Effective Cloud Albedo (CAL) and the Sunshine Duration (SDU) and covers the time period 1983-2020. SARAH-3 is based on data from the MVIRI and SEVIRI instruments on board the Meteosat satellite series (from Meteosat-2 to Meteosat-11). All SARAH-3 parameters are validated and the results are shown in this report. The SARAH-3 climate data record has undergone several updates relative to its predecessor. The main improvements are related to the new treatment of snow by using the HELSNOW algorithm, an improved retrieval of sunshine duration and new auxiliary data, e.g. the new ERA-5 water vapour and ozone data that is now used on the daily scale. As for the SARAH-2.1 climate data record (CDR), the SARAH-3 CDR will be temporally consistently extended by a corresponding Interim Climate Data Record (ICDR).

The radiation parameters of SARAH-3 have been validated using ground based observations from the Baseline Surface Radiation Network (BSRN) as a reference. As BSRN data does not include PAR and DAL, individual stations have been collected to be used as reference for those new parameters. The validation target values for the mean absolute difference between satellite-derived and surface-measured radiation are defined by the target accuracies for monthly/daily/instantaneous data of 4/11/15 W/m² for SIS, 7/15/30 W/m² for SID and 15/30/40 W/m^2 for DNI plus an uncertainty of the ground based measurements of 5 W/m² for SIS and 10 W/m² for the SDI parameters. The accuracies for PAR and DAL have been transferred into the units of the data records, i.e., µmol/m^{2}s and kLux respectively. Target accuracies for monthly/daily means of 36.8/69 µmol/m^2/s for PAR and 1.0/2.7 kLux for DAL are applied.

The mean absolute differences of the monthly mean SIS and the SDI parameters are 5.3 W/m^2 and 7.8 W/m^2 (for SID) / 16.7 W/m^2 (for DNI), respectively, which is close to the respective target accuracies. Moreover, about 88 %, 81 % and 82 % of the monthly mean absolute differences are below the threshold values, for SIS, SID and DNI, respectively. The mean absolute bias of the monthly sums of sunshine duration (SDU) has been determined to be around 15 h. The threshold of 20 h is met for more than 70% of the values. For PAR and DAL the monthly mean absolute differences are 19.7 [µmol/m^{2}s] and 2.9 [kLux] respectively, meaning the majority of values being below threshold accuracies.

The daily mean SIS data have a mean absolute difference of 10.9 W/m², which is in the range of the target accuracy of 11 W/m². The mean absolute difference of the daily mean direct, and direct normal radiation (SID and DNI) is 16.0 and 31.1 W/m^2, respectively, which is also in the range of its target values and below its threshold accuracies. The daily sums of the sunshine duration have a mean absolute deviation of about 1 hour. PAR and DAL daily means have mean absolute deviations of 26.5 [umol/m^2/s] and 3.04 [kLux], respectively.

The 30-minute instantaneous data can only be validated for the parameters SIS, SID and DNI as only the BSRN provides temporally highly-resolved data at 1-min resolution. Generally it should be mentioned that when comparing gridded and point data at the instantaneous temporal scale, larger differences are expected, because of the different spatio-temporal representativeness of the data. For the SARAH-3 instantaneous validation it is distinguished between the all-day (incl. nighttime) and daytime only validation. For the all-day validation the

SIS bias is 2.3 W/m^2 in the line with the results for the daily and monthly means. The mean absolute deviations are ~24 W/m^2. Hence the majority of instantaneous SIS values is below the threshold accuracy. For the direct radiation parameters SID and DNI the mean bias is close to 0, while the mean absolute deviations reach values of ~26 W/m^2 and 51 W/m^2, respectively for the all-day validation.

Overall, the target / threshold accuracy is therefore achieved for monthly and daily means / sums and for the instantaneous data.

A small negative decadal trend of -0.6±0.4 W/m^2/decade in the bias between the satellite-derived data record and homogeneous surface irradiance observations in Europe has been found, indicating a stability of the surface radiation data records close to the target accuracy of 0.5 W/m^2/decade and below threshold accuracy of 1 W/m^2/decade.

For the effective cloud albedo the accuracy is derived from the SIS accuracy. The target value of 0.1 is reached with exception of the winter period for latitudes above 55 degrees, where higher uncertainties might occur.

The quality of the ICDR data is assessed by comparison of the ICDR data to the corresponding data from the CDR for each parameter and temporal resolution. Overall there is a good agreement between the ICDR and the CDR data; hence the ICDR data consistently temporally extends the CDR data records. Larger differences occur only South of 60 °S due to cloudiness and sea-ice in that region.

1 The EUMETSAT SAF on Climate Monitoring (CM SAF)

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

The consortium of CM SAF currently comprises the Deutscher Wetterdienst (DWD) as host institute, and the partners from the Royal Meteorological Institute of Belgium (RMIB), the Finnish Meteorological Institute (FMI), the Royal Meteorological Institute of the Netherlands (KNMI), the Swedish Meteorological and Hydrological Institute (SMHI), the Meteorological Service of Switzerland (MeteoSwiss), the Meteorological Service of the United Kingdom (UK MetOffice) and the Centre National de la recherche scientifique (CNRS) of France. 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 (CDRs) derived from operational meteorological satellites.

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

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

As an essential partner in the related international frameworks the CM SAF 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 an international collaboration benefiting from developments at international level and pollinating the partnership with own ideas and standards,

- Intensive validation and improvement of the CM SAF climate data records,
- Taking a major role in data record assessments performed by research organisations such as WCRP (World Climate Research Programme),
- Maintaining and providing an operational and sustained infrastructure that can serve the community within the transition of mature CDR products from the research community into operational environments.

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

2 Introduction

The radiation budget at the Earth's surface is a key parameter for climate monitoring and analysis. Satellite data allow the determination of the radiation budget with a high resolution in space and time and offer a large regional coverage by the combination of different satellites. The CM SAF processed a 38 year long (1983-2020) continuous surface radiation climate data record based on observations from the Meteosat First and Second Generation satellites: Surface Solar Radiation Data record – Heliosat Version 3 (SARAH-3).

The Digital Object Identifier (DOI) of the SARAH-3 data record (1983-2020) is 10.5676/EUM_SAF_CM/SARAH/V003.

SARAH-3 contains climate data records of the surface incoming solar radiation (SIS), the surface incoming direct radiation (SDI), the Photosynthetic Active Radiation (PAR), Daylight (DAL), the effective cloud albedo (CAL) and the sunshine duration (SDU). The SARAH-3 CDR are consistently extended in time by the corresponding Interim Climate Data Record (ICDR) – a near-realtime processing of all SARAH-3 parameters based on the SARAH-3 algorithm. The validation of the ICDRs and CDRs are described in this document.

Data from the visible channels of the MVIRI / SEVIRI instruments on-board EUMETSAT's geostationary Meteosat satellites of the First and the Second Generation (Meteosat 2-11) are used. The SIS, SDI, PAR and DAL CDR are processed using a climate version of the Heliosat algorithm to obtain information about the effective cloud albedo (Cano et al. 1986; Posselt et al. 2012, Müller et al., 2015). The effective cloud albedo is used as input for the spectral version of the Mesoscale Atmospheric Global Irradiance Code (SPECMAGIC), which calculates the clear sky radiation and considers the effect of the effective cloud albedo on the irradiance. SPECMAGIC is a sophisticated eigenvector look-up table method (Mueller et al. 2009, 2012). Heliosat is extended by addition of a self-calibration method accounting for changes in the satellites (switches, degradation). For the first time, a snow detection algorithm (HELSNOW) is used in order to consider the snow reflectivity in Heliosat. Details of the retrieval method can be found in the ATBD [RD 1]. More information on the products can be found in the PUM [RD 2]

The temporally averaged CM SAF SIS, SDI, PAR, DAL, and SDU data records are presented in Figure 2-1. It is clear that these data records represent well the general structure of the spatial distribution of the surface solar radiation. In particular, the effect of clouds on the radiation parameters is very well depicted (especially for direct radiation) in the stratocumulus region close to the western South African coast and in the tropics with the large amount of cumulus clouds. More quantitative information on the quality of these data records is provided in the following sections.

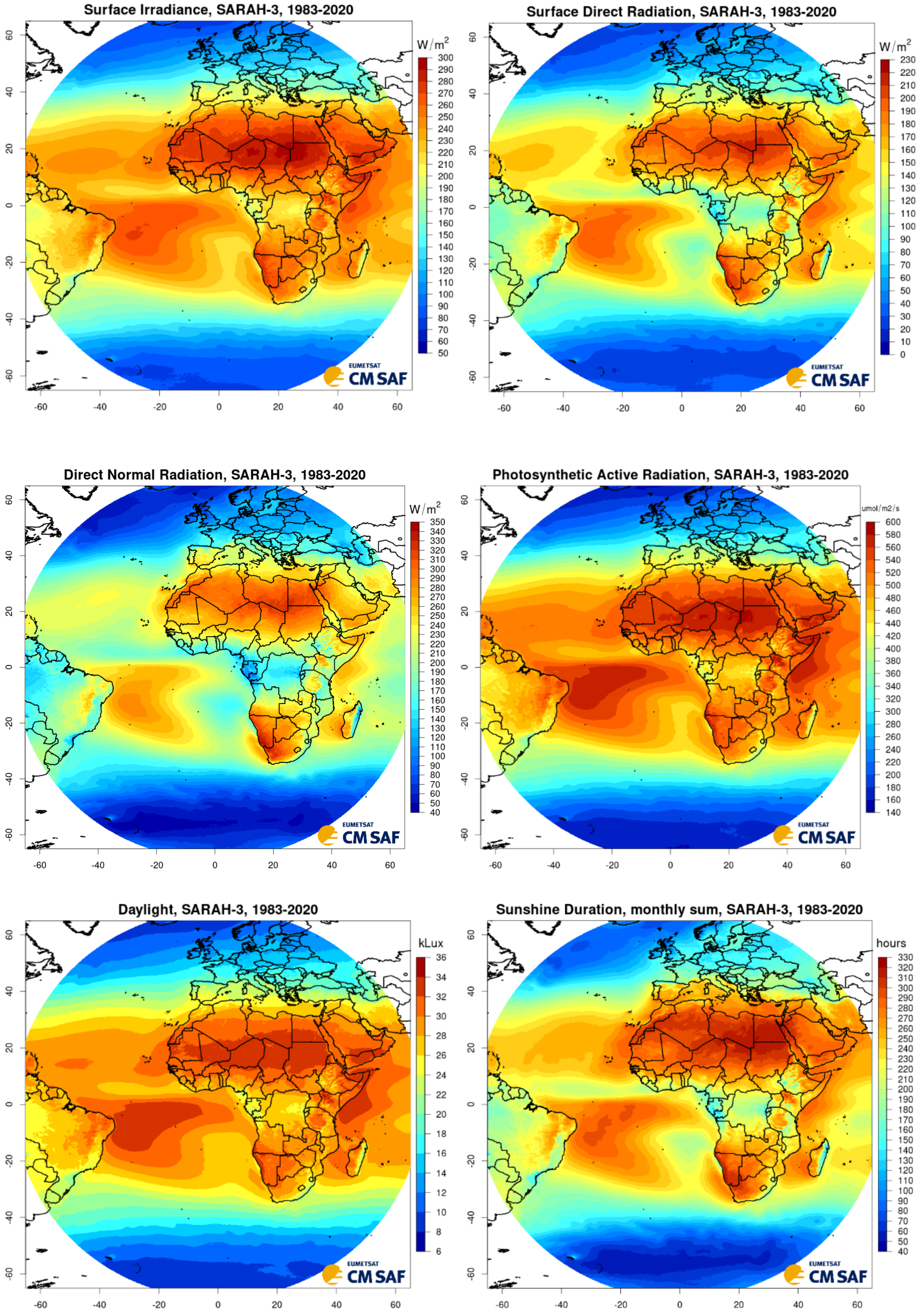


Figure 2-1: Spatial maps of the climatologies of SIS (top left), the SDI Parameters SID (top right) and DNI (middle left), PAR (middle right), DAL (bottom left), SDU (bottom right) for the SARAH-3 climate data record (1983-2020). Maps show typical spatial pattern with highest radiation amounts in the subtropics decreasing towards higher latitudes, and a local minimum in the Intertropical Convergence Zone.

3 Validation procedure

3.1 Validation data

The validation of the new SARAH-3 data records for the surface incoming solar radiation (SIS), the surface incoming direct solar radiation parameters (SDI) is performed by comparison with high-quality ground based measurements from the Baseline Surface Radiation Network (BSRN) (Ohmura et al. 1998, Driemel et al., 2018). The BSRN stations used for the validation are listed in Table 3-1, their location are shown in Figure 3-1. Thereby, only those stations were used that have an overlap of at least 12 months with the satellite data. The selected 17 stations are located mainly in the Northern Hemisphere but they cover the main climatic regions and they span a substantial part (1992-2020) of the satellite time period. Unfortunately, no high quality surface radiation data are available prior to 1992 to validate the first decade of the CM SAF surface radiation data record. However, the same data quality of the CM SAF data record is assumed for the years 1983 to 1992 than for the years that underwent validation against the BSRN reference measurements.

The effective cloud albedo (CAL) as a pure satellite product cannot be validated by comparison with ground based measurements directly. As the effective cloud albedo is the satellite observation, which is used to derive the radiation CDRs, the accuracy evaluated for the radiation CDRs can be used to estimate the accuracy of the effective cloud albedo.

Table 3-1: List of BSRN stations used for the validation of SIS and SDI parameters of the SARAH-3 data record. The number of available monthly means of surface irradiance for the validation are provided as well.

Station	Country	Code	Latitude [°N]	Longitude [°E]	Elevation [m]	Data since	# monthly means
Budapest-Lorinc	Hungary	bud	47.43	19.18	139	1.6.2019	19
Cabauw	Netherlands	cab	51.97	4.93	0	1.2.2005	191
Camborne	UK	cam	50.22	-5.32	88	1.1.2001	191
Carpentras	France	car	44.05	5.03	100	1.8.1996	267
Cener	Spain	cnr	42.82	-1.60	471	1.7.2009	138
De Aar	South Africa	daa	-30.67	23.99	1287	1.5.2000	112
Florianopolis	Brasil	Ffo	-27.53	-48.52	11	1.6.1994	216
Gobabeb	Namibia	gob	-23.56	15.04	407	1.5.2012	104
Lerwick	UK	ler	60.13	-1.18	84	1.1.2001	193
Lindenberg	Germany	lin	52.21	14.12	125	1.9.1994	291

Station	Country	Code	Latitude [°N]	Longitude [°E]	Elevation [m]	Data since	# monthly means
Palaiseu Cedec	France	pal	48.71	2.21	156	1.6.2003	166
Payerne	Switzerland	pay	46.81	6.94	491	1.9.1992	335
Reunion Island	France	run	-20.90	55.48	116	1.6.2019	19
Sede Boger	Israel	sbo	30.9	34.78	500	1.1.2003	103
Solar Village	Saudi Arabia	sov	24.91	46.41	650	1.8.1998	51
Tamanrasset	Algeria	tam	22.78	5.51	1385	1.3.2000	250
Toravere	Estonia	tor	58.25	26.46	70	1.1.1999	261

The BSRN data has been obtained from the BSRN archive at the Alfred Wegener Institute (AWI), Bremerhaven, Germany (www.bsrn.awi.de). In a first step the BSRN data has been quality controlled using the tests suggested by (Long and Shi 2008). To ensure a high quality of the reference data record, only those BSRN measurements that pass the limit tests are considered in the calculation of the daily and monthly averages. To derive monthly- and daily-averaged values from the surface measurements, the method M7 proposed by (Roesch et al. 2010) was employed to reduce the impact of missing values. By applying method M7, averages for each 15-min UTC interval are calculated from the 1-min mean BSRN data for each day and month, respectively. To derive the daily / monthly means the 96 bins (96 x 15 min = 24 h) for the corresponding day / month are averaged; the averages are only valid if all bins contain valid values. Deriving the monthly mean diurnal cycle of the shortwave fluxes allow more accurate estimates of monthly means, in particular for incomplete observations. The uncertainty of the temporally averaged global irradiance based on BSRN measurements is estimated to be ±10 W/m^2 at hourly time scale and ±4 W/m^2 at monthly time scale (Raschke et al. 2012).

To assess the quality of the satellite data record with the BSRN surface observations, the difference in the spatial representativeness between these two observing systems needs also to be considered. Depending on the local spatial distribution of surface radiation the impact can be in the range of 4 W/m^2 for monthly mean data (Hakuba et al. 2013) and even larger for daily mean surface radiation data. Due to its higher temporal and spatial variability it must be assumed that the level of uncertainty of the direct normal radiation is larger than the level of uncertainty for the irradiance.

When validating the instantaneous SARAH-3 data, it should be noted that a substantial part of the observed differences between the satellite and station data result from the difference in temporal and spatial representativeness. To better account for this difficulty, the BSRN data is temporally averaged for a time period of +-5 minutes around the local satellite acquisition time.

To assess the temporal stability of the surface radiation data records, long-term reference measurements should be employed. The Global Energy and Balance Archive (GEBA) contains monthly mean surface irradiance data records from ground observations including stations reporting prior to 1983 (Gilgen et al. 2009). For 30 European stations, which provide data between 1983 and 2018 the temporal homogeneity has been tested. These station measurements are used to assess the temporal stability of the monthly mean SIS data record from SARAH-3 and its predecessors.

The ICDR is validated by comparison to the CDR for 2020. This is done for each parameter and temporal resolution. The ICDR validation is presented in Section 7.

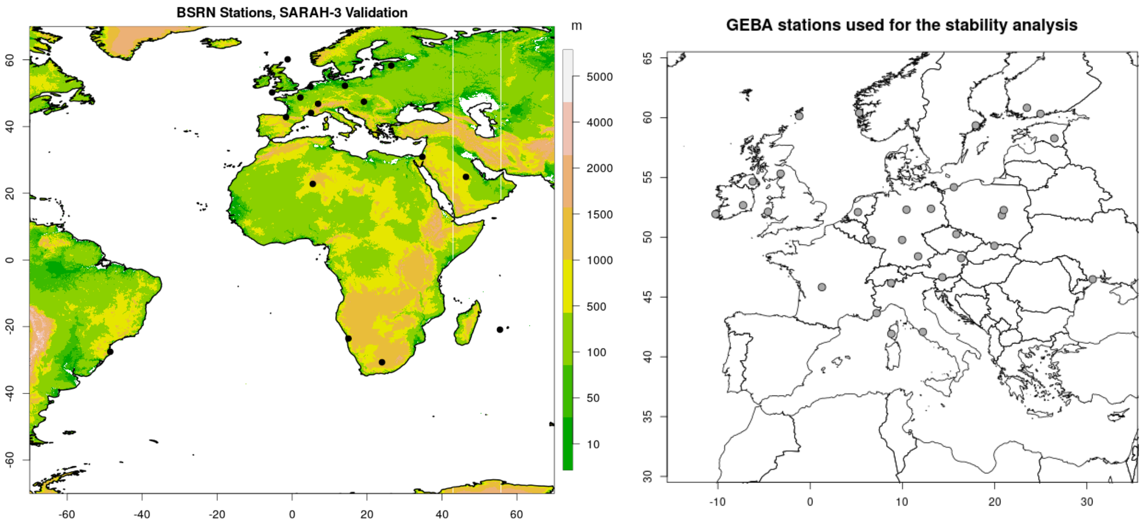


Figure 3-1: Location of the (left) BSRN and the (right) GEBA stations used for the validation. Dots are the locations of the stations. The underlying map shows the topography (BSRN stations only).

For evaluation of sunshine duration, data from the European Climate Assessment & Datasets (ECA&D) and CLIMAT observation station network were used in this study. ECA&D (Klein Tank et al., 2002) is gathering long-term daily observational series from meteorological stations all over Europe. Some automatic quality control and homogeneity checks are applied to the data. Due to national restrictions only a part of the ECA&D data is downloadable. In contrast, the main application for CLIMAT data is climate analyses and these data are therefore monthly totals. The CLIMAT data undergo routine quality control at DWD. Additionally some basic visual checks were applied to extract suspicious stations. CLIMAT and ECA&D sunshine duration data are only available for land-based stations. ECA&D and CLIMAT station data are available for a relatively high number of stations, but despite quality checks, there is no guarantee that these data are bias free. Stations were removed from the analysis if they reported apparently erroneous data, such as fixed zeros, permanently high values throughout the year or obvious jumps in the time series. CLIMAT data were accessed via the DWD Climate Data Centre.

For the validation of the photosynthetic active radiation (PAR) and daylight (DAL) data records, the SARAH-3 data sets are compared with available surface measurements. Unfortunately no networks of quality-controlled PAR and DAL data are easily available and accessible; hence, the validation of the PAR and DAL data record are based on data from selected surface stations that have been kindly provided to the CM SAF, see Table 3-2.

The PAR data from Czech Republic have been provided by Milan Fischer from Global Change Research Institute CAS in Brno. The PAR data from Peronne, France, has been kindly provided by Frédéric Bornet and Joël Léonard from INRA, Centre Hauts-de-France; it is being collected within the ICOS network (Integrated Carbon Observation System). The PAR data from Kishinev, Moldova, have been provided by Alexandr A. Aculinin from Atmospheric Research Group (ARG) of the Institute of Applied Physics(IAP), Kishinev. Claire Thomas (TRANSVALOR) strongly supported the acquisition of the above-mentioned PAR data records. The PAR data from Lampedusa, Italy, have been provided by Daniela Meloni (ENEA) (Trisolino et al., 2018).

The DAL data from Athens have been provided by Dr. Psiloglou Basil from the Institute for Environmental Research and Sustainable Development (IERSD) of the National Observatory of Athens (NOA) (Kambezidis, 2020; Psiloglou, 2021). The DAL data from Bratislava were provided by S. Darula (Slovak Academy of Science) with the help of Michal Zak (CHMI) (Darula et al., 2001). The DAL data from Vaulx-en-Velin are made available for download by Dumortier Dominique at http://idmp.entpe.fr/stafr.htm.

All PAR and DAL data have been individually processed to daily and monthly averages, which are used for the validation of the corresponding SARAH-3 PAR and DAL climate data records. It is worth mentioning that all reference stations used here for PAR and DAL are located in Europe, which limits the quality assessment of the SARAH-3 PAR and DAL data records. However, it is expected that with the availability of the two new spectral parameters (PAR, DAL) as part of SARAH-3, the data exploration and data validation from external users will intensify and help the CM SAF to collect further information on the data quality.

The validation thresholds as defined in the Requirements Review Document [RD 3] and CM SAF CDOP Product Requirements Document [AD 1] for SIS, SDI (SID, DNI), PAR, DAL and CAL are listed in Table 3-3. The requirements for PAR and DAL have been transferred from W/m^2 into $\mu mol/m^2/s$ and kLux, respectively. 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 due to the spatial representativeness and the uncertainties of the reference observations needs to be considered. This additional uncertainty is assumed to be 5 W/m^2 for SIS (10 W/m^2 for instantaneous data) and 10 W/m^2 for the SDI parameters; in the absence of detailed quantitative information on the uncertainty of the surface reference data for PAR and DAL we have considered an uncertainty of 9 $\mu mol/m^2/s$ for PAR and of 1.3 kLux for DAL (both corresponding to 2 W/m^2).

Table 3-2: List of stations used for the validation of the PAR and DAL data records from SARAH-3

Station	Country	Code	Latitude [°N]	Longitude [°E]	Parameter
Bílý Kříž	Czech Republic	BKF	49.50	18.54	PAR
Křešín	Czech Republic	KRP	49.57	15.08	PAR
Lanžhot	Czech Republic	LNZ	48.68	16.95	PAR
Rájec	Czech Republic	RAJ	49.44	16.70	PAR
Štítná	Czech Republic	STI	49.04	17.97	PAR
Třeboň	Czech Republic	TRE	49.02	14.77	PAR
Žabčice	Czech Republic	ZAB	49.02	16.62	PAR
Kishinev	Moldova	KIS	47.00	28.82	PAR
Lampedusa	Italy	LAO	35.52	12.63	PAR
Peronne	France	PER	49.87	3.02	PAR
Vaulx-en-Velin	France	VEV	45.77	4.92	DAL
Bratislava	Slovakia	BRA	48.17	17.08	DAL
Athens	Greece	NOA	39.97	23.72	DAL

Table 3-3: Accuracy and decadal stability requirements (threshold (Th), target (Ta) and optimal (Op)) for monthly, daily averaged and 30-min instantaneous (inst.) data from the SARAH-3 data record (SIS, SDI (SID, DNI), PAR, DAL, CAL, SDU);

	SIS [W/m²]			SID [W/m²]			DNI [W/m²]			PAR [µmol/m²s]			DAL [kLux]			CAL			SDU [h]		
accuracy	Th	Ta	Op	Th	Ta	Op	Th	Ta	Op	Th	Ta	Op	Th	Ta	Op	Th	Ta	Op	Th	Ta	Op
monthly	5	4	3	8	7	5	17	15	12	46	37	23	1.4	1.0	0.7	0.10	0.08	0.05	20	15	10
daily	12	11	10	18	15	12	34	30	25	92	69	46	3.4	2.7	2.1	0.2	0.1	0.08	1.5	1	0.75
Inst.	20	15	12	40	30	20	50	40	30	138	92	69	6.8	5.5	3.4	0.3	0.15	0.1			
stability	1	0.5	0.3	5	3	2	5	3	2	1	0.5	0.3	1	0.5	0.3	0.08	0.06	0.03	0.8	0.5	0.3

3.2 Data record used for evaluation

The validation results of the SARAH-3 climate data records are reported and compared with the corresponding results of its predecessors (CM SAF MVIRI-only, SARAH-1 and SARAH-2.1). In addition to the CM SAF validation activities, these data records have been widely used and evaluated by numerous users, far beyond the validation activities conducted by the CM SAF (e. g., Bojanowski et al. 2014; Hagemann et al. 2013; Sanchez-Lorenzo et al. 2013, Müller et al., 2015, Urraca et al., 2017, Pfeifroth et al., 2018, Yang and Bright, 2020).

3.3 Statistical measures

The validation employs several statistical measures and scores to evaluate the quality of the SIS and SDI data records. Beside the commonly used bias and standard deviation, here also the (mean) absolute deviation and the correlation of the anomalies derived from the surface measurements and the CM SAF data record is used. For each data record the number of months that exceed the target accuracy to characterize the quality of the data records are provided. In the following chapters the applied quality measures are described. Thereby, the variable 'y' describes the data record to be validated (e. g., SARAH-3) and 'o' denotes the reference data record (i. e., BSRN). The individual time step is marked with 'k' and 'n' is the total number of time steps.

Bias

The bias (also called mean error) is defined as the mean difference between the average of two data records, resulting from the arithmetic mean of the difference over the members of the data records. It indicates whether the data record on average over- or underestimates the reference data record.

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

Mean absolute difference

In contrast to the bias, the mean absolute difference (MAD) 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 data record.

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

Station-Mean absolute difference

The station-mean absolute difference represents the average mean absolute difference for all stations. Its value differs from the mean absolute difference due to the different number of available data values for each station:

$$\mathrm{MAD} = \frac{1}{nstation} \sum_{\mathrm{k}=1}^{nstation} MAD_{station}(k)$$

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 data record.

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

Anomaly correlation

The anomaly correlation AC 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.

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

Here, for each station the mean annual cycle ȳ and ō 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 data record is the fraction of the time steps that are outside the requested target value 'T'. The target values are given by the threshold / target accuracies of the corresponding CM SAF product, plus the non-systematic error (uncertainty) of the BSRN measurements (Ohmura et al. 1998).

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

4 Validation results

In this section the validation results of the new SARAH-3 climate data record are presented. This includes the Surface Incoming Solar Radiation (SIS), the surface incoming direct irradiance (SDI) parameters SID and DNI, the Photosynthetic Active Radiation (PAR), Daylight (DAL), sunshine duration (SDU), and the effective cloud albedo (CAL). For the classification of the quality of the SARAH-3 data record, the corresponding evaluation results of the predecessors SARAH-1 and SARAH-2.1 surface radiation data records are included, if available.

For the comparison with the BSRN data, the daily and monthly means from the SARAH-3 data record are compared with the respective daily and monthly means derived from the BSRN measurements. The means of the BSRN stations have been derived independently using the complete temporal resolution (minutes) of the BSRN stations. The instantaneous data validation is done by comparing the SARAH-3 data with the corresponding temporal averaged BSRN measurements in the time interval of +-5 minutes around the local satellite acquisition time at the respective station. The comparison results are shown by the mean bias, mean absolute difference, anomaly correlation, standard deviation and fraction of months above a given threshold for each individual station and for all stations together. Boxplots for the validation with individual stations are also show.

The statistical quantities used to define the accuracy of the variable are the mean absolute difference and the fraction of time steps above accuracy threshold. In order to match the threshold / target accuracy the mean absolute deviation should be below the threshold / target accuracy and 90% of the monthly (daily) means and the instantaneous data should be below the threshold / target accuracy plus the uncertainty of the surface measurements.

4.1 Surface Solar Irradiance (SIS)

Monthly means

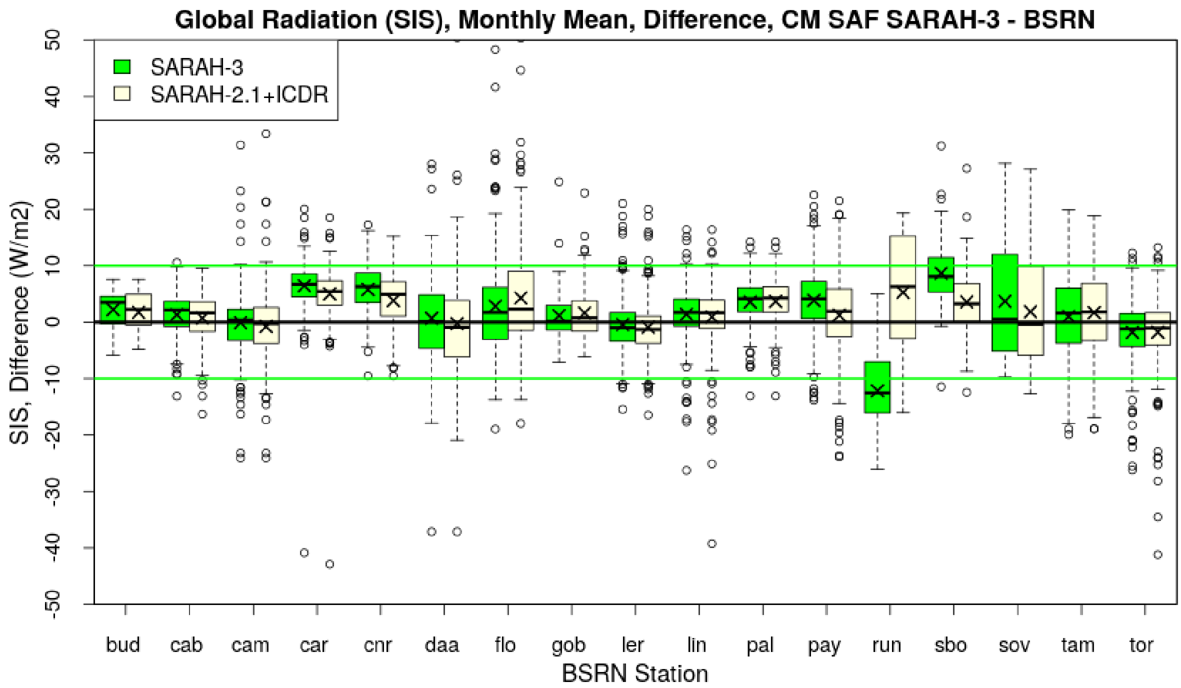
The results of the validation of the monthly mean SARAH-3 SIS data record are summarized in Table 4-1. It shows that the mean absolute difference (MAD) of the data record of 5.32 W/m^2 is close to the requested limit for the threshold accuracy of 5 W/m^2. In total only 12 % of the monthly mean data exceed the threshold accuracy requirement, keeping also an uncertainty of the surface measurement of about 5 W/m^2 in mind. The data record is also able to reproduce the anomalies of SIS that were measured at the surface, which is documented by the high correlation of the monthly anomalies of 0.93.

Also included in Table 4-1 are the corresponding values from the previous three releases of the CM SAF surface radiation data record based on observations from the MVIRI and MVIRI/SEVIRI instruments.

Table 4-1: Results of the comparison between the monthly mean surface solar irradiance derived from BSRN measurements and the two CM SAF surface radiation data records. Included are the number of analysed months, the bias, the mean absolute bias, the standard deviation, station-mean absolute bias and the fraction of months that exceed the threshold accuracy. The threshold value to determine the fraction of months that exceed the threshold is shown in brackets.

SIS	N_{mon}	Bias [W/m²]	MAD [W/m²]	SD [W/m²]	StMAD [W/m²]	AC	$Frac_{mon}$ > threshold accuracy [%]
SARAH-3	2863	2.25	5.32	6.75	5.83	0.93	12.2 (>10 W/m²)
SARAH-2.1+ICDR	2863	1.6	5.15	6.87	5.46	0.92	11.1 (>10 W/m²)
SARAH-2.1	2453	1.59	5.19	6.96	5.31	0.92	5.5 (>13 W/m²)
SARAH-2	1909	2.03	5.13	6.66	5.20	0.93	5.3 (>13 W/m²)
SARAH	1672	1.27	5.46	7.34		0.92	5.6 (>15 W/m²)
MVIRI	878	4.24	7.76	8.23		0.89	10.71 (>15 W/m²)

An illustration of the bias and the MAD at each BSRN station is shown in Figure 4-1. The box-whisker plots represent the range between the 25% and 75% percentiles (1st and 3rd quartile) by the coloured boxes; the whiskers extend to 1.5 times the interquartile range or the maximum value, whichever is smaller.



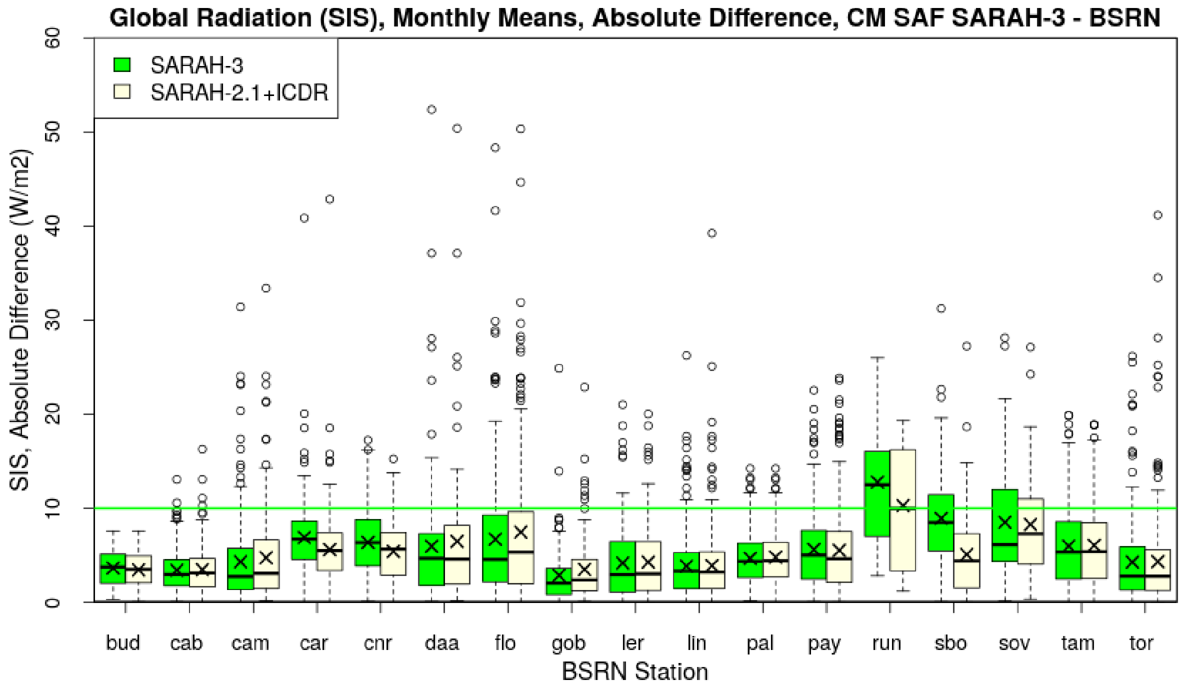


Figure 4-1: Boxplots of (top) the differences and (bottom) the absolute differences between the monthly mean BSRN surface measurements and the (green) SARAH-3 SIS data record and the (yellow) SARAH-2+ICDR SIS data record for each considered BSRN station. The green lines indicate the target value of 10 W/m^2. The crosses indicate the mean of the differences and the absolute differences, respectively.

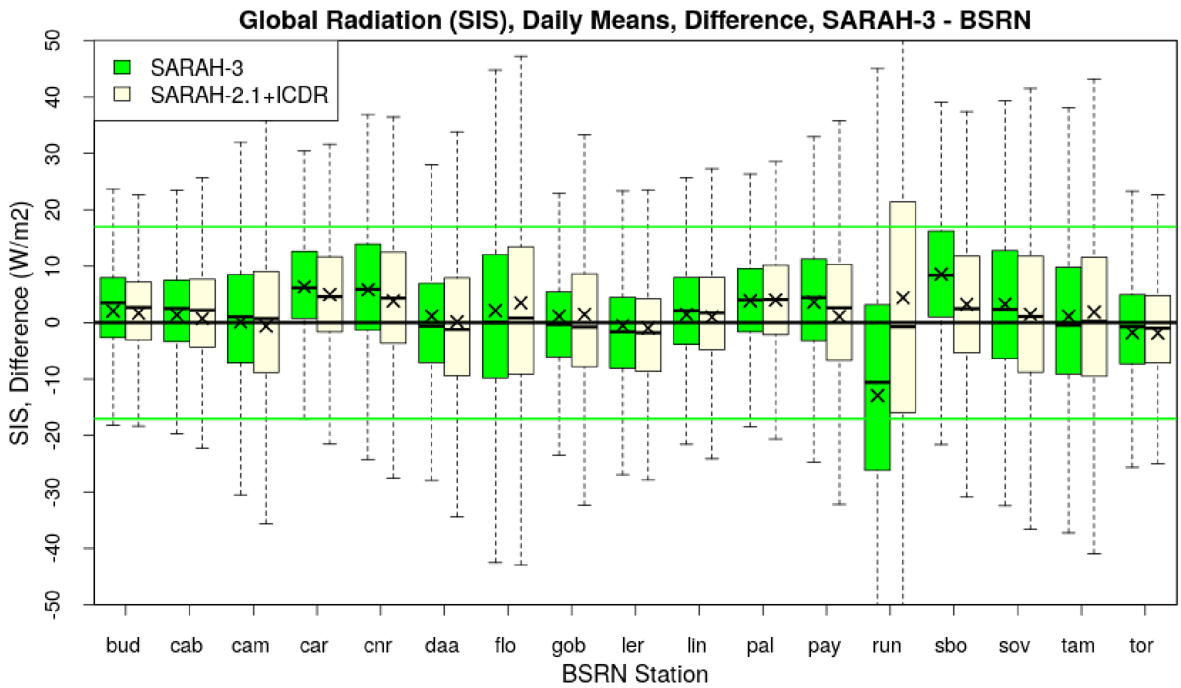
Daily means

Table 4-2 provides the validation result for the daily means of the new SARAH-3 SIS data record, the SARAH-2.1+ICDR data and the previous CM SAF climate data records SARAH-2, SARAH-1 and MVIRI solar radiation. As expected, the mean bias is very comparable to the value derived for the monthly means while the mean absolute difference values for the daily means are about twice as high compared to those for the monthly means. Still, the mean absolute difference of the SARAH-3 SIS daily mean data record (i. e., 10.9 W/m^2) is below the target value of 11 W/m². More than 80 % of the daily MAD values meet the accuracy threshold requirement. Thus, the accuracy requirement is overall fulfilled for the daily means. For the daily means, the SARAH-3 SIS data record shows improved performance compared to the SARAH-2.1 SIS data record, beside for the bias, which is slightly higher than for SARAH-2.1 (see Section 6). Main reasons for the improvements shown at the daily scale is the new consideration of snow and the new auxiliary data (especially water vapor), which both are available on the daily scale for SARAH-3.

Table 4-2: Results of the comparison between the daily mean surface solar irradiance derived from BSRN measurements and the two CM SAF surface radiation data records. Included are the number of analysed days, the bias, the mean absolute bias, the standard deviation, station-mean absolute bias and the fraction of months that exceed the threshold accuracy. The threshold value to determine the fraction of days that exceed the threshold is shown in brackets.

SIS	N_{day}	Bias [W/m²]	MAD [W/m²]	SD [W/m²]	StMAD [W/m²]	AC	$Frac_{day}$ > threshold accuracy [%]
SARAH-3	84789	2.18	10.9	15.8	11.32	0.96	19.6 (>17 W/m²)
SARAH-2.1 + ICDR	84815	1.52	11.5	16.8	11.99	0.95	21.4 (>17 W/m²)
SARAH-2.1	72087	1.51	11.70	17.2	11.92	0.95	16.8 (>20 W/m²)
SARAH-2	57128	1.74	11.78	17.2	11.96	0.95	16.9 (>20 W/m²)
SARAH	48605	1.12	12.1	17.9	/	0.95	11.3 (>25 W/m²)
MVIRI	29790	4.41	15.05	23.36	/	0.92	16.3 (>25 W/m²)

The bias and the MAD of the SIS daily mean from the SARAH-3 data record for the individual BSRN stations are shown in Figure 4-2. Generally, the CM SAF SARAH-3 SIS performs well at all stations with mean absolute difference values in the range of the target accuracy; the accuracy is below the target accuracy for over 80 % of the daily mean values.



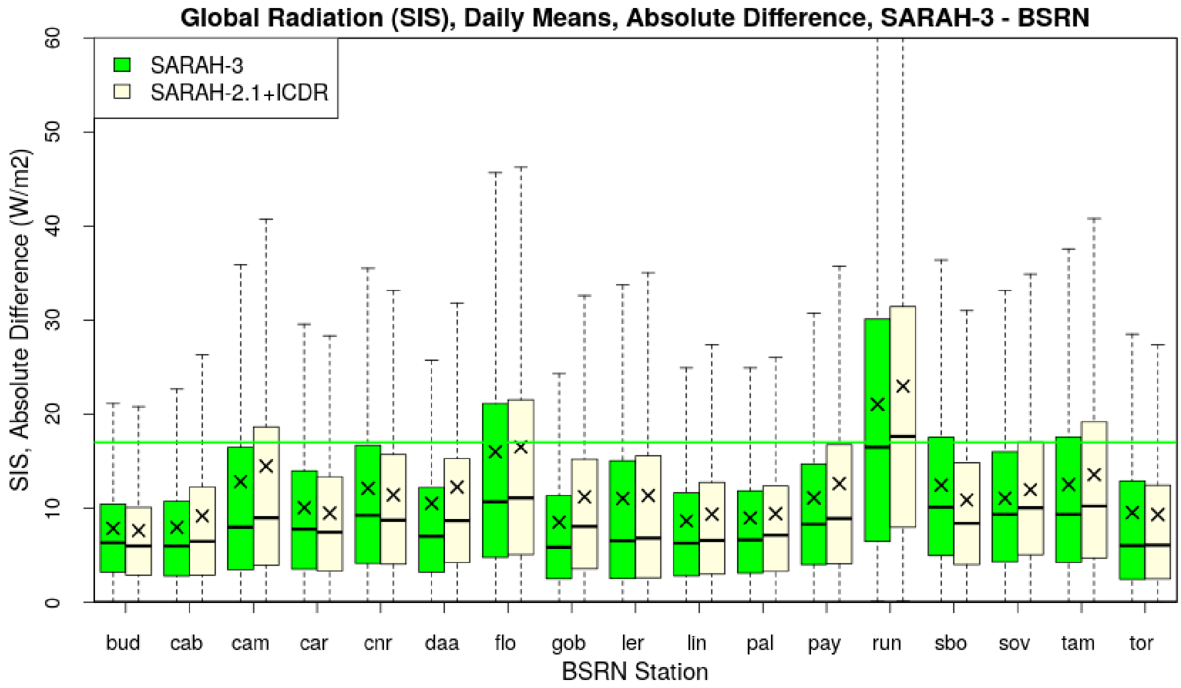


Figure 4-2: Boxplots of (top) the differences and (bottom) the absolute differences for the comparison of daily mean SIS between the BSRN stations and the (green) SARAH-3 and (yellow) SARAH-2.1+ICDR Surface radiation data. No outliers are shown here. The green lines indicate the target accuracy for the SIS daily means. The crosses indicate the mean of the differences and the absolute differences, respectively.

Instantaneous data

The validation results of the 30-minute instantaneous SIS data is summarized in Table 4-3. In this table the validation is divided into all measurements and daytime-only measurements. As expected, the deviations for daytime-only are larger (bias ~4 W/m^2) than for total (bias ~2 W/m^2). The MAD values are ~45 W/m^2 and 25 W/m^2, respectively.

Figure 4-3 shows the validation results of the SARAH-3 30-min instantaneous SIS data record with reference to the individual BSRN measurements. The bias is relatively small for all stations, but for Reunion Island larger deviations occur. Also for the MAD, the largest values occur for Reunion Island. However for the majority of stations the threshold accuracy is met.

Table 4-3: Validation summary of the SARAH-3 instantaneous data of SIS with reference to BSRN measurements. Validation is done for daytime only measurements and total (day and night) measurements.

SIS	N	Bias [W/m^2]	MAD [W/m^2]	SD [W/m^2]	StMAD [W/m^2]	Cor	Frac$_{mon}$ > threshold [%]
SARAH-3 tot	3,941,018	2.3	24.5	59.4	25.3	/	22.0 (> 30 W/m^2)

SARAH-3 day	2,146,546	4.2	44.9	80.3	47.1	0.97	40.4 (> 30 W/m^2)

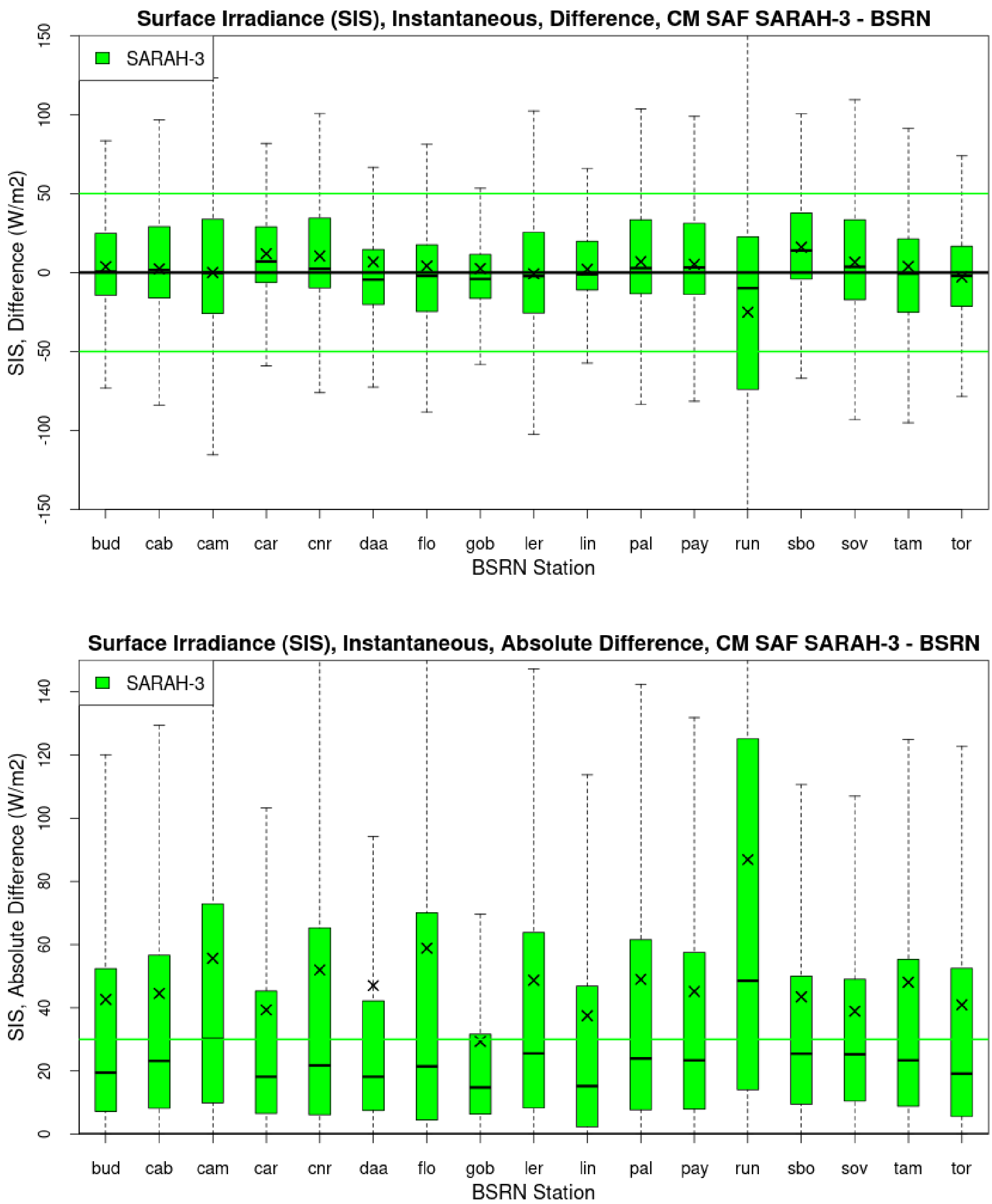


Figure 4-3: Boxplots of (top) the differences and (bottom) the absolute differences between the instantaneous BSRN surface measurements and the corresponding SARAH-3 SIS data record for each considered BSRN station. The crosses indicate the mean of the differences and the absolute differences, respectively. Note that only daytime observations are used for the boxplots.

4.2 Surface Direct Radiation (SDI) parameters

This section presents the validation results of the SARAH-3 SDI data records compared to the BSRN surface reference observations.

The SDI record consists of the surface direct radiation relative to the horizontal surface (SID) and the direct normalized radiation relative to a surface faced normal to the sun (DNI). Both SID and DNI are evaluated separately in the following sections.

4.2.1 Surface Direct Radiation (SID)

Monthly means

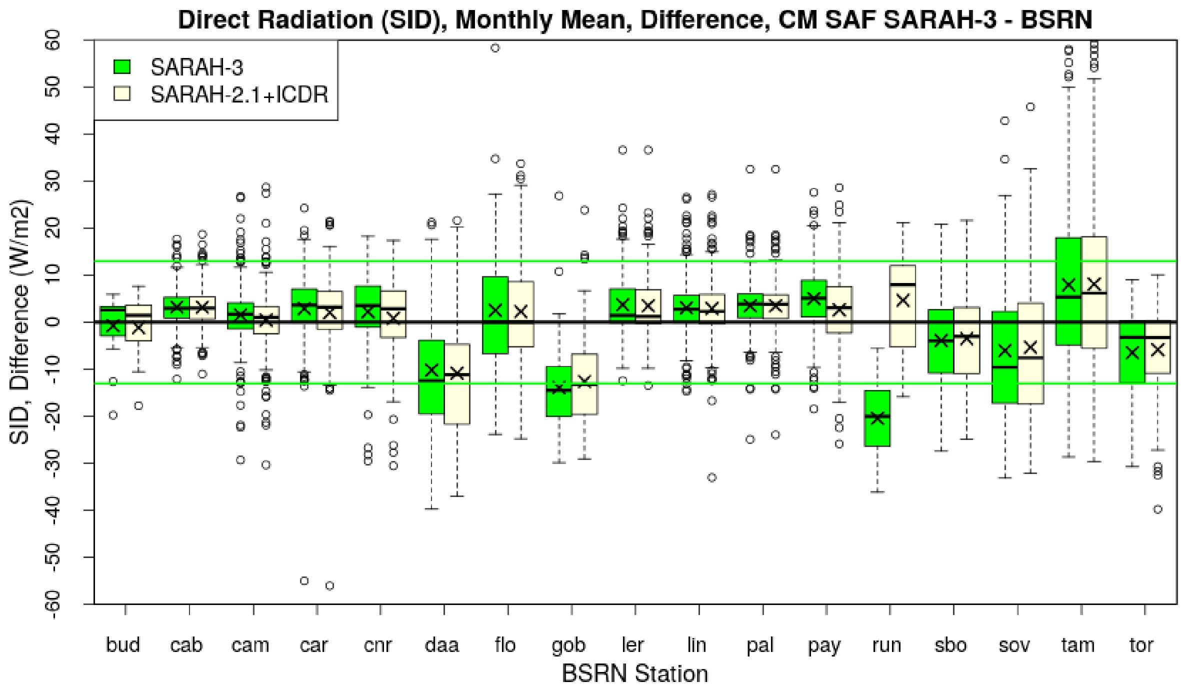
Table 4-4 shows the validation results of the monthly mean direct surface radiation (SID) a component from the new CM SAF SARAH-2.1 SDI data record compared to the observations from the BSRN measurements. A small bias of about 1 W/m^2 is found in the SARAH-3 SID data. The mean absolute difference is 7.8 W/m^2 and hence below the target accuracy of 8 W/m^2. The standard deviation is larger for the direct radiation than for global radiation (11.2 W/m^2 compared to 6.75 W/m^2). 19% of the monthly mean values show deviations larger than the target accuracy plus station data uncertainty. The anomaly correlation is very good with a value of 0.90.

Table 4-4: Results of the comparison between the monthly mean surface solar direct radiation derived from BSRN measurements and the SARAH SID surface radiation data records. Included are the number of analysed months, the bias, the mean absolute bias, the standard deviation, station-mean absolute bias and the fraction of months that exceed the threshold accuracy.

SID	N_{mon}	Bias [W/m^2]	MAD [W/m^2]	SD [W/m^2]	StMAD [W/m^2]	AC	$Frac_{mon}$ > threshold accuracy [%]
SARAH-3	2708	0.99	7.84	11.2	9.09	0.90	19.0 (>13W/m^2)
SARAH-2.1+ICDR	2708	0.70	7.78	11.2	8.54	0.90	18.2 (>13W/m^2)
SARAH-2.1	2347	0.87	7.8	11.3	8.70	0.89	7.7 (>20W/m^2)
SARAH-2	1828	1.36	7.8	11.2	8.58	0.90	7.5 (>20W/m^2)
SARAH	1587	0.98	8.2	11.6		0.89	8.4 (>20W/m^2)
MVIRI	805	0.89	11.0	15.67		0.83	15.4 (>20W/m^2)

For comparison with the previous versions of the CM SAF surface radiation data record, Table 4-4 also shows the results of the validation of the surface direct radiation (SID) for SARAH-2.1+ICDR, SARAH-2.1, SARAH-1 and the CM SAF MVIRI data records.

Figure 4-4 presents the bias and the absolute bias of the monthly means of SID from SARAH-3 and from SARAH-2.1+ICDR data record for each BSRN station. For the SID parameter the threshold accuracy is achieved at almost all used BSRN station. Overall the SARAH-3 shows a comparable quality for SID at the individual BSRN stations compared to SARAH-2.1+ICDR. However for Reunion Island SARAH-3 is underestimating the reference measurements while SARAH-2.1 + ICDR is overestimating the reference data. The measurements at La Reunion Island are conducted in a Coastal region with strong local gradients in elevation and, more relevant, surface irradiance (see Section 10). The update of the spatial grid in SARAH-3 compared to SARAH-2 resulted, in the case of La Reunion, in the use of a SARAH-3 grid box that is corresponding less to the BSRN surface measurements than that nearest grid box from SARAH-2.



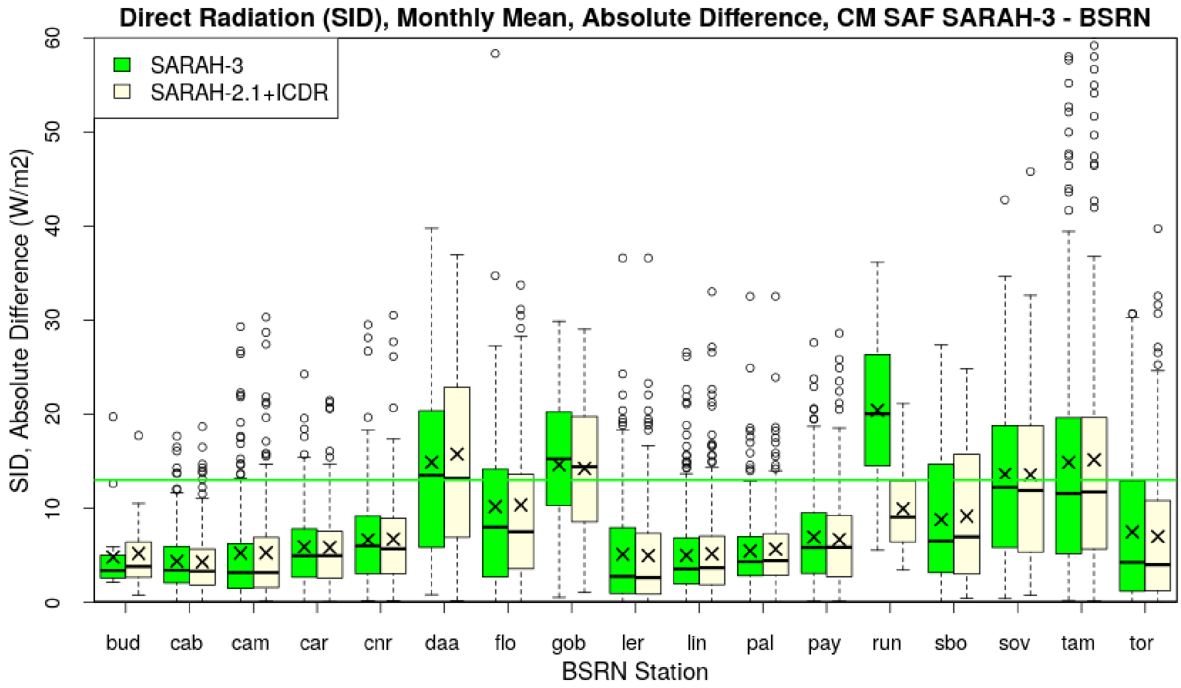


Figure 4-4: Boxplots of (top) the differences and (bottom) the absolute differences between the monthly mean BSRN surface measurements and the (green) SARAH-3 SID data record, and the (yellow) SARAH-2.1+ICDR SID data record for each considered BSRN station. The solid green line indicates the threshold value of 13 W/m² for SID. The crosses indicate the mean of the differences and the absolute differences, respectively.

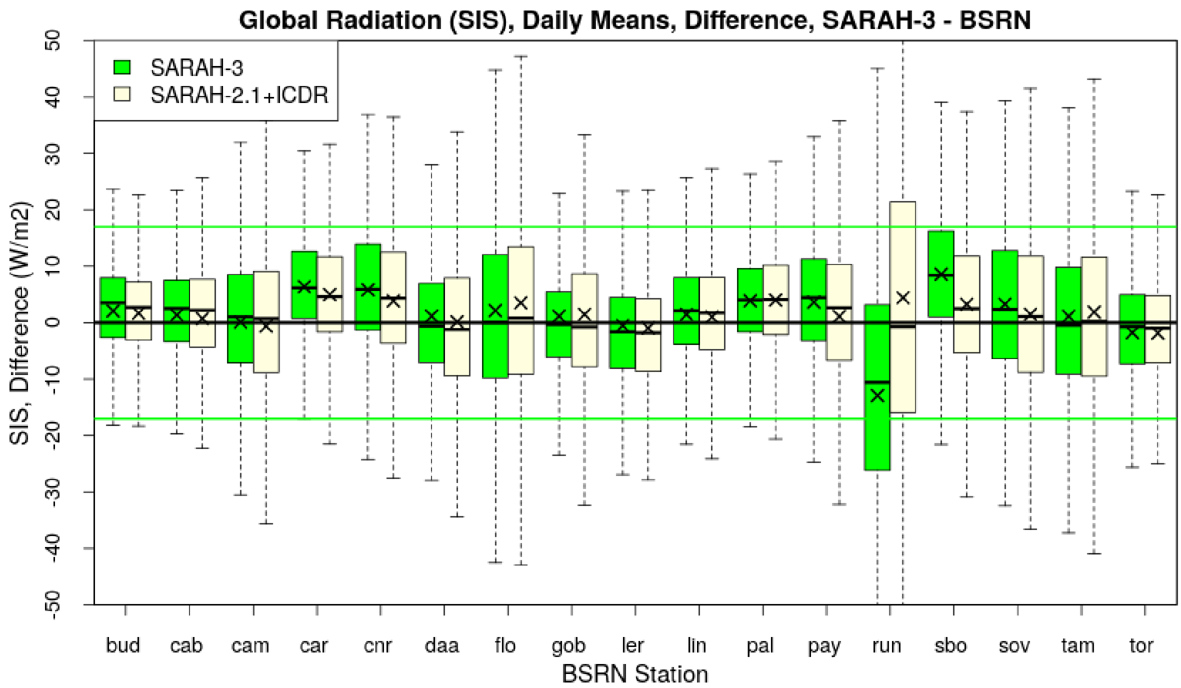
Daily means

The validation results for the daily means of the CM SAF SARAH-3 SID data record are shown in Table 4-5. The mean absolute difference of SID is larger than for the daily mean SIS data record (16.2 W/m² compared to 10.9 W/m²), but close to the target accuracy of 15 W/m² and below the threshold accuracy of 18 W/m². As for SIS, also the daily mean SID shows a larger spread than the corresponding monthly means. For comparison, the evaluation results for the surface direct irradiance (SID) from the SARAH-2.1+ICDR, SARAH-2.1, SARAH-2, SARAH-1 and the MVIRI surface radiation data records are also reported in Table 4-5. As for SARAH-3 SIS daily means, SARAH-3 SID daily means show an improvement compared to its predecessors.

Table 4-5: Results of the comparison between the daily mean surface solar direct radiation derived from BSRN measurements and the SARAH-3 SID surface radiation data record. Also shown are the results of the comparison between the daily mean surface solar direct radiation derived from BSRN measurements and the SARAH-3 predecessors SARAH-2.1+ICDR, SARAH-2.1, SARAH-2, SARAH-1 and the MVIRI based solar radiation data record. Included are the number of analysed days, the bias, the mean absolute bias, the standard deviation, station-mean absolute bias and the fraction of days that exceed the target accuracy.

SID	N_{day}	Bias [W/m²]	MAD [W/m²]	SD [W/m²]	StMAD [W/m²]	AC	$Frac_{day}$ > target W/m² [%]
SARAH-3	76512	0.92	16.0	24.0	17.58	0.93	25.3 (>20W/m²)
SARAH-2.1+ICDR	76537	0.63	17.0	25.5	18.70	0.92	27.2 (>20W/m²)
SARAH-2.1	65697	0.79	17.2	25.9	18.85	0.92	19.3 (>30W/m²)
SARAH-2	51929	0.89	17.6	26.2	18.76	0.92	19.8 (>30W/m²)
SARAH	43549	0.77	17.9	26.6		0.92	20.5 (>30W/m²)
MVIRI	26614	0.74	20.73	31.74		0.89	23.4 (>30W/m²)

The results for the individual stations shown in Figure 4-5, show similar features as for the monthly mean SID data. Larger mean absolute differences are found at the desert stations of Gobabeb and Tamanrasset, consistent with the results from SARAH-2. For the other stations, the majority of daily mean values of SID are below the target accuracy.



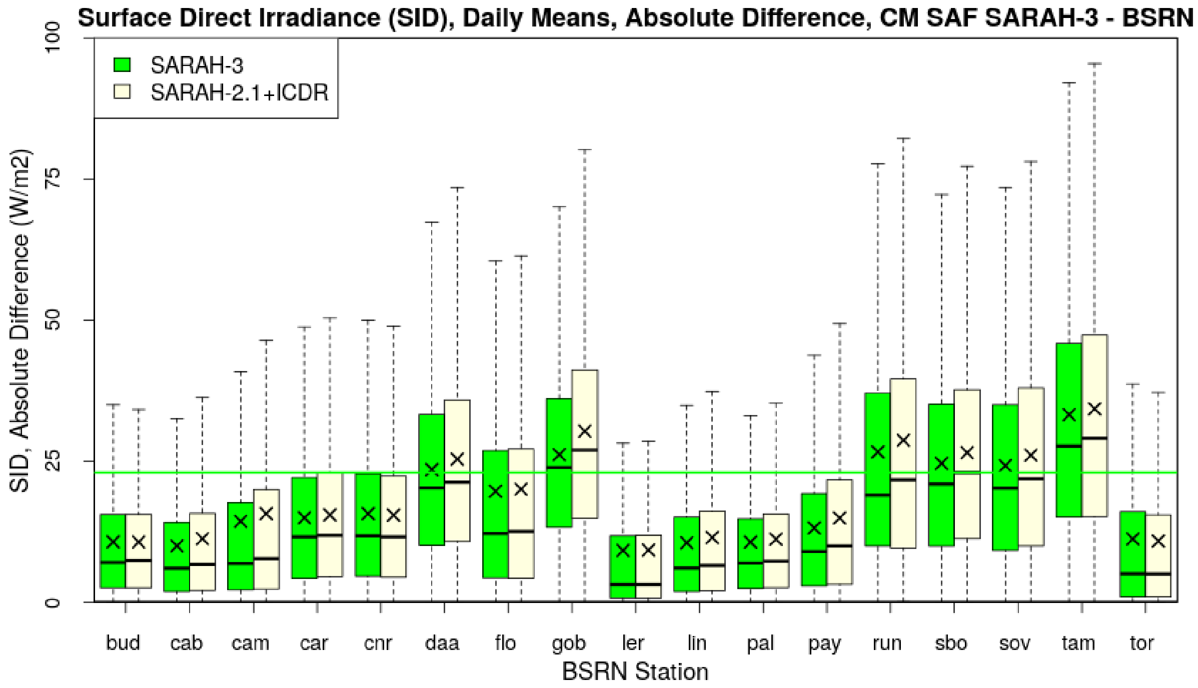


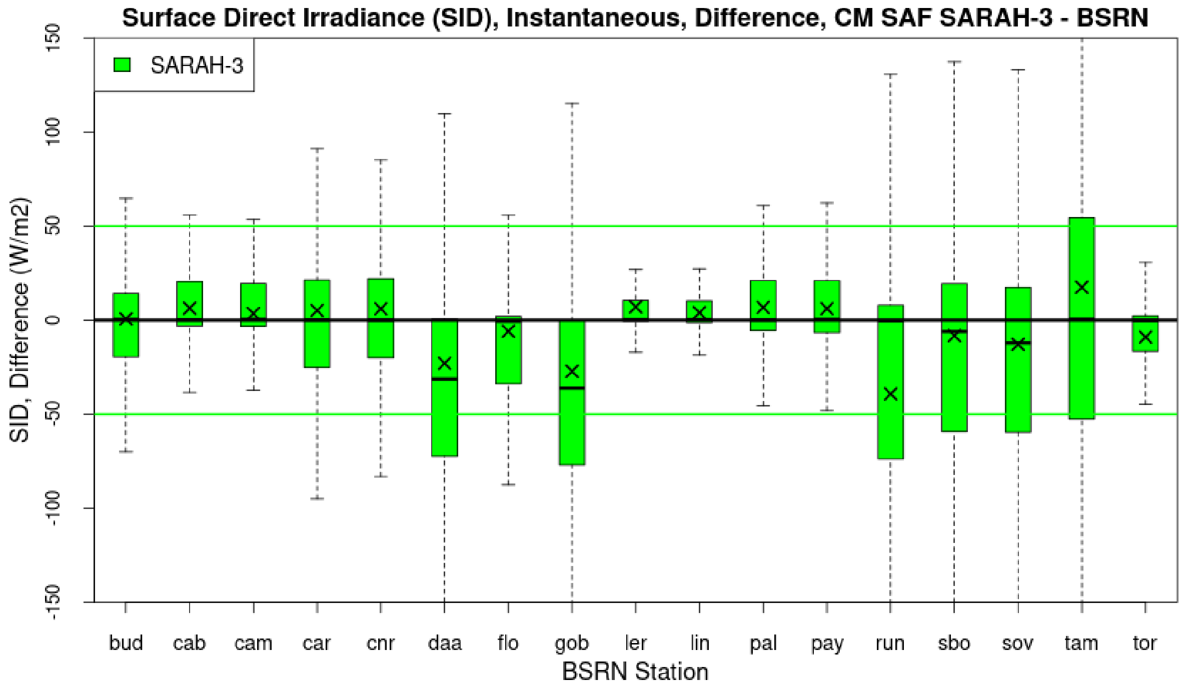
Figure 4-5: Boxplots of (top) the differences and (bottom) the absolute differences for the comparison of daily mean SID data between the BSRN stations and the (green) SARAH-3 and (yellow) SARAH-2.1+ICDR data records. No outliers are shown here. The crosses indicate the mean of the differences and the absolute differences, respectively.

Instantaneous data

Table 4-6: Validation summary of the SARAH-3 instantaneous data of SID with reference to BSRN measurements. Validation is done for daytime only measurements and total (day and night) measurements.

SID	N	Bias [W/m²]	MAD [W/m²]	SD [W/m²]	StMAD [W/m²]	Cor	$Frac_{mon}$ > threshold [%]
SARAH-3 tot	3,762,519	0.53	25.7	67.0	28.0	/	15.9 (> 50 W/m²)
SARAH-3 day	2,026,608	0.94	47.8	91.28	53.1	0.98	29.5 (> 50 W/m²)

The validation results of the SARAH-3 SID 30-minute instantaneous data is summarized in Table 4-6. The mean bias is very small, while the mean absolute deviation (MAD) are 25.7 W/m² and 47.8 W/m² for the total and daytime only validation, respectively. For the majority of measurements the threshold accuracy is met. The relatively high standard deviations indicate several outliers. Largest deviations occur for the stations of Gobabeb, Tamanrasset and Reunion Island (see Figure 4-6).



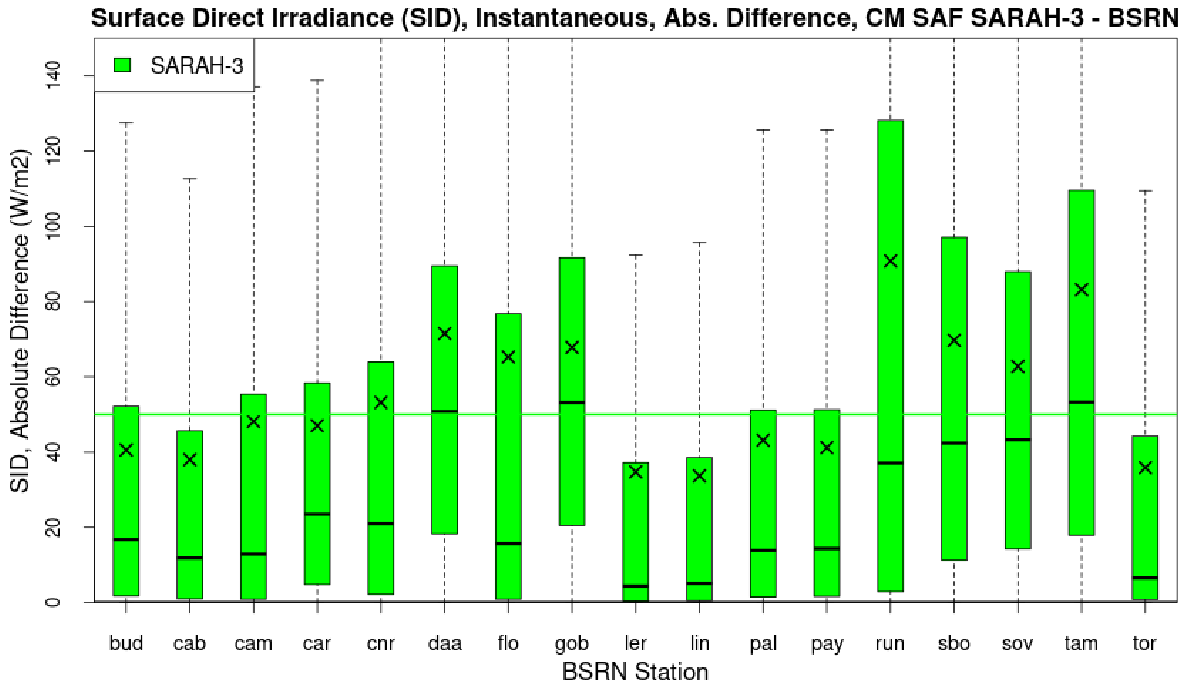


Figure 4-6: Boxplots of (top) the differences and (bottom) the absolute differences between the instantaneous BSRN surface measurements and the corresponding SARAH-3 SID data record for each considered BSRN station. The black x shows the mean of the deviations, which is in general larger than the median as there are several outliers taking effect. Note that only daytime observations are used for the boxplots.

4.2.2 Surface Direct Normal Radiation (DNI)

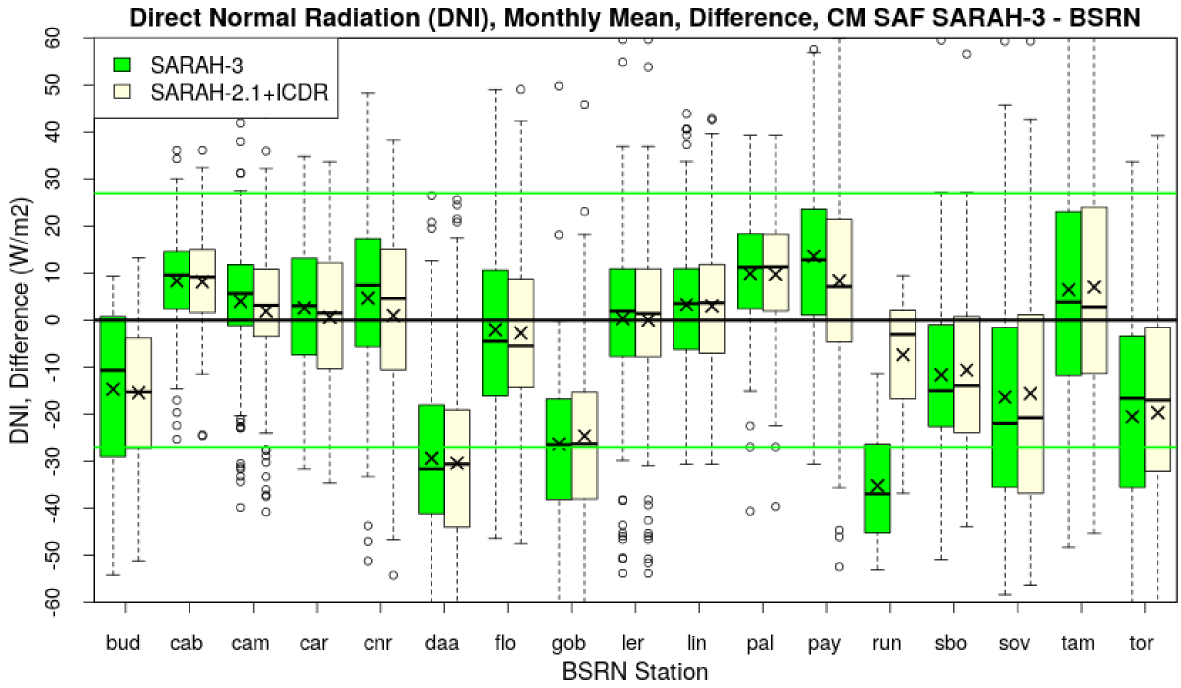
Monthly means

Table 4-7 shows the validation results of the monthly mean direct normal surface radiation (DNI) from the new CM SAF SARAH-3 surface radiation data record compared to the observations from the BSRN measurements. A small negative bias of -0.89 W/m^2 is found in the SARAH-3 DNI data record. The mean absolute difference is 16.7 W/m^2, i.e., close to the threshold accuracy of 17 W/m^2. The standard deviation and, thus, the spread is larger for DNI than for SID (22 W/m^2 compared to 11 W/m^2). More than 80 % of the monthly mean values are better than the threshold accuracy value including measurement uncertainty. The anomaly correlation reaches a value of 0.89.

Table 4-7: Results of the comparison between the monthly mean surface solar direct normal radiation derived from BSRN measurements and the SARAH-3 DNI surface radiation data record. Also shown are the results of the comparison between the monthly mean surface solar direct radiation derived from BSRN measurements and the SARAH-2.1+ICDR, SARAH-2.1, SARAH-2 and SARAH-1 surface radiation data records.

DNI	N_{mon}	Bias [W/m^2]	MAD [W/m^2]	SD [W/m^2]	StMAD [W/m^2]	AC	$Frac_{mon}$ > threshold [%]
SARAH-3	2627	-0.89	16.7	22.1	18.84	0.89	18.5 (>27 W/m^2)
SARAH-2.1+ICDR	2627	-1.78	16.5	21.9	17.50	0.88	17.5 (>27 W/m^2)
SARAH-2.1	2263	-1.82	16.4	21.9	17.97	0.88	14.7 (>30 W/m^2)
SARAH-2	1794	-0.89	16.4	21.9	17.75	0.88	14.4 (>30 W/m^2)
SARAH-1	1541	3.25	17.5	22.9		0.87	16.4 (>30 W/m^2)

For comparison with the previous versions of the CM SAF surface radiation data record, Table 4-7 also shows the results of the validation of the direct normal radiation (DNI) for the SARAH-2.1+ICDR, SARAH-2.1, SARAH-2 and SARAH-1 data records.



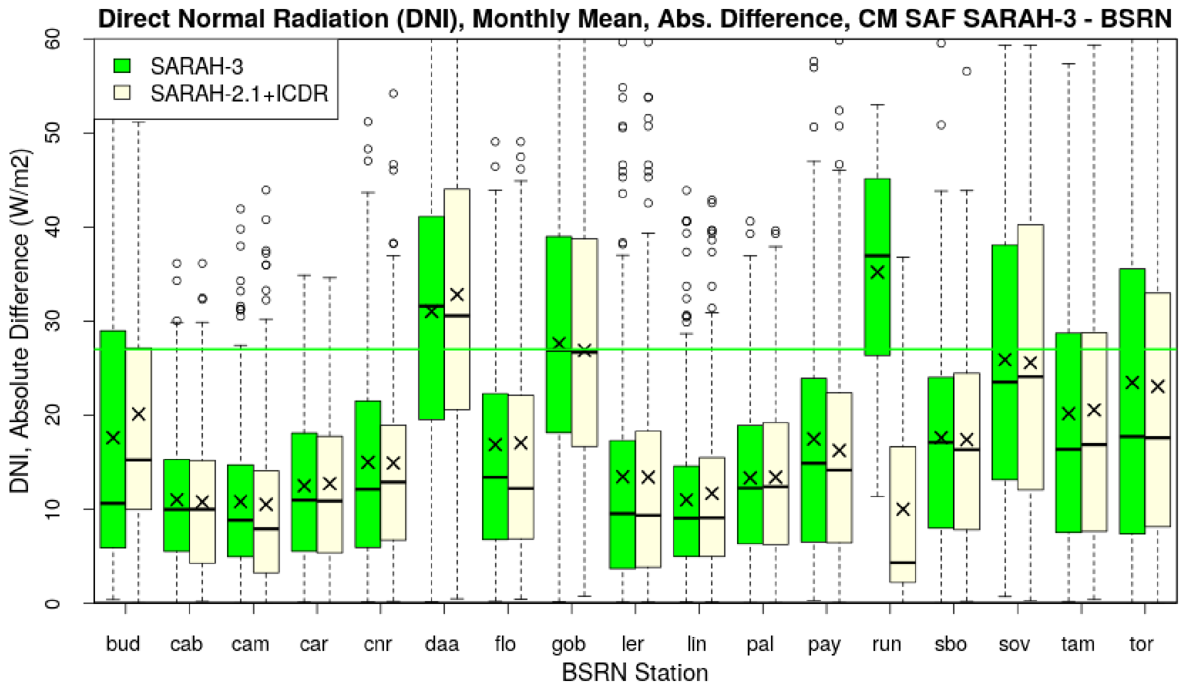


Figure 4-7: Boxplots of (top) the differences and (bottom) the absolute differences between the monthly mean BSRN surface measurements and the (green) SARAH-3 DNI data record, and the (yellow) SARAH-2.1+ICDR DNI data record for each considered BSRN station. The solid green line indicates the threshold value of 27 W/m2 for DNI. The crosses indicate the mean of the differences and the absolute differences, respectively.

The results for the individual BSRN stations are shown in Figure 4-7. At the stations of De Aar and Gobabeb and Reunion Island more than 50% of the DNI monthly means do not fulfill the target value requirement (green line in Figure 4-7). As for SID, the SARAH-2 data record shows lower accuracies, in absolute terms, for desert stations; However in relative terms the deviations are not as different for these locations compared to the other stations.

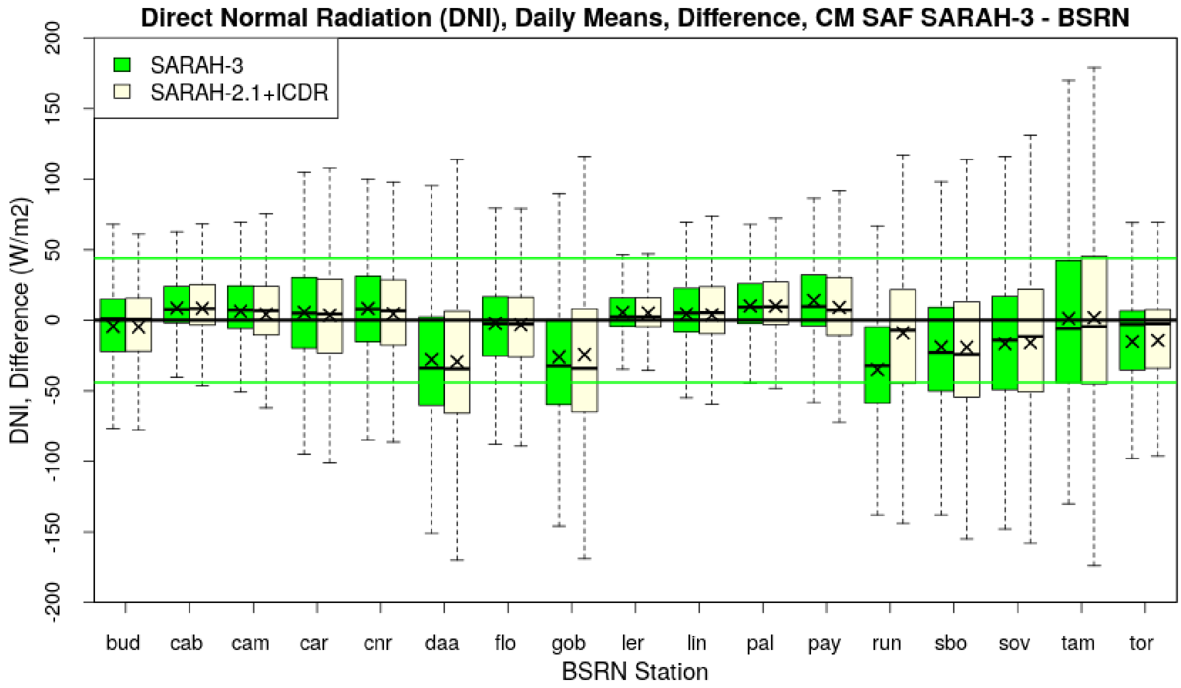
Daily means

The validation results for the daily means of the DNI of SARAH-3 are shown in Table 4-8. The mean absolute difference is larger than for the daily mean SID data record (31 W/m^2 compared to 16 W/m^2), but below the threshold value of 34 W/m^2 required to meet the threshold accuracy. As for SIS, also the daily mean DNI shows a larger spread than the corresponding monthly means. For comparison with the SARAH-3 surface radiation data record, the evaluation results for the surface direct normal irradiance (DNI) from the SARAH-2.1+ICDR, SARAH-2.1, SARAH-2 and the SARAH-1 data record are also reported in Table 4-8. As for SIS and SID daily means, the improved performance of SARAH-3 compared to its predecessors can be seen.

Table 4-8: Results of the comparison between the daily mean surface solar direct normal radiation derived from BSRN measurements and the SARAH-3 DNI surface radiation data record. Also shown are the results of the comparison between the monthly mean surface solar direct radiation derived from BSRN measurements and the SARAH-2.1+ICDR, SARAH-2.1, SARAH-2 and SARAH-1 data records.

DNI	N_{day}	Bias [W/m^2]	MAD [W/m^2]	SD [W/m^2]	StMAD [W/m^2]	AC	$Frac_{day}$ > threshold [%]
SARAH-3	71331	0.33	31.1	43.3	32.92	0.93	26.1 (>44W/m^2)
SARAH-2.1+ICDR	71354	-0.69	33.0	46.2	34.83	0.92	28.3 (>44W/m^2)
SARAH-2.1	60528	-0.82	33.4	46.8	35.71	0.91	32.3 (>40W/m^2)
SARAH-2	49075	-0.81	33.4	46.8	35.45	0.91	32.4 (>40W/m^2)
SARAH	41253	3.8	34.0	48.4		0.91	32.8 (>40W/m^2)

The results for the individual stations are shown in Figure 4-8. The validation results at the individual BSRN stations show the same features as for the monthly mean DNI data. For the SARAH-3 daily mean DNI data, for all stations more than 50 % of the daily mean bias difference of DNI is within the threshold accuracy value including measurement uncertainty.



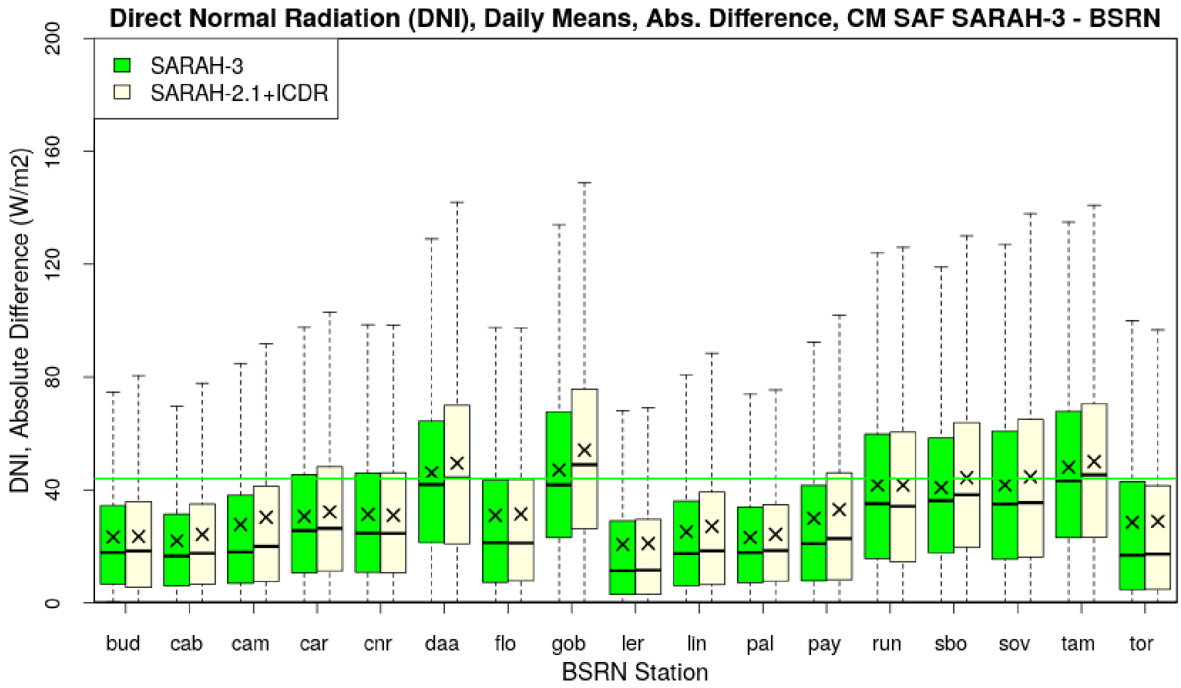


Figure 4-8: Boxplots of (top) differences and (bottom) the absolute differences for the comparison of daily mean DNI between the BSRN stations and the (green) SARAH-3 and (yellow) SARAH-2.1+ICDR climate data record. No outliers are shown here. The crosses indicate the mean of the differences and the absolute differences, respectively.

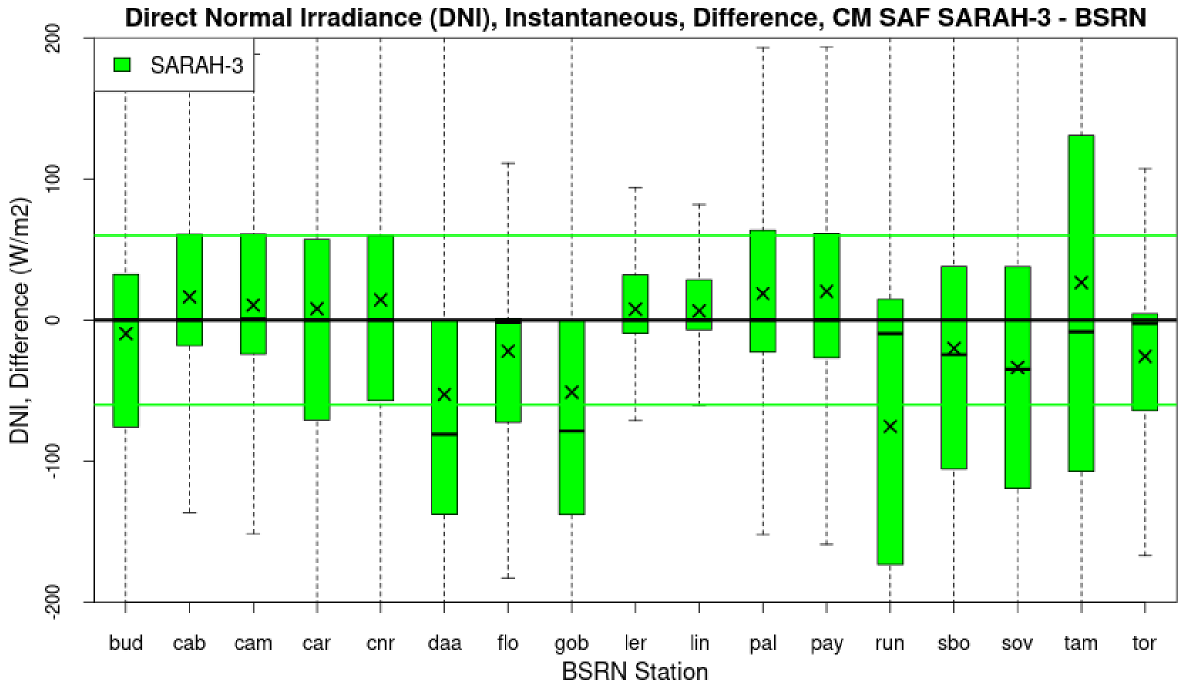
Instantaneous data

The validation results of the 30-minute instantaneous DNI data is summarized in Table 4-9. In this table the validation is divided into all measurements and daytime-only measurements. As expected, the mean absolute deviations for daytime-only are larger (~97 W/m^2) than for total (~51 W/m^2). The mean bias values are very small, in line with the validation results of the monthly and daily mean DNI data. The majority of instantaneous DNI data fulfill the threshold accuracy.

Table 4-9: Validation summary of the SARAH-3 instantaneous data of DNI with reference to BSRN measurements. Validation is done for daytime only measurements and total (day and night) measurements.

DNI	N	Bias [W/m^2]	MAD [W/m^2]	SD [W/m^2]	StMAD [W/m^2]	Cor	Frac$_{mon}$ > threshold [%]
SARAH-3 tot	3,789,081	0.13	51.0	117.6	53.2	/	24.4 (> 60 W/m^2)
SARAH-3 day	1,995,311	0.22	96.8	162.01	103.3	0.92	46.3 (> 60 W/m^2)

Figure 4-9 shows the validation results of the instantaneous SARAH-3 DNI data for the individual BSRN stations. While the overall bias is close to 0, positive and negative biases occur at that individual stations. The largest negative biases in the DNI instantaneous data occur at Reunion Island, De Aar and Gobabeb. For the latter one the threshold accuracy for the median deviation is not met. A positive bias occurs at Tamanrasset. Concerning the mean absolute biases (see Figure 4-9 (bottom)) the largest deviation occur at Reunion Island, which has a strong local variability of surface irradiance (see Section 10). For some stations the threshold accuracy is not met.



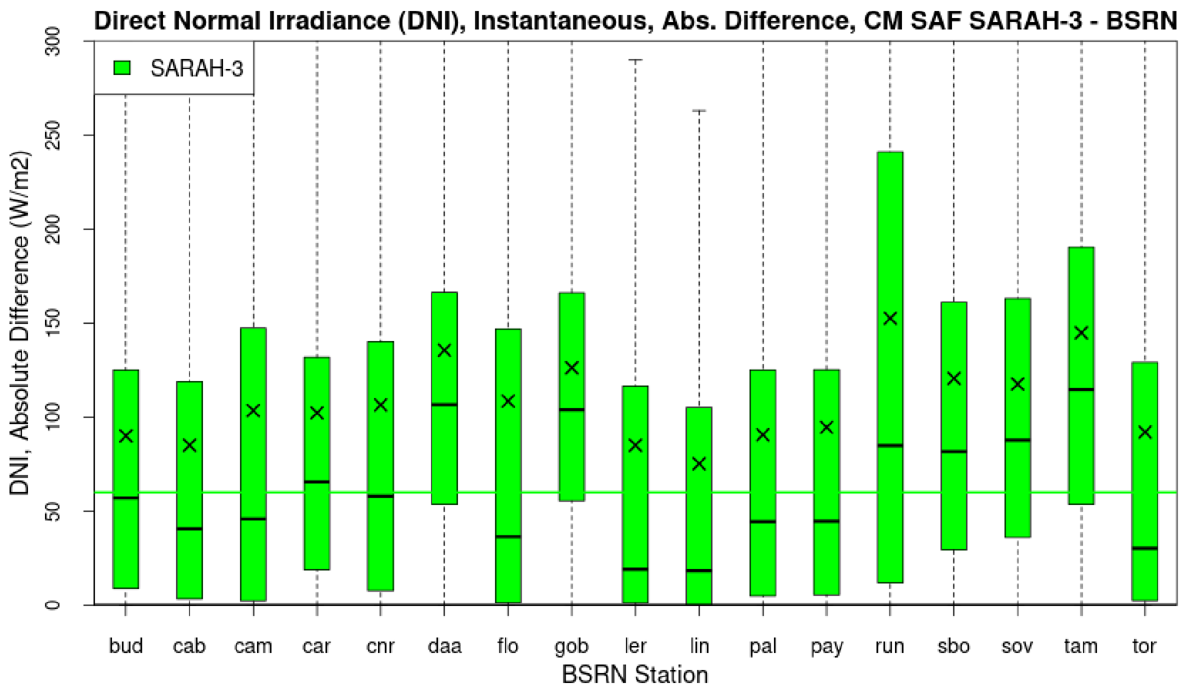


Figure 4-9: Boxplots of (top) the differences and (bottom) the absolute differences between the instantaneous BSRN surface measurements and the corresponding SARAH-3 DNI data record for each considered BSRN station. The black x shows the mean of the deviations, which is in general larger than the median as there are several outliers taking effect. Note that only daytime observations are used for the boxplots.

4.3 Photosynthetic Active Radiation (PAR)

The Photosynthetic Active Radiation (PAR) is a new radiation parameter included for the first time in the series of SARAH climate data records. PAR is mostly used in Agrometeorolgy and Biology and its most common unit is “micromole per m^2*second” (µmol/m^2/s). There is a conversion factor of 1 W/m^2 ≈ 4.6 µmol/m^2/s.

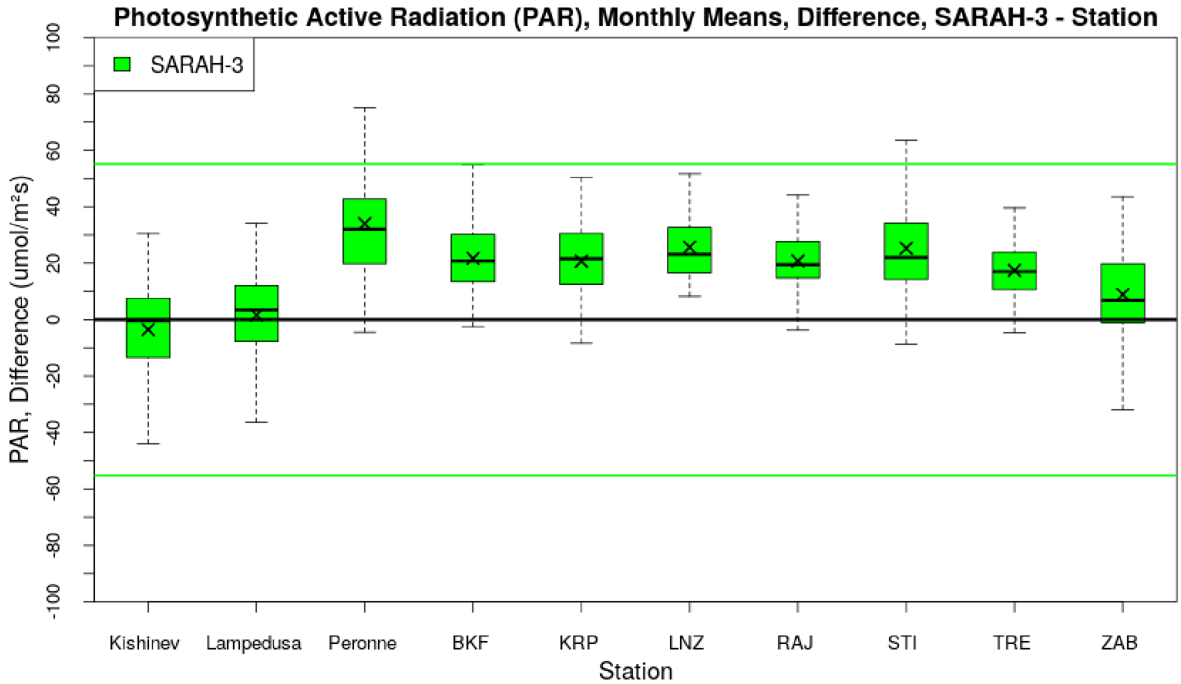
Monthly means

The validation results of the SARAH-3 PAR monthly means are shown in Table 4-10. The mean bias is 14.5 µmol/m^2/s and the mean absolute deviation is 19.7 µmol/m^2/s. The anomaly correlation is 0.89.

Table 4-10: Results of the comparison between the monthly mean Photosynthetic Active Radiation (PAR) station measurements and the SARAH-3 PAR data record.

PAR	N_{mon}	Bias [µmol/ m^2/s]	MAD [µmol/ m^2/s]	SD [µmol/ m^2/s]	StMAD [µmol/ m^2/s]	AC	$Frac_{mon}$ > target [%]
SARAH-3	1064	14.5	19.7	24.1	18.84	0.89	3.8 (>46 µmol/m^2/s)

Figure 4-10 shows the validation results for the individual stations concerning monthly mean PAR. The accuracy threshold is met for all stations.



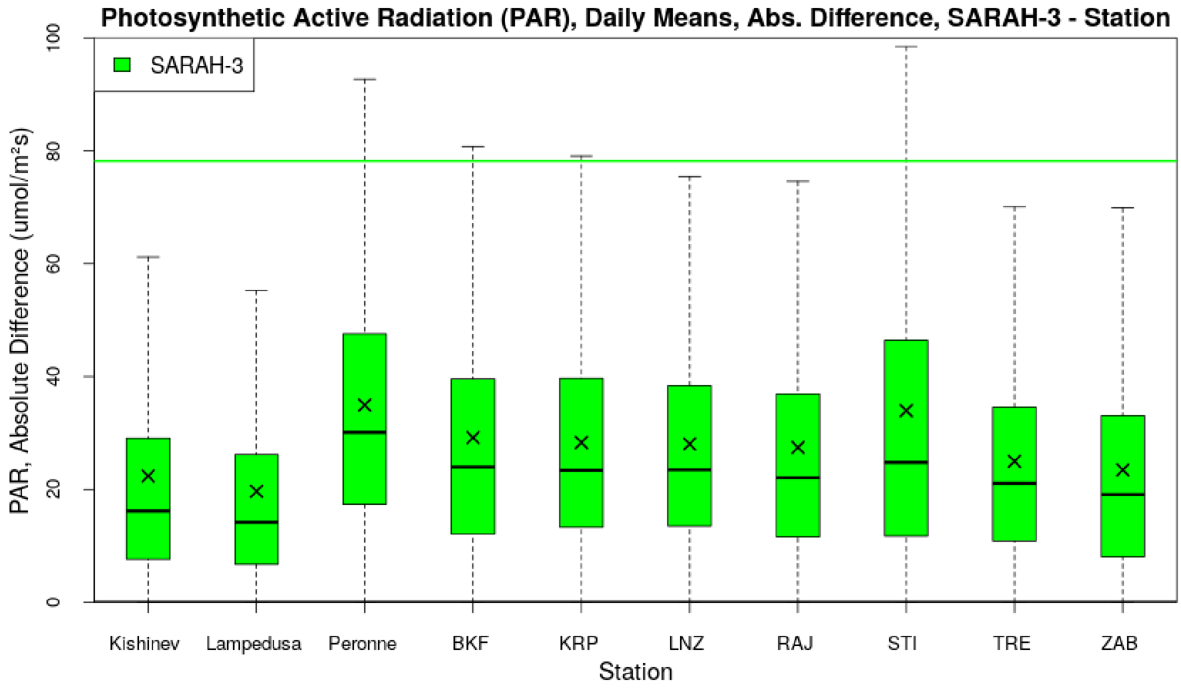


Figure 4-10: Boxplots of (top) the differences and (bottom) the absolute differences at the individual stations for the monthly means of the Photosynthetic Active Radiation (PAR) of SARAH-3. The crosses indicate the mean of the differences and the absolute differences, respectively.

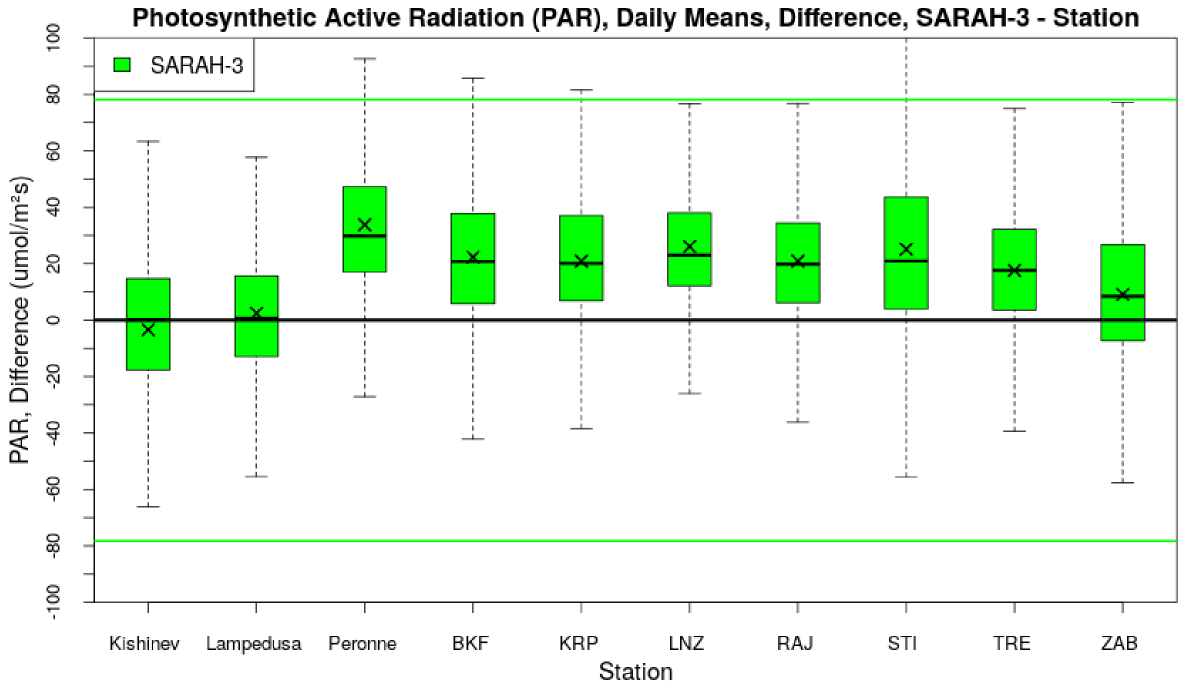
Daily means

The results of the validation of the PAR daily means are summarized in Table 4-11.

Table 4-11: Validation results of the Photosynthetic Active Radiation (PAR) daily means.

PAR	N_{day}	Bias [µmol/ m^2/s]	MAD [µmol/ m^2/s]	SD [µmol/ m^2/s]	StMAD [µmol/ m^2/s]	AC	$Frac_{mon}$ > target [%]
SARAH-3	31532	14.7	26.5	32.7	27.25	0.98	3.48 (>78 µmol/m^2/s)

Figure 4-11 shows the validation results of the SARAH-3 PAR daily means with reference to ten individual stations. Overall there is a slight positive bias, while for Kishinev and Lampedusa the agreement between SARAH-3 PAR and the station measurements is excellent.



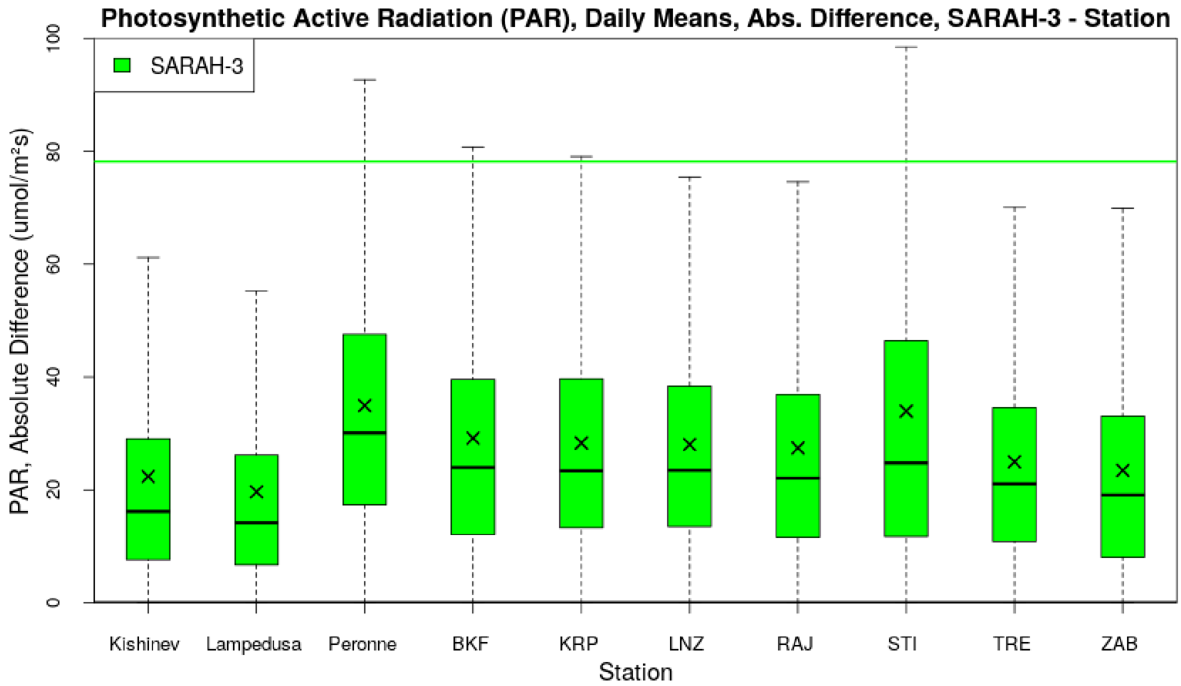


Figure 4-11: Boxplots of (top) the differences and (bottom) the absolute differences at the individual stations for the daily means of the Photosynthetic Active Radiation (PAR) of SARAH-3. The crosses indicate the mean of the differences and the absolute differences, respectively.

4.4 Daylight (DAL)

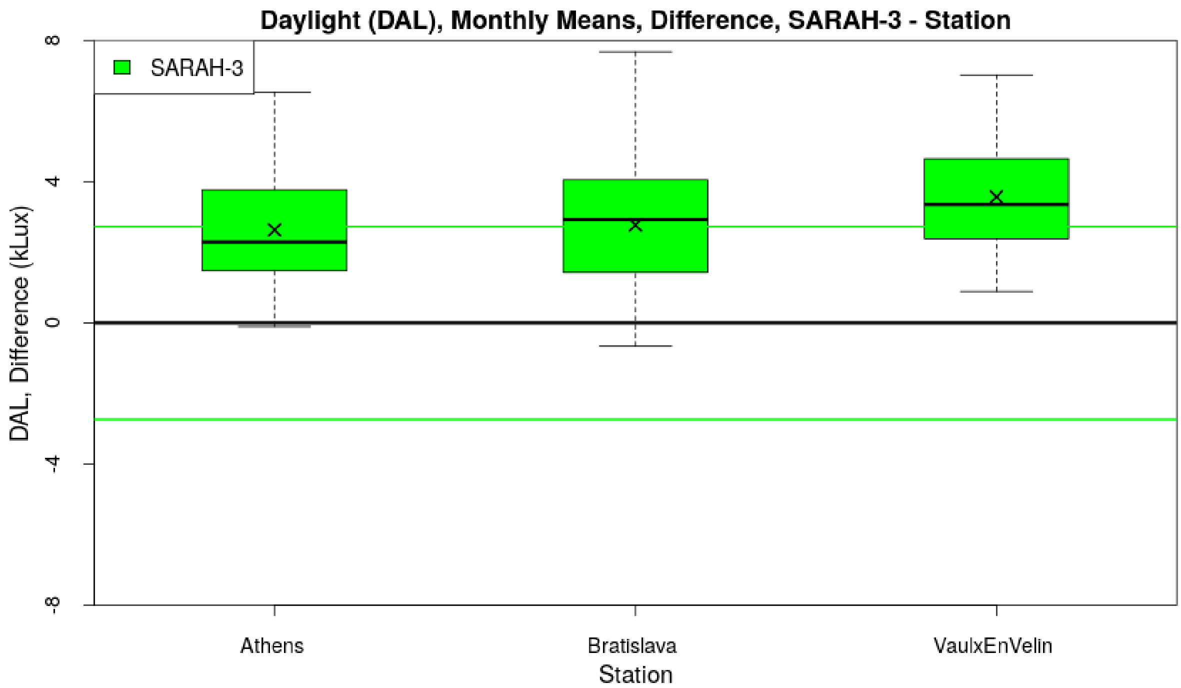
Monthly means

The validation of the SARAH-3 Daylight monthly means is summarized in Table 4-12. Overall there is a positive bias of SARAH-3 DAL, and a relative high percentage of monthly means exceed the threshold accuracy.

Table 4-12: Results of the comparison between the monthly mean Daylight (DAL) station measurements and the SARAH-3 DAL data record. The unit of DAL in kLux.

DAL	N_{mon}	Bias [kLux]	MAD [kLux]	SD [kLux]	StMAD [kLux]	AC	$Frac_{mon}$ > threshold [%]
SARAH-3	584	2.92	2.92	1.6	3.0	0.87	48.5 (>2.7 kLux)

Figure 4-12 shows the results of the comparisons between the SARAH-3 Daylight monthly means and three individual stations. The smallest mean and mean absolute biases are found for the station of Athens.



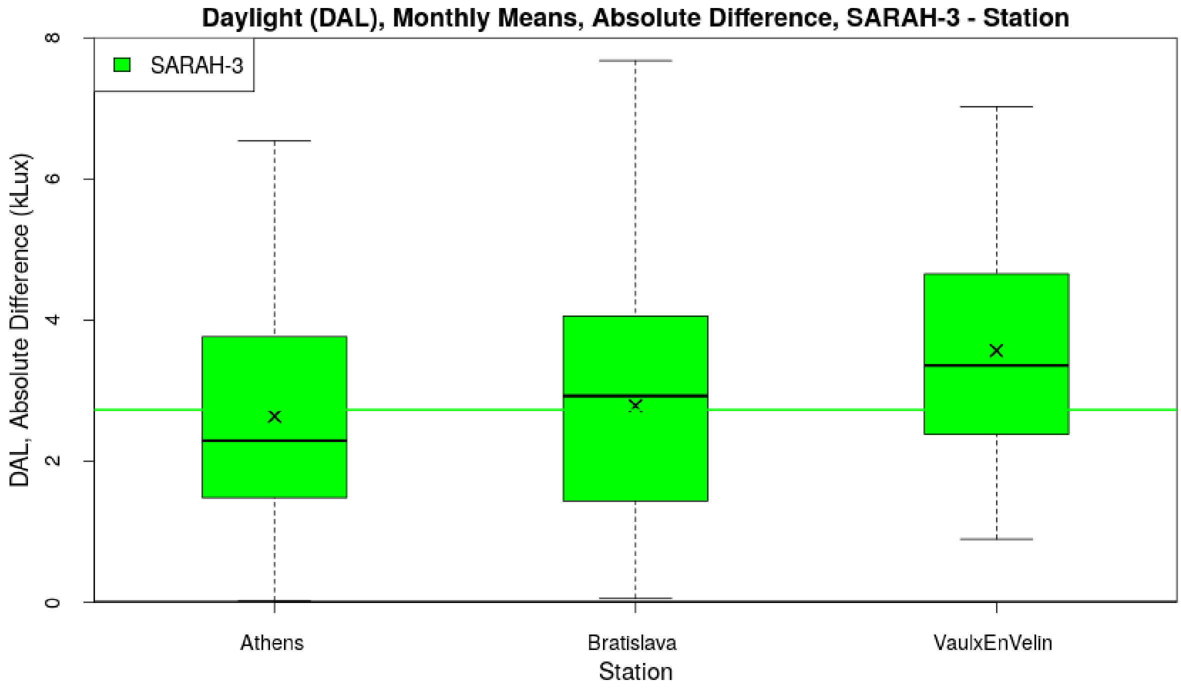


Figure 4-12: Boxplots of (top) the differences and (bottom) the absolute differences at the individual stations for the monthly means of the Daylight (DAL) of SARAH-3. The crosses indicate the mean of the differences and the absolute differences, respectively.

Daily means

The validation results of the Daylight daily means is summarized in Table 4-13. As for the DAL monthly means, the daily means show a positive bias of SARAH-3 DAL relative to the DAL stations measurements. The threshold accuracy is met for than 80% of the daily mean values.

Table 4-13: Results of the comparison between the daily mean Daylight (DAL) station measurements and the SARAH-3 DAL data record. The unit of DAL in kLux.

DAL	N_{mon}	Bias [kLux]	MAD [kLux]	SD [kLux]	StMAD [kLux]	AC	$Frac_{mon}$ > threshold [%]
SARAH-3	17775	2.87	3.04	2.3	3.08	0.95	19.2 (>4.8 kLux)

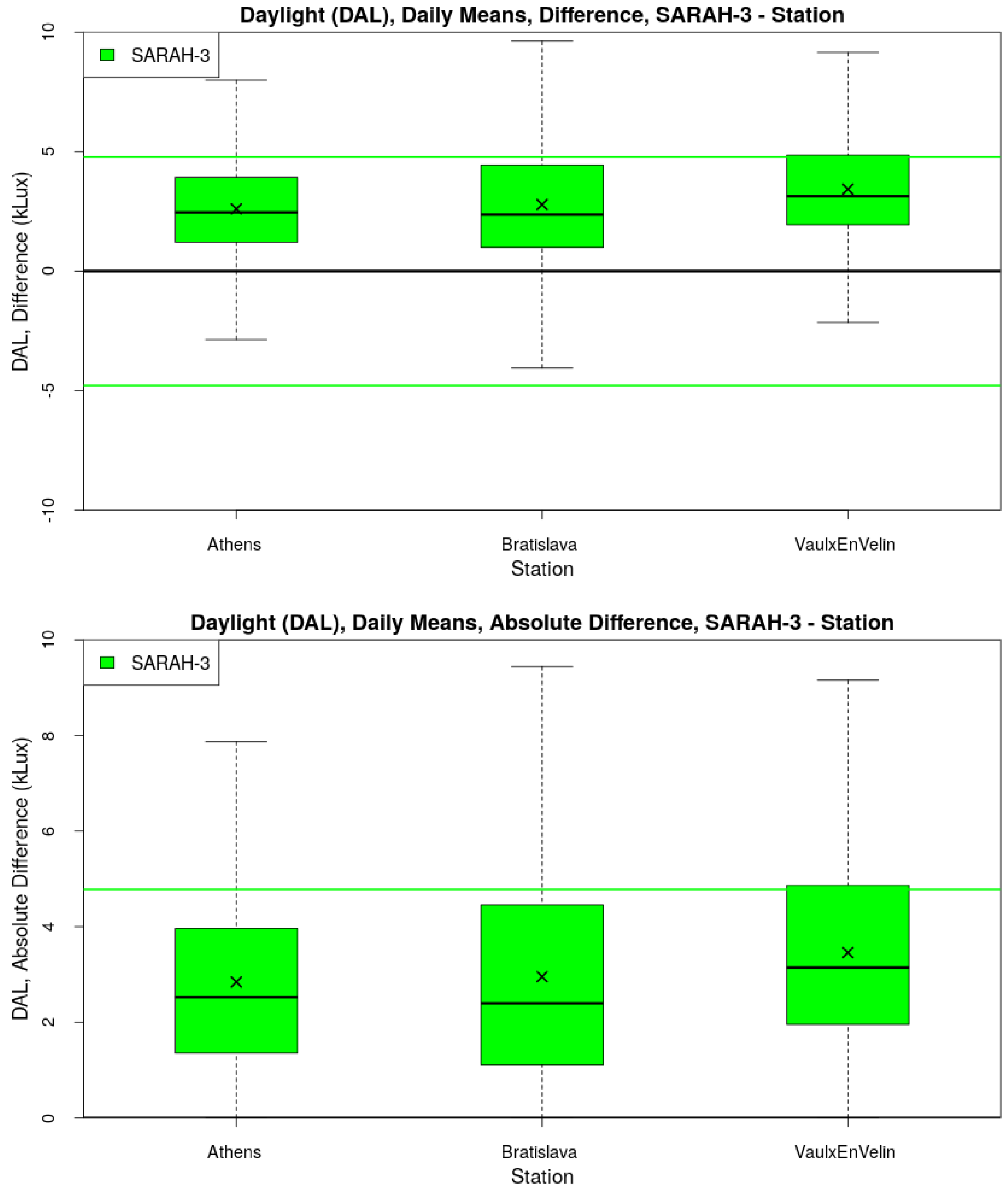


Figure 4-13: Boxplots of (top) the differences and (bottom) the absolute differences at the individual stations for the daily means of the Daylight (DAL) of SARAH-3. The crosses indicate the mean of the differences and the absolute differences, respectively.

4.5 Effective cloud albedo (CAL)

The effective cloud albedo is derived from the satellite observations using:

Equation 4-1
$$n = \frac{R - R_{srf}}{R_{\max} - R_{srf}}$$

Here, R is the observed reflection, R_{srf} is the clear sky reflection, and R_{max} the measure for the maximum cloud reflection. The effective cloud albedo (CAL; also called Cloud Index n, cf. Equation 4-1) is therefore a satellite observable and cannot be directly validated by comparison with ground-based measurements. The uncertainties in the retrieval of the effective cloud albedo are discussed in the Algorithm Theoretical Baseline Document (ATBD) (RD 1). However, since the effective cloud albedo is used to derive the solar irradiance, the known accuracy of SIS can be used to estimate the accuracy of the effective cloud albedo.

Uncertainties in SIS are due to uncertainties in the effective cloud albedo and due to uncertainties in the clear sky irradiance. Here, perfect clear sky irradiance (no errors) is assumed, which relates all uncertainties in SIS to the effective cloud albedo. The results obtained in the following can be considered the lower limit of the accuracy for the effective cloud albedo.

The relation between the effective cloud albedo CAL and the solar irradiance is pre-dominantly given by:

Equation 4-2
$$SIS = (1 - CAL) \cdot SIS_{clear}$$

Based on Equation 4-2 the “worst case” accuracy of the effective cloud albedo can be derived as a function of the clear sky irradiance, based on error propagation, assuming an error-free estimation of the clear sky irradiance:

Equation 4-3
$$\Delta CAL = \Delta SIS / SIS_{clear}$$

The SIS mean absolute difference, ΔSIS, as derived from comparison to surface reference measurements consists of the mean absolute difference for cloudy and for clear sky. Figure 4-14 shows the uncertainty of the effective cloud albedo, ΔCAL, according to Equation 4-3, i.e., neglecting possible uncertainty of the clear-sky surface irradiance. The estimated uncertainty of surface irradiance, ΔSIS, however, includes a contribution from clear-sky situations. It is clear that this evaluation method is a workaround, but the effective cloud albedo is a satellite observable and can not be validated “directly”.

Monthly means

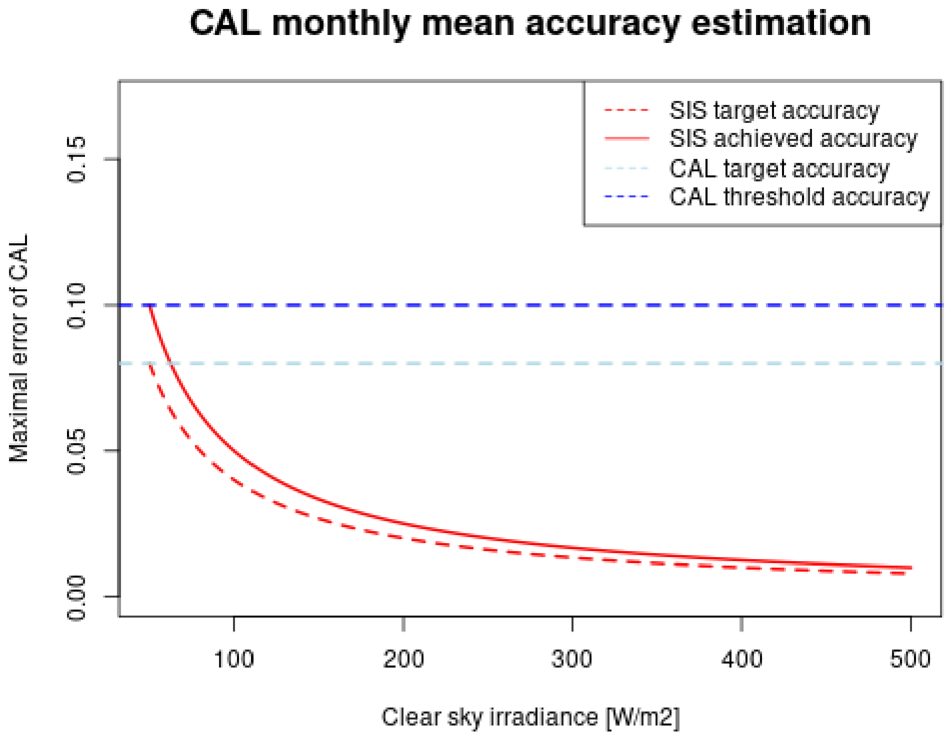


Figure 4-14: Maximum error of the monthly mean effective cloud albedo in dependency of the clear sky irradiance based on the derived SIS accuracy. The target accuracy is 4 W/m². For the achieved SIS accuracy the mean absolute difference given in Table 4-1 has been used.

Figure 4-14 shows that values above the target accuracy of 0.08 only occur for clear sky irradiances below 62 W/m². Values above the threshold accuracy of 0.1 only occur for clear sky irradiances below 50 W/m². Hence, it can be concluded that the target accuracy of the effective cloud albedo is achieved with exception of the winter months above latitude of 55° North and South, respectively. During the winter period at high latitudes slant geometry for the retrieval of the effective cloud albedo is given (slant viewing geometry and low solar zenith angle) in addition to long-lasting cloud coverage. As discussed in the PUM (RD 2) this leads to a higher uncertainty in the effective cloud albedo. Hence, it is likely that the target and threshold accuracy is not met during the winter period at high latitudes.

Daily means

The same method as for the monthly means is applied to estimate the uncertainty of the daily mean effective cloud albedo.

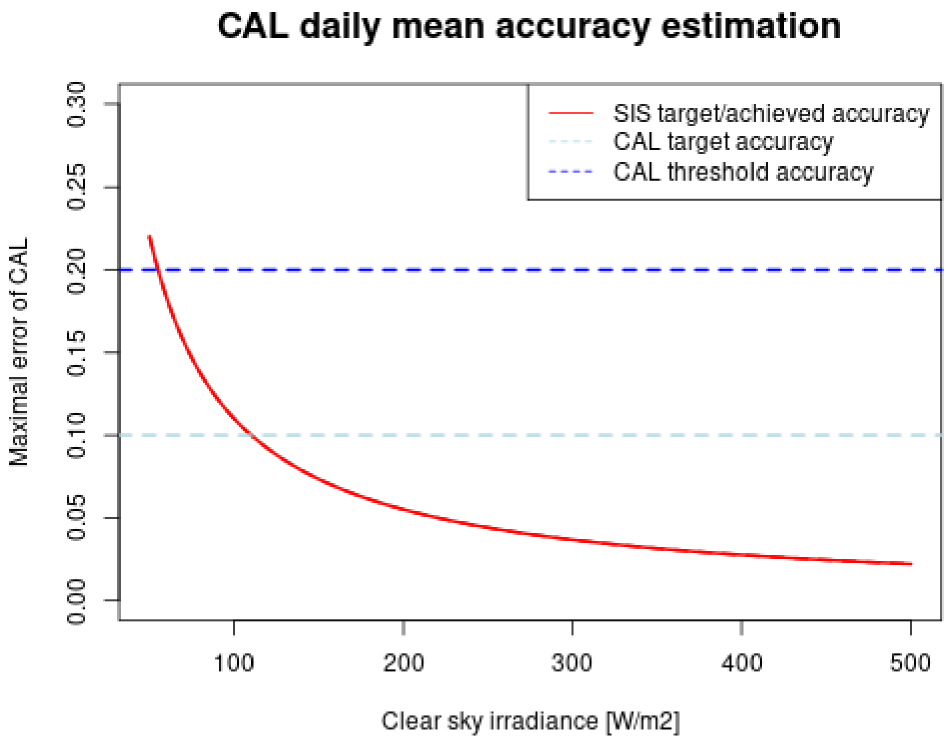


Figure 4-15: Maximal error of the effective cloud albedo (daily mean) for different clear sky irradiance values based on the derived SIS accuracy for daily means. The target accuracy is 11 W/m². For the achieved SIS accuracy the mean absolute difference given in Table 4-2 has been used.

In Figure 4-15 it is shown that values above the target accuracy of 0.1 only occur for clear sky irradiances below 110 W/m². Values above the threshold accuracy of 0.2 only occur for clear sky irradiances below 55 W/m². Hence, based on the evaluated SIS accuracy it can be stated that the target accuracy of the effective cloud albedo is achieved for the majority of the Meteosat disk throughout the year. However, the method fails to provide secure information whether the target accuracy is fulfilled during the winter period (+/-1.5 month period around the respective winter solstice). During the winter period at high latitudes a slant geometry for the retrieval of the effective cloud albedo is given (slant viewing geometry and low solar zenith angle) in addition to long-lasting cloud coverage. As discussed in the PUM (RD 2) this leads to a higher uncertainty in the effective cloud albedo. Hence, it is likely that the target and the threshold accuracy is not met during the winter period at high latitudes.

4.6 Sunshine Duration (SDU)

Monthly sums

Table 4-14 shows the validation results of sunshine duration (SDU) monthly sums from the new CM SAF SARAH-3, and the SARAH-2.1+ICDR, SARAH-2.1 and SARAH-2 surface radiation data sets compared to the observations from CLIMAT measurements. A positive bias of 6.2 h is found in the SARAH-3 SDU data set. The mean absolute difference is 15.4h and therefore close to the target accuracy of 15h. Considering the uncertainty of the surface measurement, the target accuracy requirement is fulfilled. The standard deviation and, thus, the spread is 20.4h. More than 70% of the monthly sum values are better than the threshold accuracy value excluding measurement uncertainty. The anomaly correlation reaches a good value of 0.88.

Table 4-14: Results of the comparison between the sunshine duration monthly sums derived from CLIMAT station data and the SARAH-3, SARAH-2.1+ICDR, SARAH-2.1 and SARAH-2 SDU sunshine duration data set.

SDU	N_{mon}	Bias [h]	MAD [h]	SD [h]	stMAD	AC	$Frac_{mon}$ > threshold [%]
SARAH-3	139786	6.24	15.40	20.37	15.43	0.88	26.6 (>20h)
SARAH-2.1+ICDR	139786	8.49	16.59	21.28	16.54	0.88	29.5 (>20h)
SARAH-2.1	137811	8.45	16.6	21.3	/	0.88	13.7 (>30h)
SARAH-2	117373	7.23	18.7	24.3	/	0.84	18.5 (>30h)

The Figure 4-16 and Figure 4-17 show the Bias and MAD for all used CLIMAT stations and their spatial distribution. Bias and MAD are lower in Central Europe, UK, South Africa and parts of South America, increase in the Mediterranean, and are highest in West Africa. The region of West Africa is known for large low-level cloud, which might be underestimated by the satellite retrieval. This might lead to an overestimation of sunshine duration in these regions. But, as Figure 4-18 shows, most MAD values are within the threshold accuracy.

Please note that the spatial distribution of the available reference stations is highly biased towards Europe, in particular Germany. As each monthly sum is equally weighted for the estimation of the average quality assessment parameters in Table 4-14 the provided averaged numbers are biased towards the quality performance in Europe / Germany.

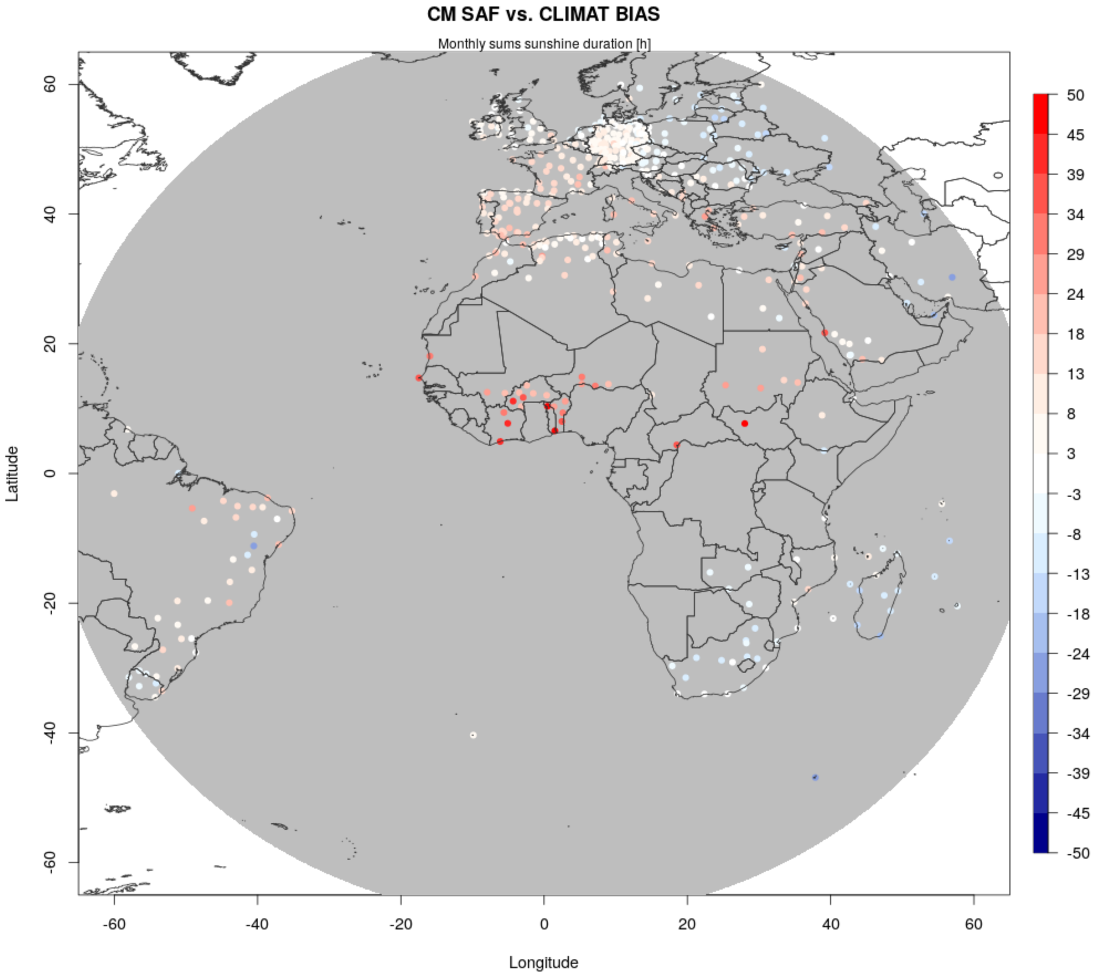


Figure 4-16: Bias for the comparison of sunshine duration monthly sums of CLIMAT station data and SARAH-3 SDU.

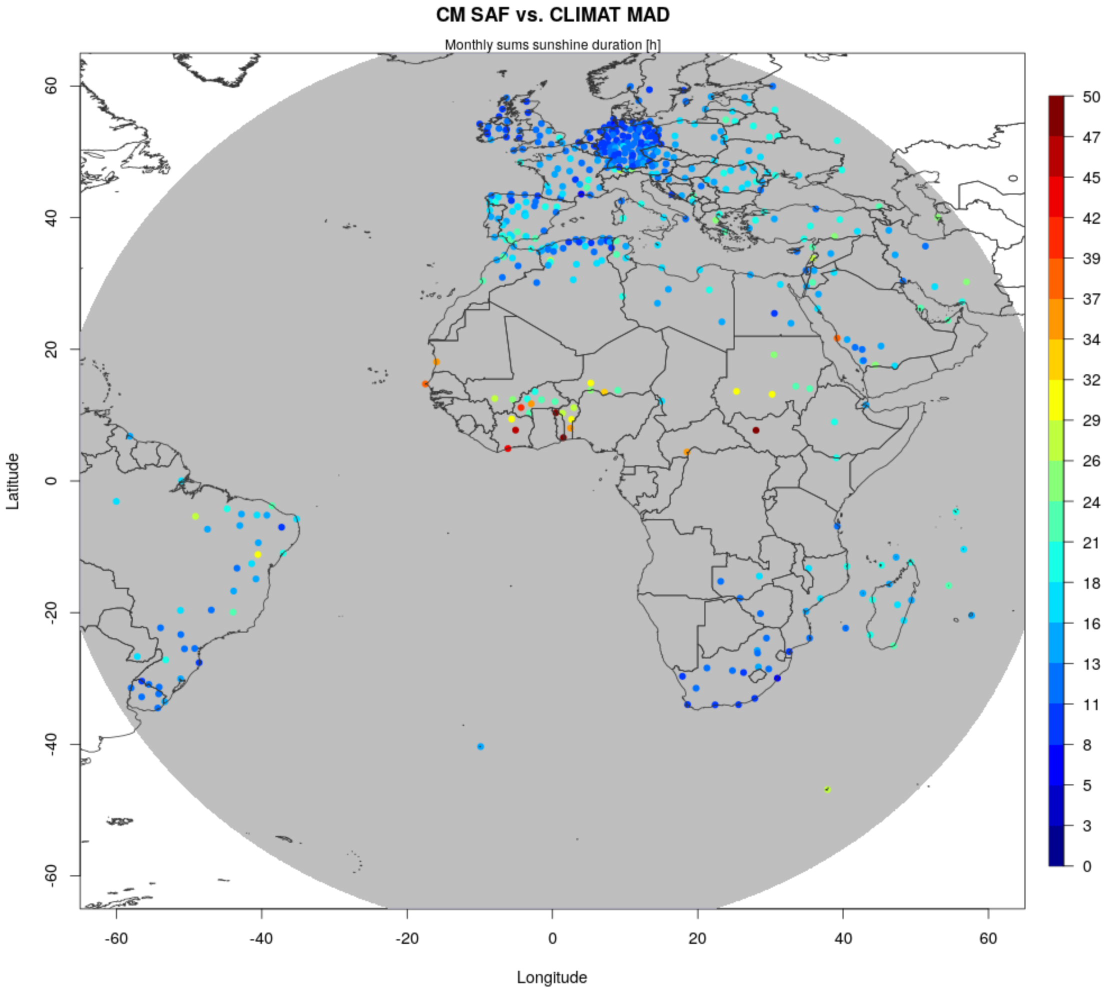


Figure 4-17: Mean absolute difference (MAD) for the comparison of sunshine duration monthly sums of CLIMAT station data and SARAH-3 SDU.

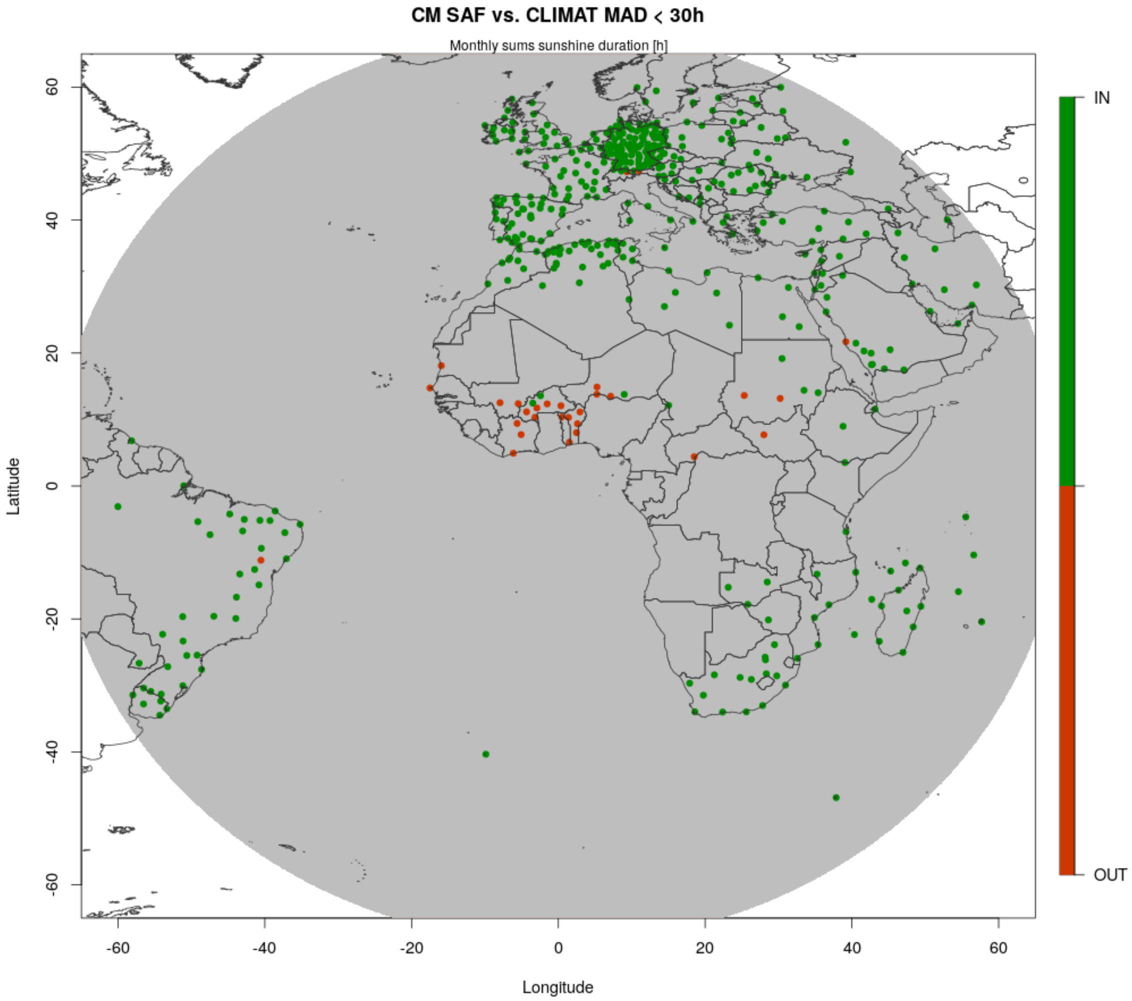


Figure 4-18: Stations matching the threshold accuracy (MAD < 30h) for the comparison of sunshine duration monthly sums of CLIMAT station data and SARAH-3 SDU.

Daily sums

Table 4-15 shows the validation results of the sunshine duration (SDU) daily sums from the new CM SAF SARAH-3 and its predecessor SARAH-2.1 surface radiation data set compared to the observations from the ECA&D measurements. A positive bias of 0.25 h (i.e. 15 minutes) is found in the SARAH-3 SDU data set. The mean absolute difference is 1.05 h and therefore in the range of the target accuracy of 1 h. The standard deviation and, thus, the spread is 1.64 h. More than 70 % of the daily sum values are better than the threshold accuracy value excluding measurement uncertainty. The anomaly correlation reaches a good value of 0.91.

Table 4-15: Results of the comparison between the sunshine duration daily sums derived from ECA&D station data and the SARAH-3, SARAH-2.1+ICDR, SARAH-2.1 and SARAH-2 SDU sunshine duration data records.

SDU	N_{day}	Bias [h]	MAD [h]	SD [h]	AC	$Frac_{day}$ > 1.5 h [%]
SARAH-3	4,579,221	0.25	1.05	1.64	0.91	23.5

SDU	N_{day}	Bias [h]	MAD [h]	SD [h]	AC	$Frac_{day}$ > 1.5 h [%]
SARAH-2.1+ICDR	4,575,907	0.30	1.07	1.64	0.91	23.8
SARAH-2.1	2,642,777	0.37	1.01	1.45	0.93	22.8
SARAH-2	2,484,980	0.44	1.35	1.97	0.87	32.7

The Figure 4-19 and Figure 4-20 show the Bias and MAD for all used ECA&D stations and their spatial distribution. Bias and MAD are lowest in Germany, while somewhat higher deviations were found in Spain. As Figure 4-21 shows, most MAD values are within the target accuracy, even though for several stations in Spain the threshold accuracy is not met – keeping in mind the much higher average sunshine durations and excluding measurement uncertainty.

Please note that the spatial distribution of the available reference stations is highly biased towards Germany / The Netherlands. As each daily sum is equally weighted for the estimation of the average quality assessment parameters in Table 4-15 the provided averaged numbers are biased towards the quality performance in Germany / The Netherlands.

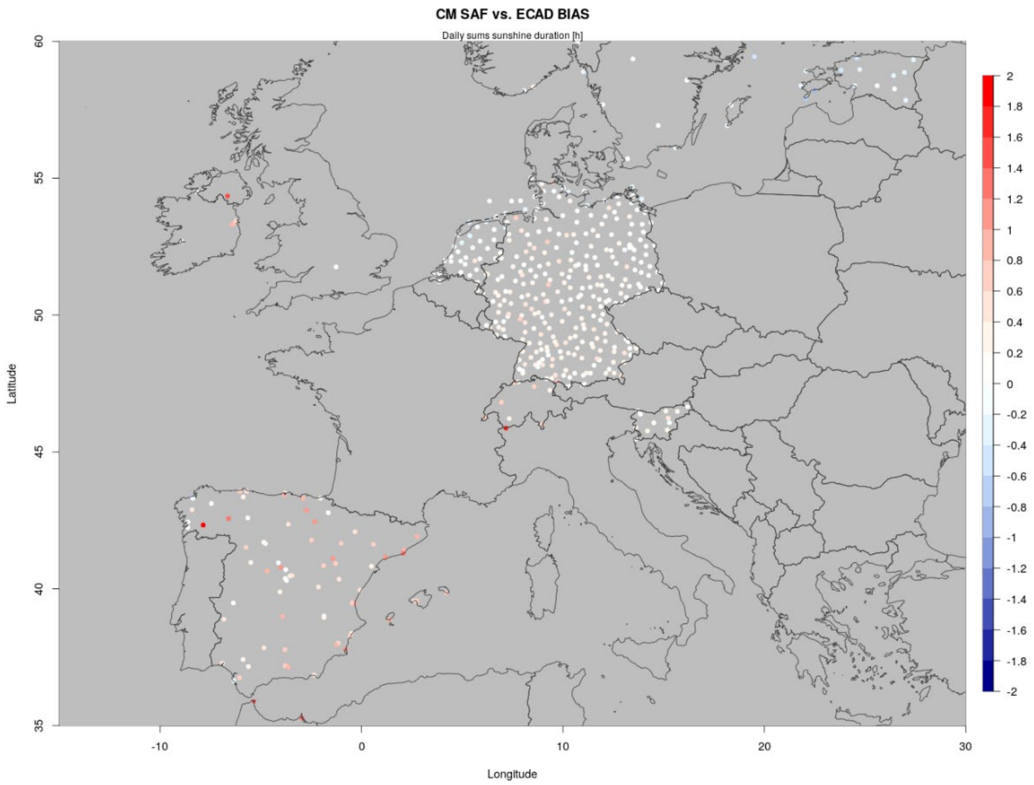


Figure 4-19: Bias for the comparison of sunshine duration daily sums of ECA&D station data and SARAH-3 SDU.

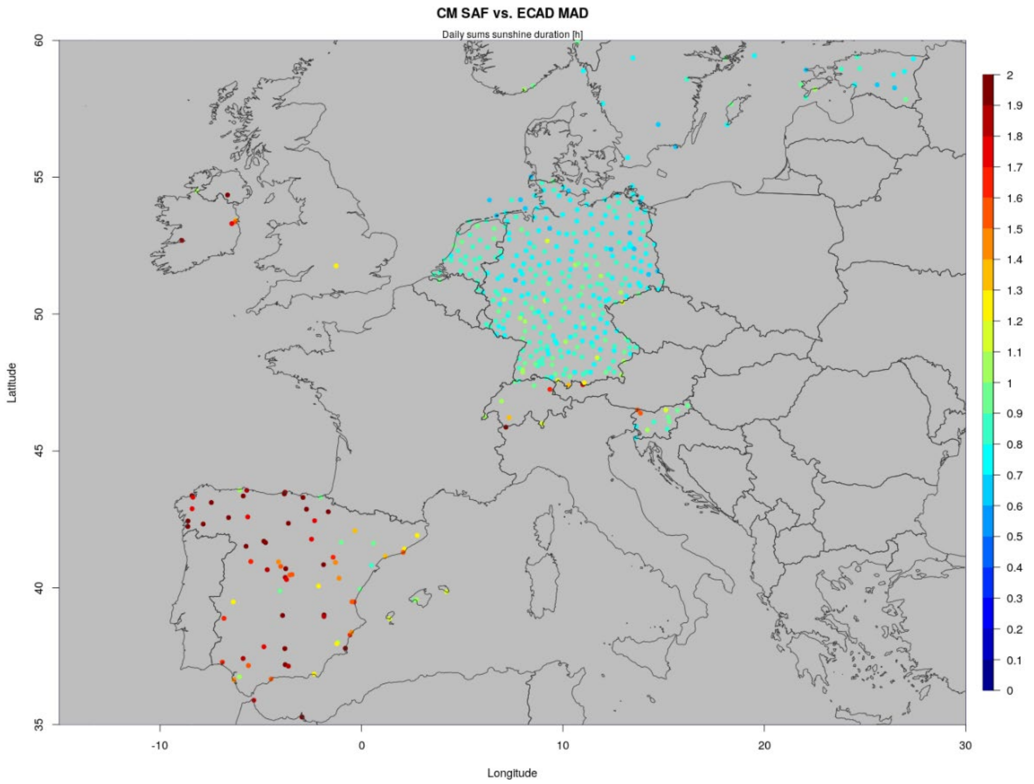


Figure 4-20: Mean absolute difference (MAD) for the comparison of sunshine duration daily sums of ECA&D station data and SARAH-3 SDU.

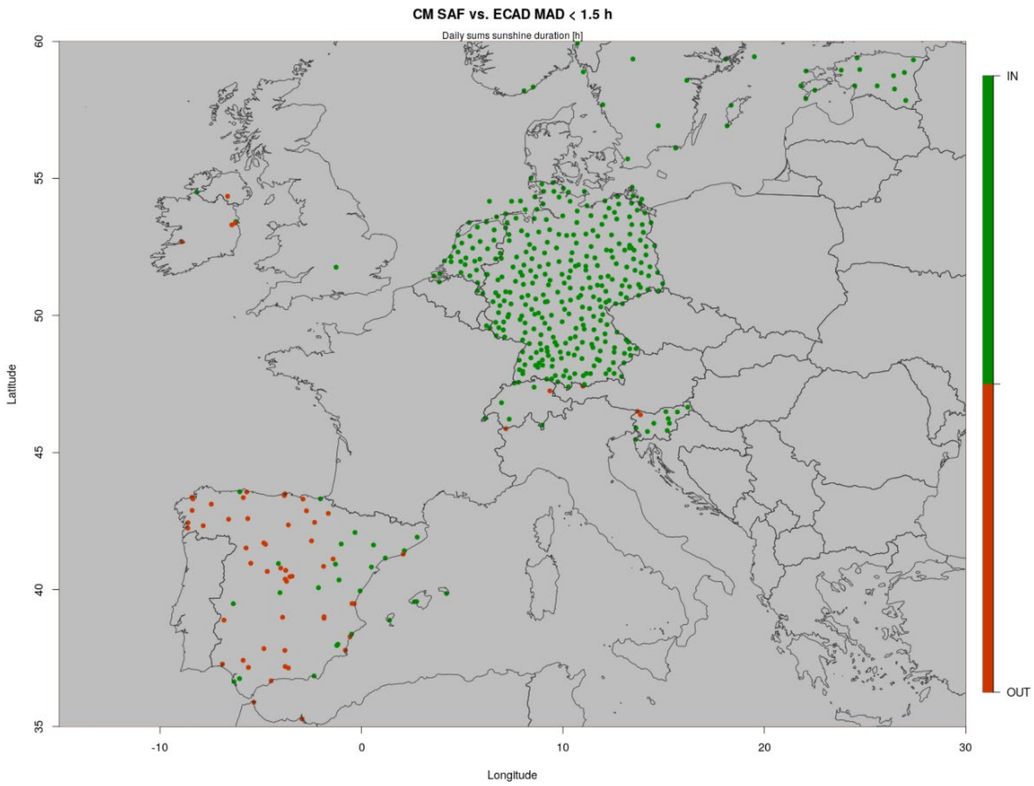


Figure 4-21: Stations matching the threshold accuracy (MAD < 1.5h) for the comparison of sunshine duration daily sums of ECAD station data and SARAH-3 SDU.

5 Influence of the new treatment of snow using HELSNOW and the new surface albedo background maps

The improved consideration of snow covered surfaces in the retrieval of the Effective Cloud Albedo and hence in the retrieval of the surface solar radiation parameters results in higher surface radiation in regions frequently effected by snow. Hence the mean surface radiation is significantly increased in mountainous areas like the European Alps or the Scandinavian Mountains (see Figure 5-1), with values in the order of 10 W/m^2 and more.

Further the new monthly climatological spectral surface albedo background maps based on MODIS satellite observations (Blanc et al. 2014) lead to changes in SARAH-3 relative to SARAH-2.1 mainly in desert regions (see Figure 5-1) mostly in the range of ±5 W/m^2.

More details on the algorithm to generate the SARAH-3 climate data record can be found in the Algorithm Theoretical Basis Document [RD 1].

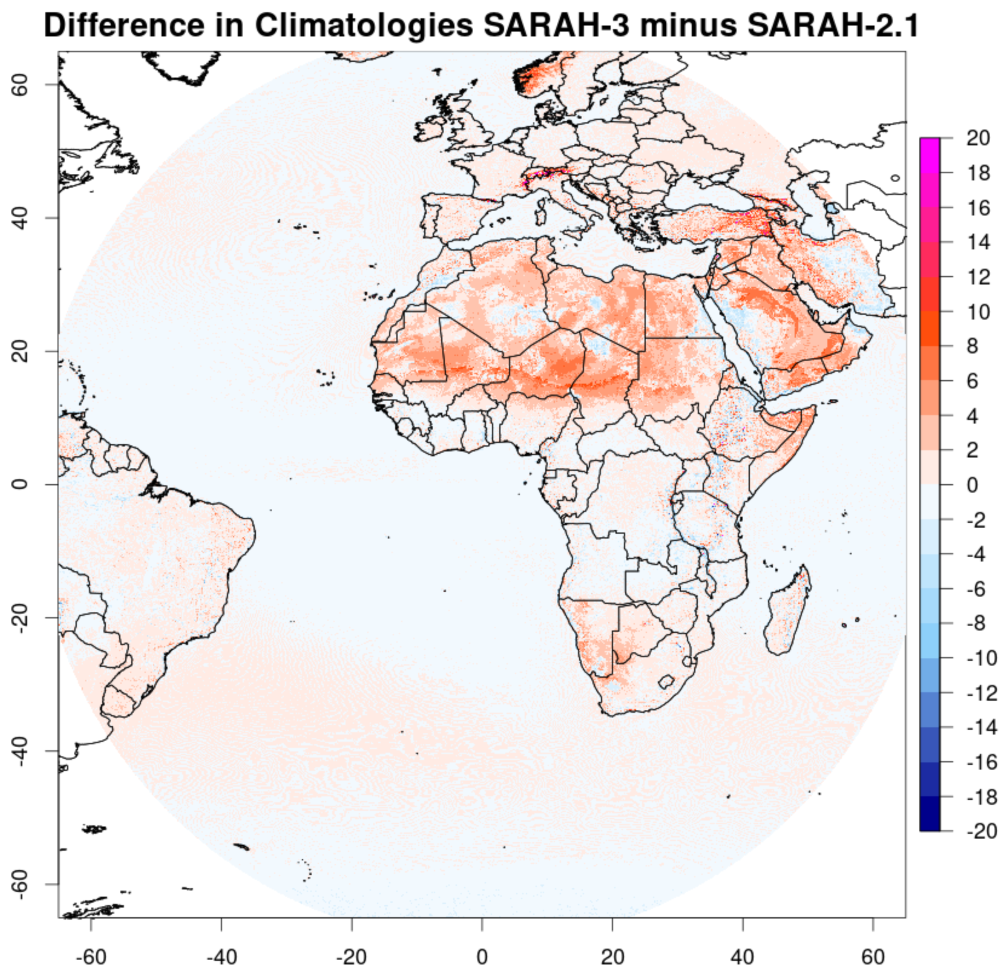


Figure 5-1: Mean Difference between SARAH-3 and SARAH-2.1 global radiation (SIS) in W/m^2. Reddish colors indicate higher global radiation values in SARAH-3, bluish colors indicate lower values in SARAH-3

6 Stability of the solar surface irradiance data records

The definition of a climate data record requests that the time series is homogeneous over time, so that it can be meaningfully statistically analysed by, for instance, performing anomaly or trend analysis. Artificial steps and/or temporal trends in the data record, e. g., due to changes in the satellite instrument, would result in unrealistic changes and trends, which do not represent changes or trends of the climate.

Special attention is given to the times when the satellite instruments changed. Table 6-1 gives an overview of the major operational periods (longer than 3 months) of the individual Meteosat satellites. Switches between satellites for a few days due to the decontamination procedure are not listed here. For a complete listing of Meteosat operational periods see Decoster et al. (2014) and documentation by EUMETSAT (EUM/OPS/DOC/08/4698)

Table 6-1: Major operational periods for the used Meteosat satellites

Satellite	Instrument	From	To
Meteosat 2	MVIRI	16 Aug 1981	11 Aug 1988
Meteosat 3	MVIRI	11 Aug 1988	19 Jun 1989
Meteosat 4	MVIRI	19 Jun 1989	24 Jan 1990
Meteosat 3	MVIRI	24 Jan 1990	19 Apr 1990
Meteosat 4	MVIRI	19 Apr 1990	4 Feb 1994
Meteosat 5	MVIRI	4 Feb 1994	13 Feb 1997
Meteosat 6	MVIRI	13 Feb 1997	3 Jun 1998
Meteosat 7	MVIRI	3 Jun 1998	31 Dec 2005
Meteosat 8	SEVIRI	1 Jan 2006	10 Apr 2007
Meteosat 9	SEVIRI	11 Apr 2007	20 Jan 2013
Meteosat 10	SEVIRI	21 Jan 2013	20 Feb 2018
Meteosat 11	SEVIRI	21 Feb 2018	31 Dec 2020

A common method to assess the homogeneity of a climate data record is to analyse the anomalies with respect to any obvious steps. Changes in the mean state from one satellite to the other would be visible as an increase or decrease in positive or negative anomalies. Figure 6-1 shows the Hovmoeller diagram of the monthly mean anomalies of SIS and SDI parameters. The time range contains the full time period of the SARAH-3 data record starting with Meteosat 2 in 1983 until Meteosat 11 in 2020. No obvious steps are present in the time series of the anomaly for the whole time range, pointing to a reasonable stability of the SARAH-3 climate data record.

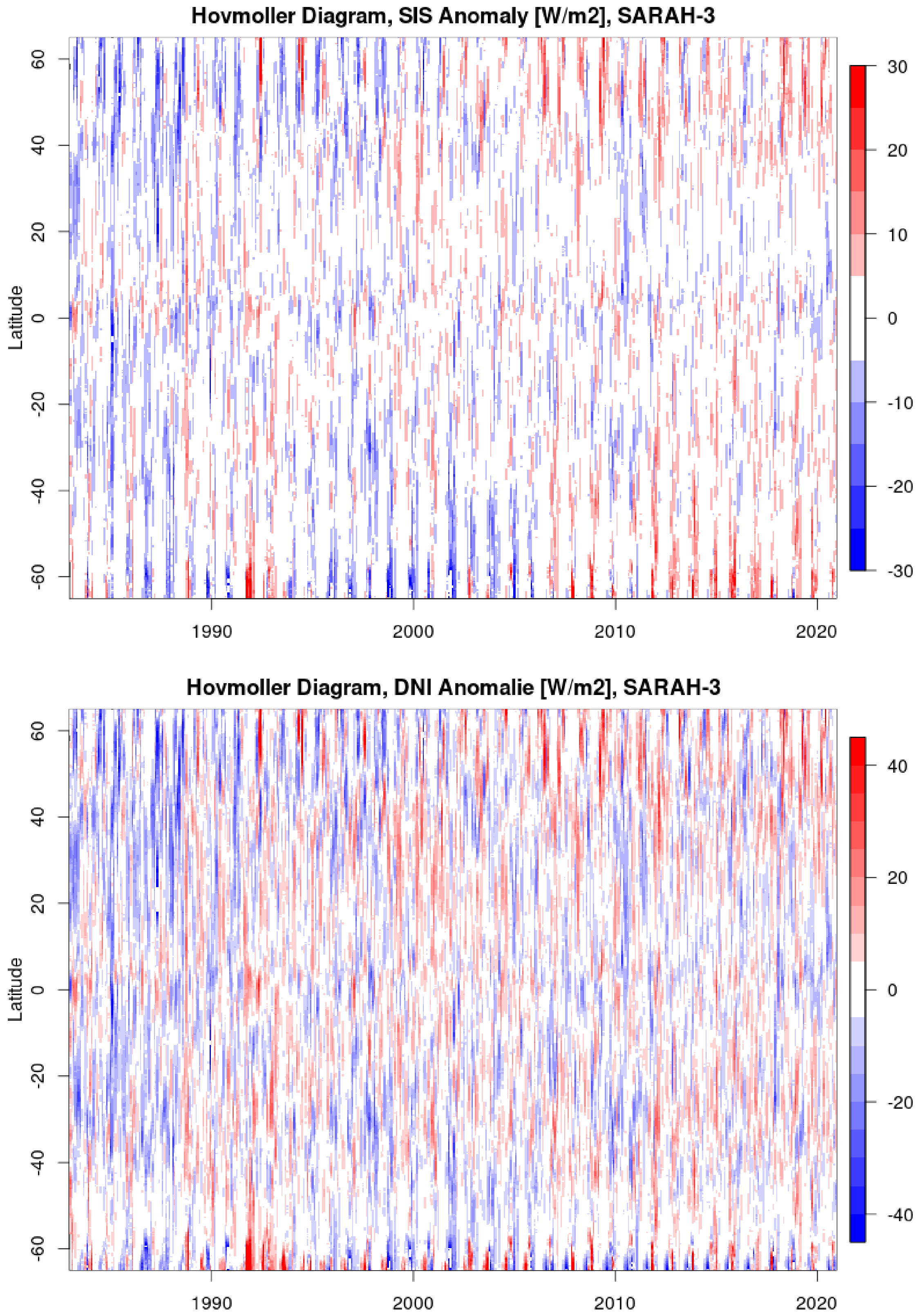


Figure 6-1: Hovmoeller diagrams for the full time period (1983-2020) of the monthly mean SARAH-3 anomalies of (top) SIS and (bottom) DNI.

To evaluate and quantify the stability of the SARAH-3 data record, surface reference measurements from the GEBA (Global Energy Balance Archive) are used. While the BSRN observations follow a high quality standard and are considered as a GCOS reference observing network, the data in the GEBA have a longer temporal coverage, which is important for the assessment of the temporal stability. To assess the temporal stability of the satellite-based data, the reference observations need to be stable over time as well. Selected European GEBA stations have been assessed with respect to their temporal stability and partly adjusted to ensure their homogeneity (Sanchez-Lorenzo et al. 2013). Only GEBA stations considered to be homogeneous are used here.

Figure 6-2 shows the temporal evolution of the average bias between the monthly mean SARAH-3 and SARAH-2.1 SIS data record and the measurements from the GEBA stations. Only stations with more than 95% available monthly means between 1983 and 2018 are considered to avoid artificial shifts in the time series due to changes in data availability.

A negative decadal trend of -0.6 ± 0.4 W/m^2/decade of the bias between SARAH-3 and GEBA is detected for the time period of 1983 to 2018. This trend is found to be statistically significant, but is close to the respective target accuracy (0.5 W/m^2/decade). In addition, Figure 6-2 shows the corresponding time series of the bias of the SARAH-2.1 SIS data record, which exhibits a somewhat more negative trend of -0.8 W/m^2/decade compared to the GEBA surface observations for the time period 1983 to 2017. The temporal stability of the SARAH-1 data record has been worse (-1.7 W/m^2/decade). Overall the stability of the new SARAH-3 climate data record is slightly improved compared to its predecessor. More details on the temporal variability and trends of the SARAH-2 climate data record can be found in Pfeifroth et al., 2018.

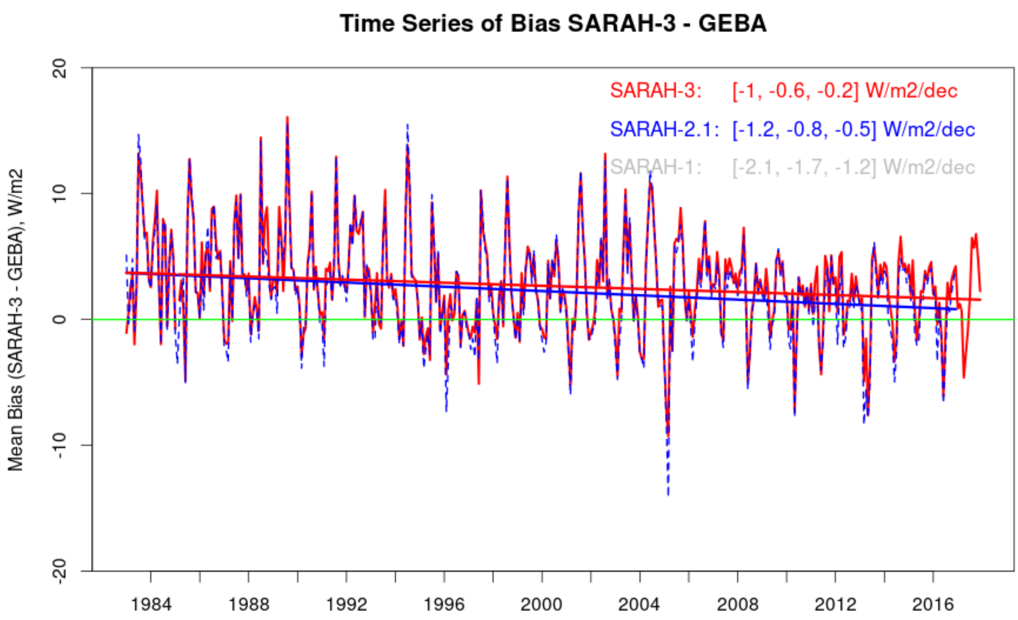


Figure 6-2: Temporal evolution of the normalized differences between the CM SAF SARAH data records and the GEBA data for the time period 1983-2018. The green line represents the zero trend line. The black and the red straight lines represent the linear regressions of the time series for the SARAH-3 and SARAH-2.1 global irradiance data records.

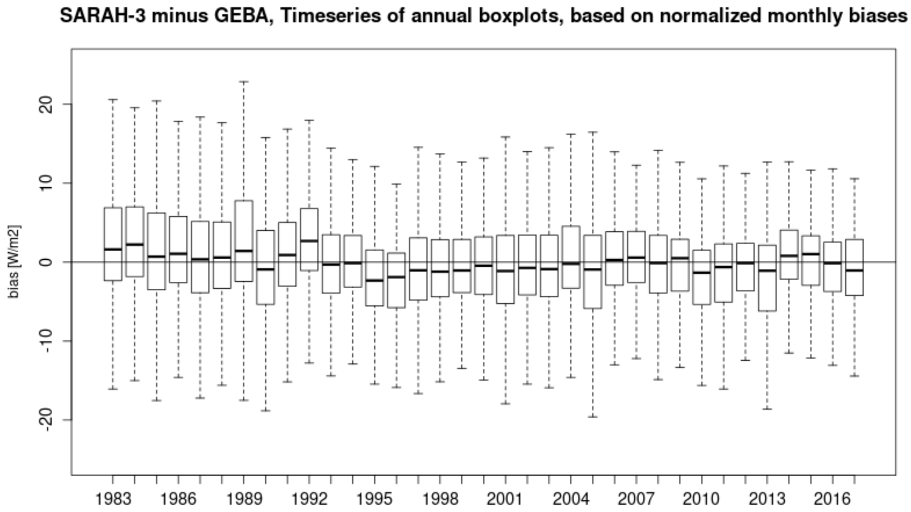


Figure 6-3: Annual boxplots of the differences between the SARAH-3 surface irradiance and the data from the GEBA data base, based on the time series of the normalized biases; outliers are not shown.

To further explore the temporal stability of the SARAH-3 surface irradiance data record and to assess the random error, Figure 6-3 shows the annual boxplots of the differences between the SARAH-3 derived monthly irradiance and the data from GEBA data base. The temporal evolution of the annual median values generally follows the mean bias as shown in Figure 6-2, without the annual cycle. The spread of the differences is indicated by the white boxes and the whiskers; for the sake of Figure clarity and to limit the impact of outlies these are not shown in Figure 6-3. The length of the whiskers of the boxplots decrease over time, documenting a reduced variability in the difference between the satellite- and the surface-based irradiance data. This reduced variability might indicate an improving accuracy of the satellite data record (i.e., a reduction of the random error over time), but might also point to improved performance of the surface solar radiation measurements.

7 ICDR data validation

The SARAH-3 CDR is consistently extended in time by the corresponding Interim Climate Data Record (ICDR). Here, the SARAH-3 ICDR data are validated with reference to the SARAH-3 data records for the year 2020. In following the pixel-wise mean biases and mean absolute biases are presented for each parameter and temporal resolution.

7.1 Solar Surface Irradiance (SIS)

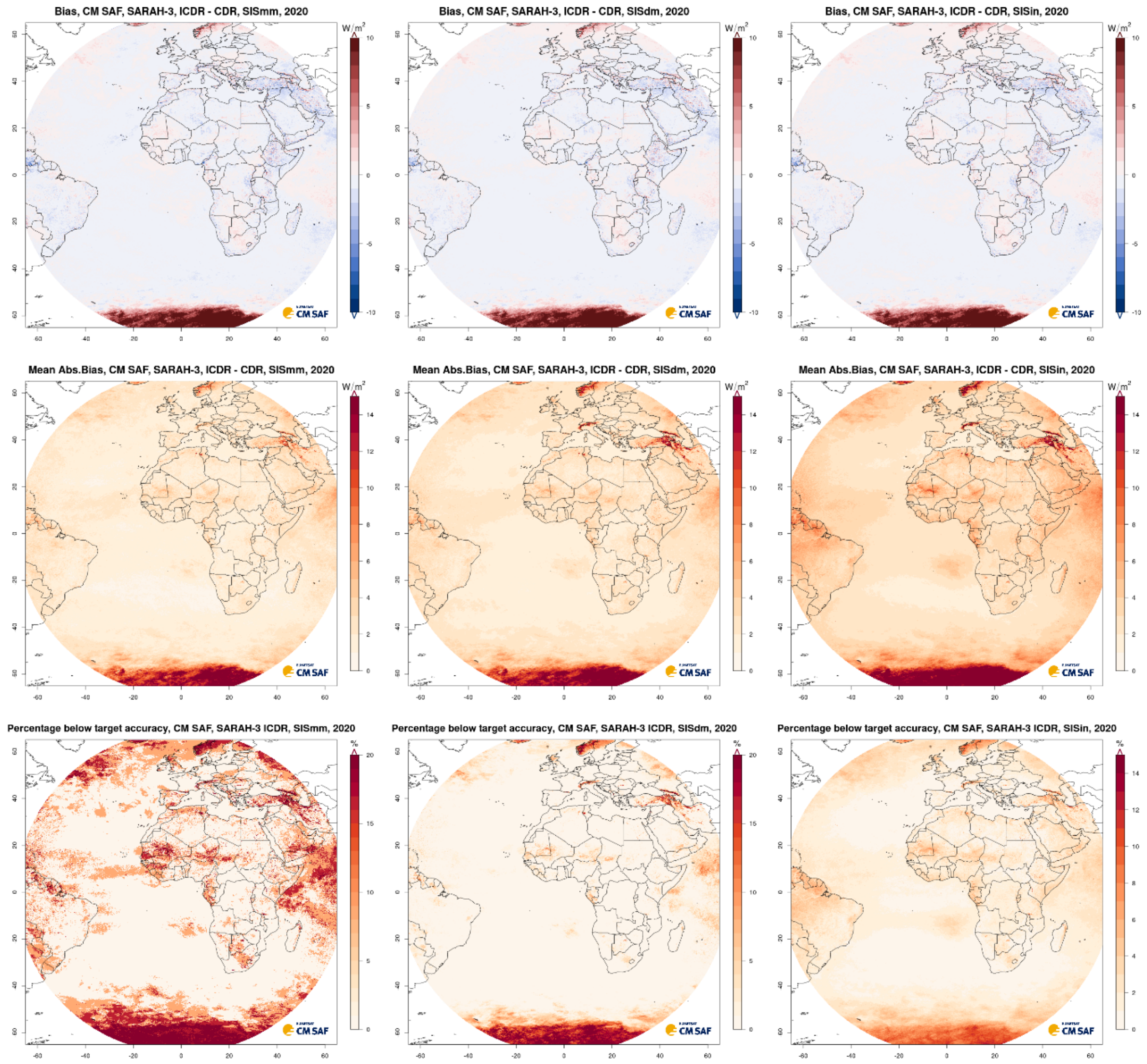


Figure 7-1: Bias (top row, ICDR minus CDR), mean absolute bias (middle row, ICDR minus CDR) and percentage of values with MAB exceeding the target requirement (bottom row) of the SARAH-3 ICDR Surface Incoming Solar Radiation (SIS) monthly (left), daily (middle) and instantaneous (right) data for 2020.

7.2 Surface Direct Irradiance Parameters

SID:

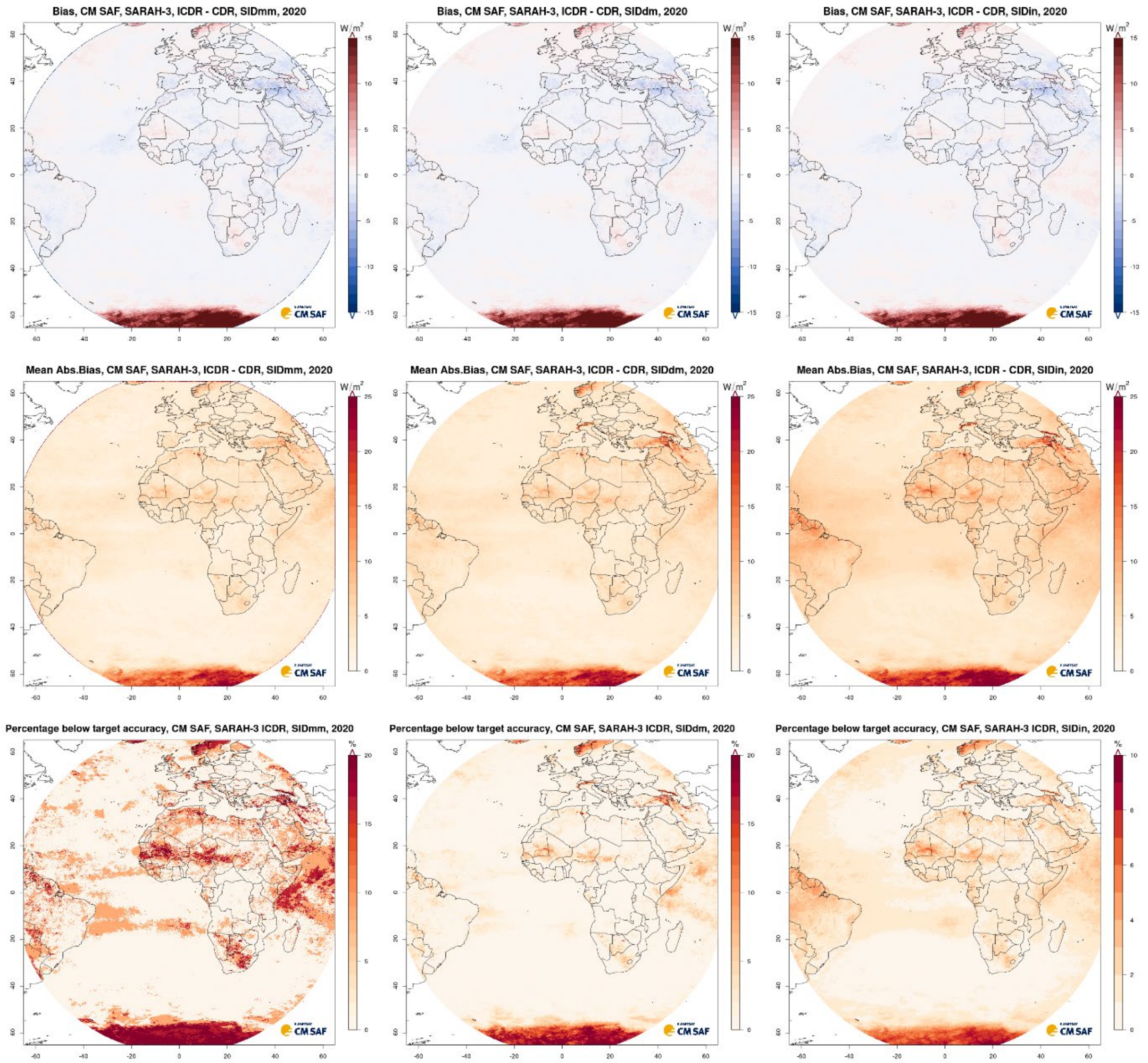


Figure 7-2: Bias (top row, ICDR minus CDR), mean absolute bias (middle row, ICDR minus CDR) and percentage of values with MAB exceeding the target requirement (bottom row) of the SARAH-3 ICDR Surface Incoming Direct Radiation (SID) monthly (left), daily (middle) and instantaneous (right) data for 2020

DNI:

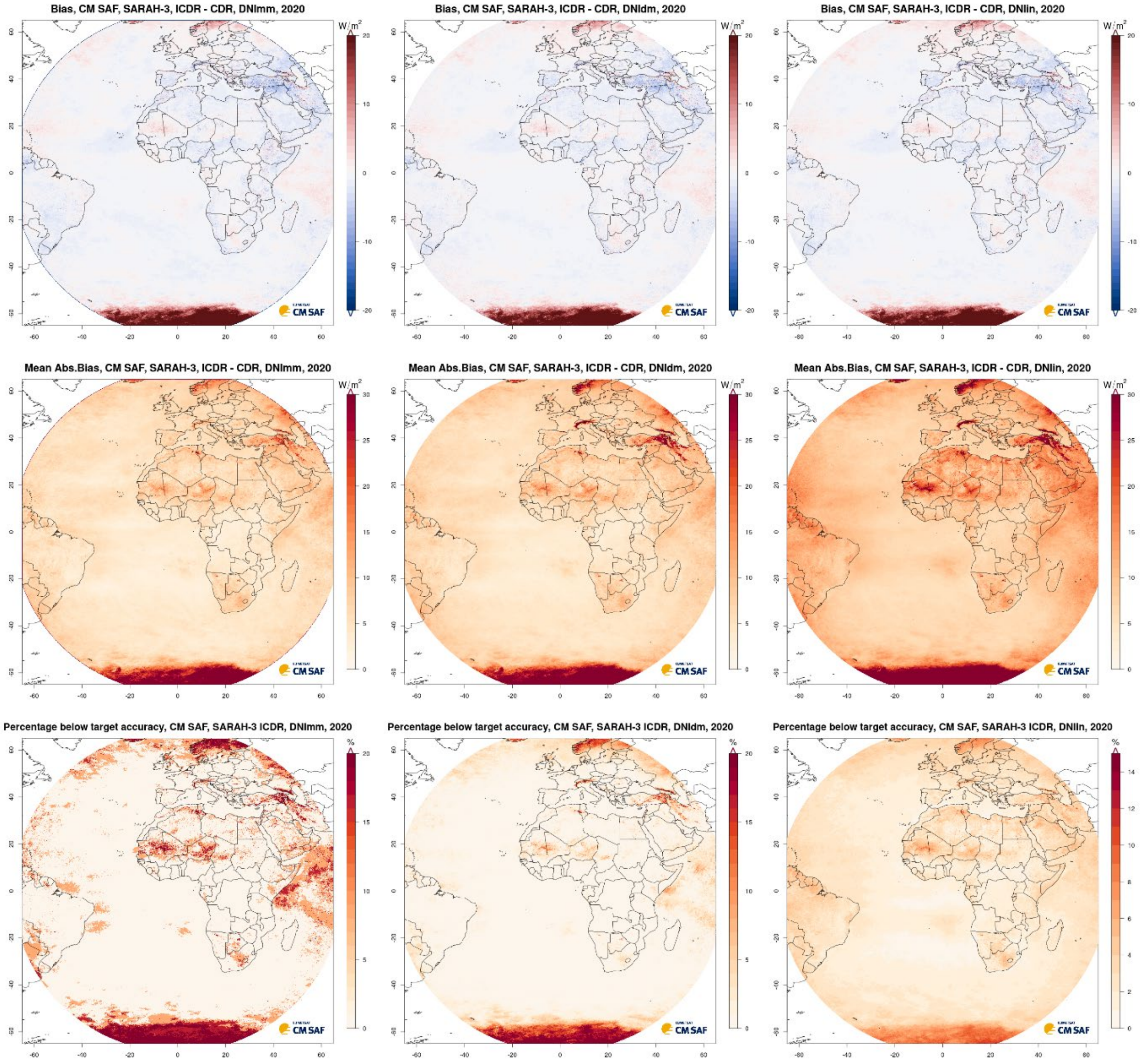


Figure 7-3: Bias (top row, ICDR minus CDR), mean absolute bias (middle row, ICDR minus CDR) and percentage of values with MAB exceeding the target requirement (bottom row) of the SARAH-3 ICDR Surface Direct Normal Irradiance (DNI) monthly (left), daily (middle) and instantaneous (right) data for 2020

7.3 Photosynthetic Active Radiation – PAR

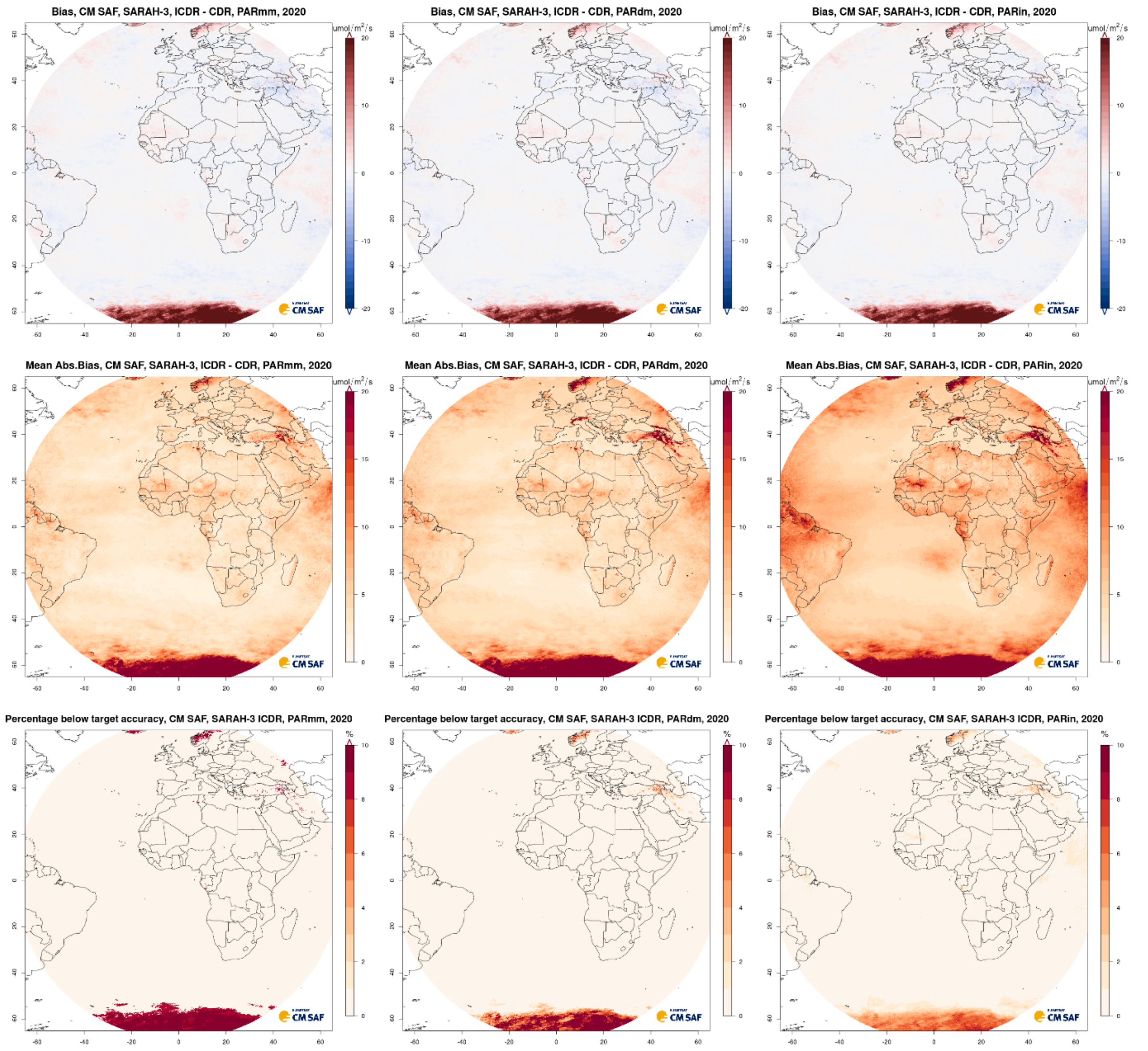


Figure 7-4: Bias (top row, ICDR minus CDR), mean absolute bias (middle row, ICDR minus CDR) and percentage of values with MAB exceeding the target requirement (bottom row) of the SARAH-3 ICDR Photosynthetic Active Radiation (PAR) monthly (left), daily (middle) and instantaneous (right) data for 2020

7.4 Daylight (DAL)

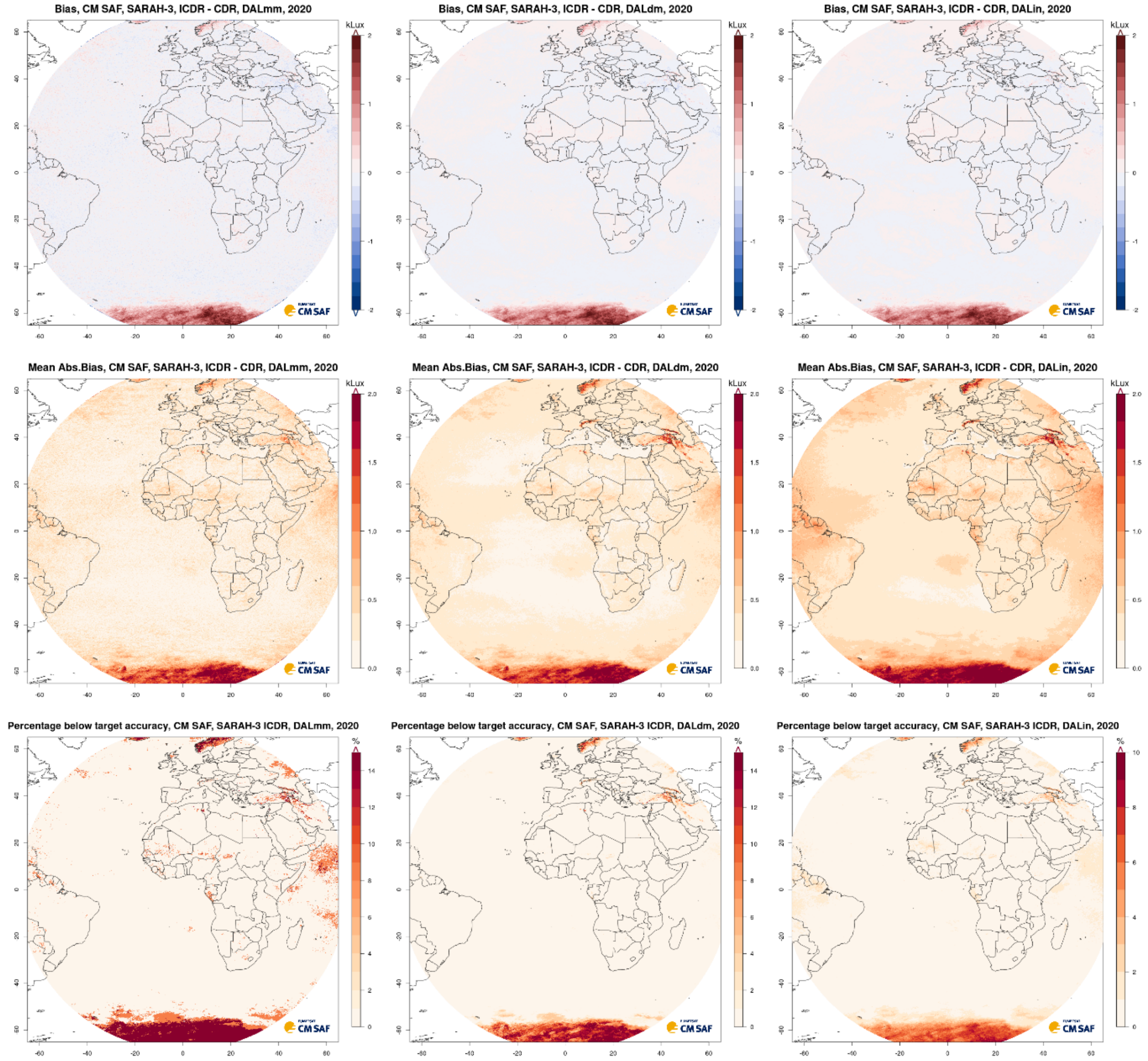


Figure 7-5: Bias (top row, ICDR minus CDR), mean absolute bias (middle row, ICDR minus CDR) and percentage of values with MAB exceeding the target requirement (bottom row) of the SARAH-3 ICDR Daylight (DAL) monthly (left), daily (middle) and instantaneous (right) data for 2020

7.5 Effective Cloud Albedo (CAL)

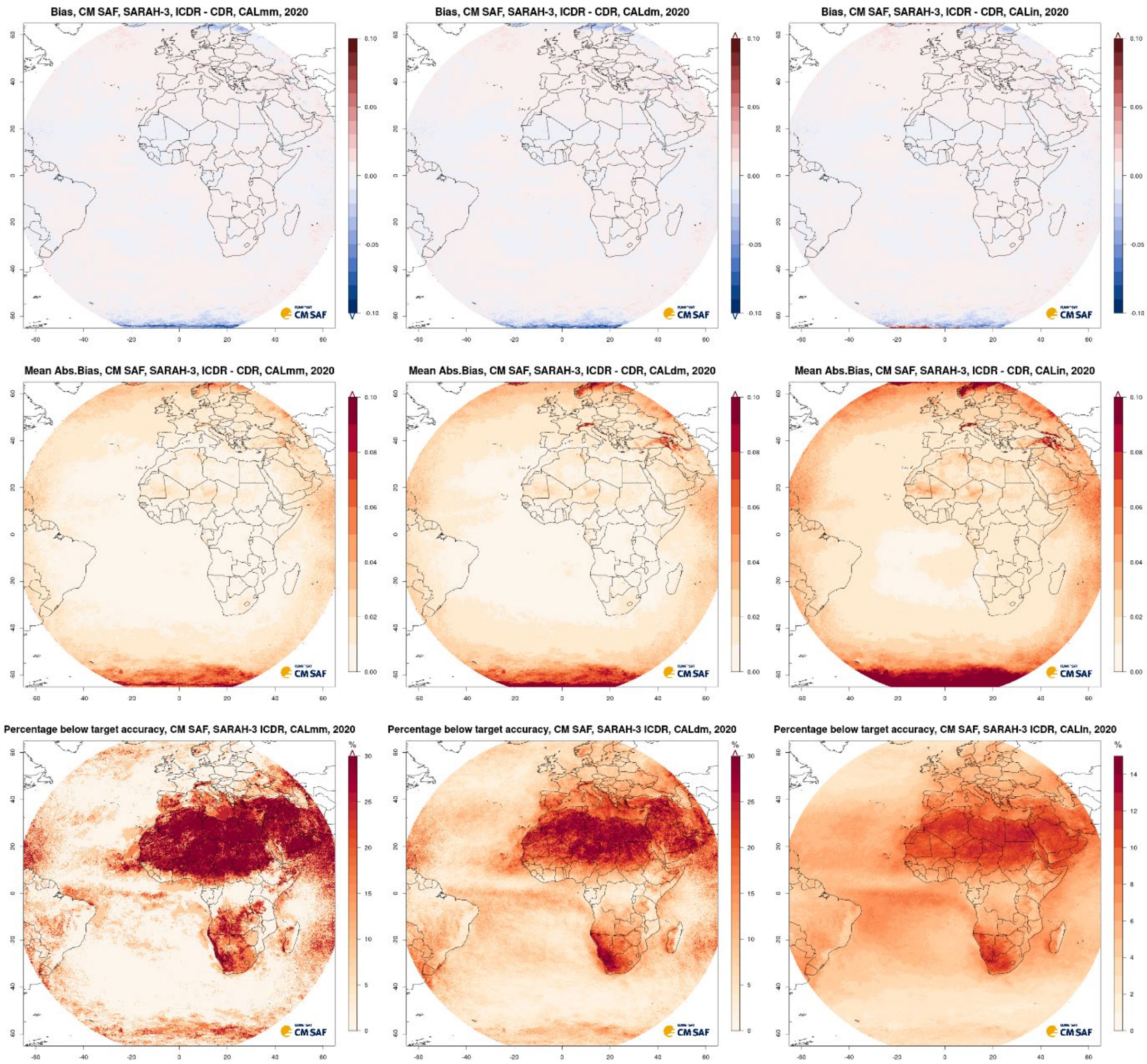


Figure 7-6: Bias (top row, ICDR minus CDR), mean absolute bias (middle row, ICDR minus CDR) and percentage of values with MAB exceeding the target requirement (bottom row) of the SARAH-3 ICDR Effective Cloud Albedo (CAL) monthly (left), daily (middle) and instantaneous (right) data for 2020. For the quality assessment of the ICDR CAL data, when deriving the number of exceedances of the target accuracy, the relative differences to the CDR have been used, which results in comparable large number of months that exceed the target accuracy in regions with low CAL values, namely in desert areas.

7.6 Sunshine Duration (SDU)

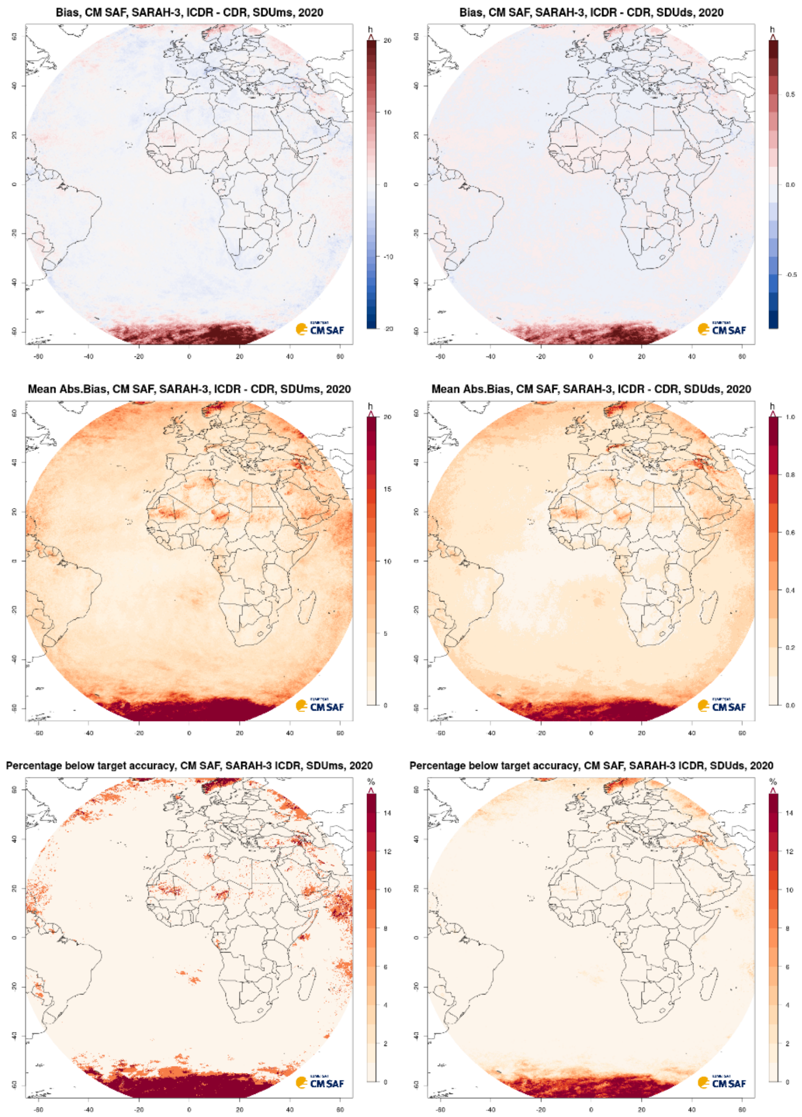


Figure 7-7: Bias (top row, ICDR minus CDR), mean absolute bias (middle row, ICDR minus CDR) and percentage of values with MAB exceeding the target requirement (bottom row) of the SARAH-3 ICDR Sunshine Duration (SDU) monthly (left) and daily (right) data for 2020

7.7 ICDR Validation Summary

Overall the validation of the ICDR data for 2020 reveals a good agreement to the SARAH-3 CDR data record. There are two main reasons for the differences found between the ICDR and the CDR:

1) Different auxiliary data, namely water vapour, ozone, snow coverage.

2) Differences in the time range used for the statistical analysis to generate the daily snow cover information and the Effective Cloud Albedo (CAL).

The differences in the auxiliary data (ERA5 vs ECMWF operational product) are rather small and only impact the simulated clear-sky surface radiation. Almost all differences between the CDR and the ICDR data that can be seen in Figure 7-1 to Figure 7-7 are due to the use of different time intervals to determine the statistical properties from the satellite data.

While in the SARAH-3 CDR the current month is used for deriving the snow information and the Effective Cloud Albedo, the preceding 30 days (relative to the currently processed day) are used in the ICDR processing, as it is by design only possible to look backwards in time in the ICDR processing. The associated differences mainly impact the radiation parameters in Alpine and other snow-affected regions as well as in the southern Atlantic Ocean. In the latter region, the high frequency of clouds and the strong seasonality of sea-ice causes differences in the statics to derive the minimum reflections. It is worth noting that for the quality assessment of the ICDR CAL data, when deriving the number of exceedances of the target accuracy, the relative differences to the CDR have been used, which results in comparable large number of months that exceed the target accuracy in regions with low CAL values, namely in desert areas.

We conclude that, even though some differences between the ICDR and the CDR data remain, the ICDR data records consistently extent the SARAH-3 data record in time; the SARAH-3 ICDR data can be used in combination with the SARAH-3 CDR data (e.g., as reference climatology) to assess anomalies of surface radiation components.

8 Conclusion and Recommendation

8.1 Conclusion

The satellite-derived CM SAF SARAH-3 climate data record of the surface incoming solar irradiance (SIS), direct irradiance (SDI), photosynthetic active radiation (PAR), daylight (DAL), sunshine duration (SDU), and effective cloud albedo (CAL) have been validated by comparison with surface reference measurements. The reference data have been obtained from 17 high-quality ground-based stations of the BSRN network (SIS, SDI), the ECA&D and the CLIMAT data bases (SDU), and several stations provided directly from the stations scientists (PAR, DAL). The applied validation thresholds combine the target accuracy defined in the PRD [RD 2], which is based on the GCOS accuracy requirement for the variables of the surface radiation budget, and the uncertainty of the surface reference measurements. It is worth to mention that the quality target requirements have been substantially sharpened for the SARAH-3 climate data records compared to the previous versions of the CM SAF SARAH climate data records.

Prior to 1992 no BSRN measurements are available. Thus, the data record could not be validated with BSRN ground based measurements for the period 1983-1992. For the surface solar irradiance (SIS) from the SARAH-3 data record the mean absolute difference (MAD) of the monthly means (5.32 W/m^2) and the daily means (10.9 W/m^2) is in the range of the required target accuracy of 4 W/m² and 11 W/m². For the instantaneous SIS data, the MAD is ~24 W/m^2 and 45 W/m^2 for total and daytime only measurements, respectively.

For the surface solar direct irradiance (SDI) parameters (SID and DNI), the mean absolute differences (MAD) of the monthly means are 7.8 W/m^2 and 16.7 W/m^2. The MAD values for the daily means are 16.0 W/m^2 and 31.1 W/m^2. These measures are below the required threshold accuracies of 8 W/m² and 17 W/m² for the SID and DNI monthly means, and also below the threshold accuracy of 18 W/m^2 and 34 W/m^2 for the SID and DNI daily means. The SID and DNI instantaneous MAD is ~26 W/m^2 and 51 W/m^2 with reference to BRSN data, respectively.

The accuracy of the SARAH-3 sunshine duration (SDU) data record is 15 h and 1 h for the monthly and daily sums, respectively; even further reduced compared to the previous version of the SARAH climate data record and within the required accuracy.

For the new SARAH-3 parameters PAR and DAL, the MAD of the monthly means are 19.7 µmol/m^2/s and 2.6 kLux. For the daily means the MAD values are 26.5 µmol/m^2/s and 3.4 kLux. These measures are below the thresholds for daily/monthly mean PAR and DAL, respectively.

The comparison of the CM SAF SARAH-3 SIS climate data record with its predecessor CM SAF SARAH-2.1 shows that no improvement is visible at the monthly scale, while an improvement on the daily scale is visible. This also holds on average for the surface direct irradiance (SDI) parameters. This can be explained by the fact that algorithm updates for snow and the new daily auxiliary data mainly positively effects the daily radiation data. Overall the mean bias for most parameters is slightly increased in the SARAH-3 data record compared to its predecessor, which is mainly a consequence of the new treatment of snow and associated to the use of the new surface albedo data. However the bias remains with about 2 W/m^2 for global and 1 W/m^2 for direct radiation small, keeping in mind that also the surface observations have some uncertainty.

The stability of the SARAH-3 SIS data record has been validated against European surface measurements from the GEBA database. A small negative linear trend of -0.6 ± 0.4 W/m^2/decade was found, which is close to the target stability requirement of 0.5 W/m^2/decade. Compared to the previous CM SAF SARAH data records the stability over the full time period has further increased.

Overall, it is shown that the target / threshold accuracy is achieved for the monthly and daily means of the radiation parameters of the CM SAF SARAH-3 climate data record.

This validation also demonstrates the accuracy of the effective cloud albedo. It is determined by the accuracy of SIS by a worst case approach. The worst case accuracy for CAL monthly means is 0.1 (threshold), 0.08 (target) and 0.05 (optimal) for periods and regions with a monthly mean clear sky irradiance above 50, 65 W/m² and 100 W/m², respectively. Hence, the requested accuracy is achieved for these cases. For the daily mean CAL the threshold (0.2), the target (0.1) and the optimal (0.08) accuracy is met for daily mean clear sky irradiances above 55, 110 and 135 W/m², respectively.

The SARAH-3 ICDR data records have been validated for 2020 with reference to the SARAH-3 CDR. Overall there is a good agreement for the overlapping time period. The combined data record SARAH-3 CDR + ICDR can be used for climate monitoring application. For Alpine and other snow-affected areas as well as for the southernmost part of the data region uncertainties can be higher.

In general, for SIS, SDI, PAR, DAL and CAL higher uncertainties are expected for regions with long lasting snow cover and desert regions with bright surfaces, even though improvements have been made with the HELSNOW daily snow cover detection. For the SDI direct radiation parameters higher uncertainties are also expected in regions with high temporal and spatial variability in aerosol properties.

Table 7-1: Extract of achieved validation results for SARAH-3 parameters (SIS, SID, DNI, PAR, DAL, SDU and CAL).

Product	Summary on mean error (absolute)
SIS: Surface Incoming Solar Radiation.	Mean Absolute Difference (MAD) of ~5 W/m² and ~90% of MAD below 5 W/m² (+ uncertainty of ground based measurements) for monthly means and ~80% below 12 W/m² for daily means, respectively). Instantaneous daytime MAD ~45 W/m^2
SID: Surface Incoming Direct Radiation.	MAD of ~8 W/m² and ~80 % of (monthly) absolute difference values below 8 W/m² (+ uncertainty of ground based measurements) for monthly means.

Product	Summary on mean error (absolute)
DNI: Direct Normal Irradiance at Surface.	MAD of ~17 W/m² and ~80 % of (monthly) absolute difference values below 17 W/m² (+ uncertainty of ground based measurements) for monthly means.
PAR: Photosynthetic Active Radiation	MAD of ~20 μmol/m^2/s and 27 μmol/m^2/s for monthly and daily data
DAL: Daylight	MAD of ~2.5 kLux and ~3.4 kLux for monthly and daily data
CAL: Effective cloud albedo	Uncertainty of 0.1 for monthly means and 0.2 for daily means. Uncertainty of 0.05 (monthly) and 0.1 (daily) for clear sky irradiance monthly means above ~100 W/m².
SDU: Sunshine duration.	MAD of ~15h for monthly sums and 73% of absolute difference values below 20h (+ uncertainty of ground based measurements) and 77% below 1.5h for daily sums, respectively.

8.2 Recommendations

Despite the high quality of the SARAH-3 data records, further improvements are still possible. These include the use of updated aerosol information, e.g., with higher temporal / spatial resolution, to further improve the accuracy of the clear-sky surface radiation. Possible improvements of the retrieval algorithm include an update of the clear-sky look-up-table in the SPECMAGIC model, better consideration of broken cloud effects in the estimation of direct solar radiation and the further improvement in the detection and the treatment of snow-covered surfaces.

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10 Appendix A: Glossary

AC	Anomaly correlation
ATBD	Algorithm Theoretical Baseline Document
BSRN	Baseline Surface Radiation Network
CAL	Effective Cloud Albedo
CDOP	Continuous Development and Operational Phase
CDR	Climate Data Record
CLIMAT	Measurements from Surface Climate Stations
CM SAF	Satellite Application Facility on Climate Monitoring
DAL	Daylight
DNI	Direct Normal Irradiance
DWD	Deutscher Wetterdienst
ECV	Essential Climate Variable
ECA&D	European Climate Assessment & Dataset
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FCDR	Fundamental Climate Data Record
FD	Flux dataset (ISCCP)
FRAC	Fraction of days larger than the target value
GCOS	Global Climate Observing System
GEBA	Global Energy Balance Archive
GEWEX	Global Energy and Water Cycle Experiment
ISCCP	International Satellite Cloud Climatology Project
MAD	Mean absolute deviation for the monthly, daily or hourly means
MVIRI	METEOSAT Visible and Infra-Red Imager
PAR	Photosynthetic Active Radiation
PUM	Product User Manual
SARAH	Surface Solar Radiation Dataset – Heliosat
SD	Standard deviation

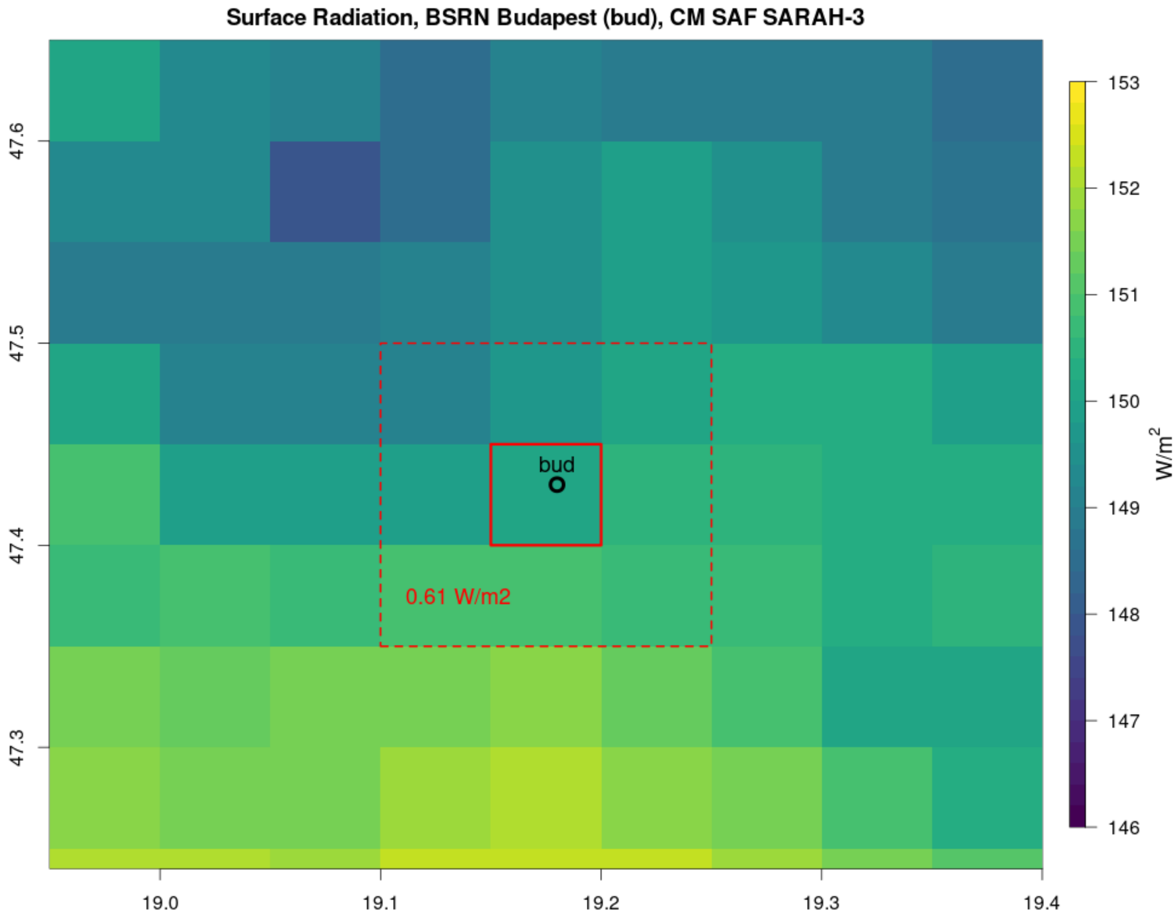
SDI	Surface Direct Irradiance (consists of SID and DNI)
SDU	Sunshine Duration
SEVIRI	Spinning Enhanced Visible and Infrared Imager
SID	Surface Incoming Direct radiation, commonly called direct irradiance
SIS	Surface Incoming Solar radiation, commonly called global irradiance or surface solar irradiance
SRB	Surface Radiation Budget
WMO	World Meteorological Organisation

11 Appendix B: Surface Irradiance Variability at BSRN stations

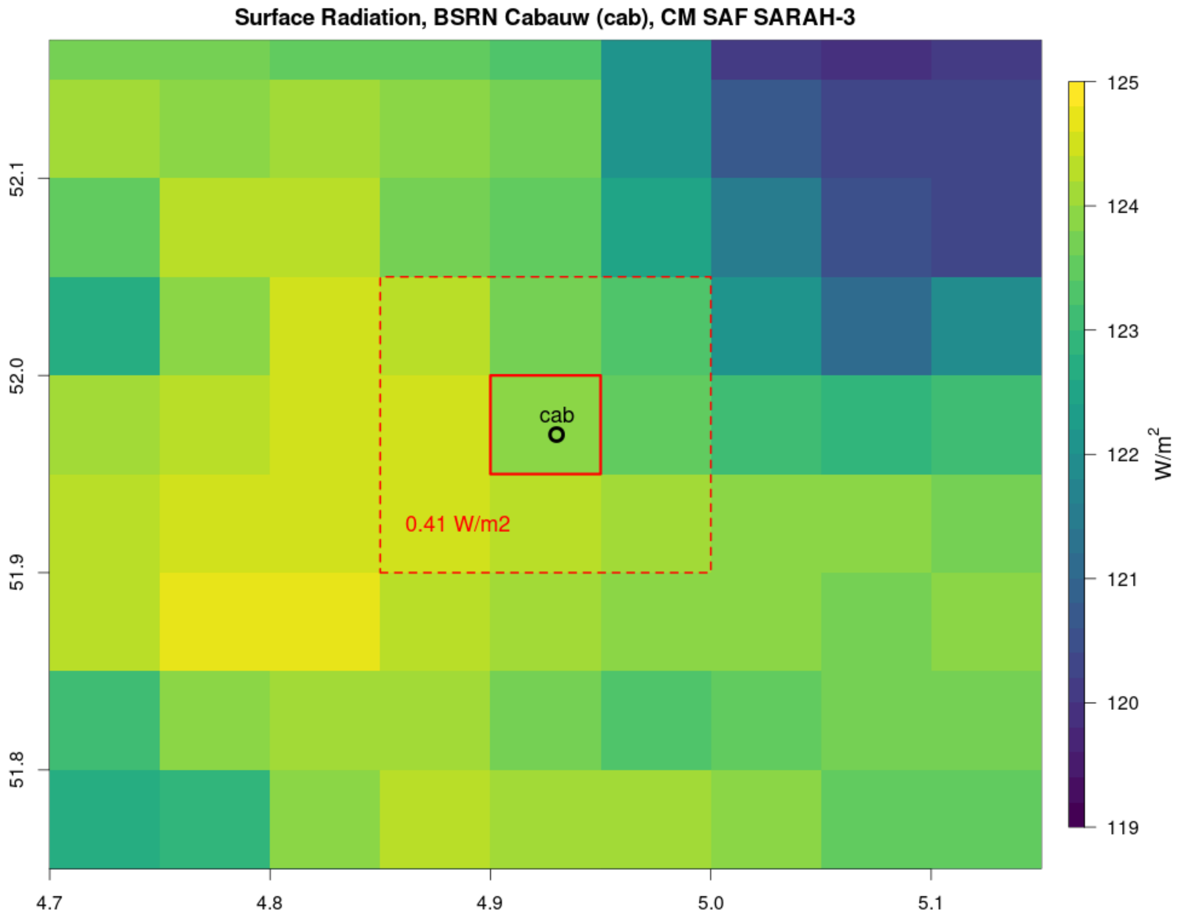
The Baseline Surface Radiation Network has been proposed by WMO under the World Climate Research Programme (WCRP) in 1988; the setup of stations started in the mid 1990s. Besides high requirements on the long-term commitment and the quality of the data collection, the locations of the stations were supposed to be representative of a larger surrounding area for use in satellite and model data validation (Driemel et al., 2018). In recent years the requirement on the representativity has been somehow relaxed to allow the inclusion of additional high-quality surface radiation measurements. As a consequence, not all current BSRN stations are equally suited for the validation of gridded radiation data (i.e., derived from satellite or models). Some stations, e.g., Sonnblick (son) and Izana (iza), are intentionally left out for the validation of the SARAH-3 data records due to their, obviously, very small range of representativity. For the BSRN stations used for the validation of SARAH-3 the spatial distribution of the climatological average of SARAH-3 SIS is shown here in relation to the station location to document the local features and possible limitations that limit the comparability of the surface measurements and the satellite-derived estimates. For the validation the value of the nearest neighbor grid box from SARAH-3 data was used.

The subsequent figures display, for each BSRN station used for the validation of SARAH-3, the climatology (1983 to 2020) of the SARAH-3 surface solar irradiance in the close proximity of the BSRN stations. The location of the BSRN station is indicated by the black circle, the SARAH-3 grid box used for the validation is marked with a red square. The 3 x 3 grid boxes surrounding the grid box used for the validation are marked by a dashed line; the standard deviation of the climatological SARAH-3 SIS values from these 9 grid boxes are given in the plot (red numbers). The standard deviation is a measure of the representativity of the station location; a high standard deviation indicates a low representativity of the BSRN station location and, subsequently, a reduced suitability of the measurements for the validation of gridded data records, e.g., as derived from satellite, which need to be taken into account when interpreting the difference between the gridded data and the surface measurements.

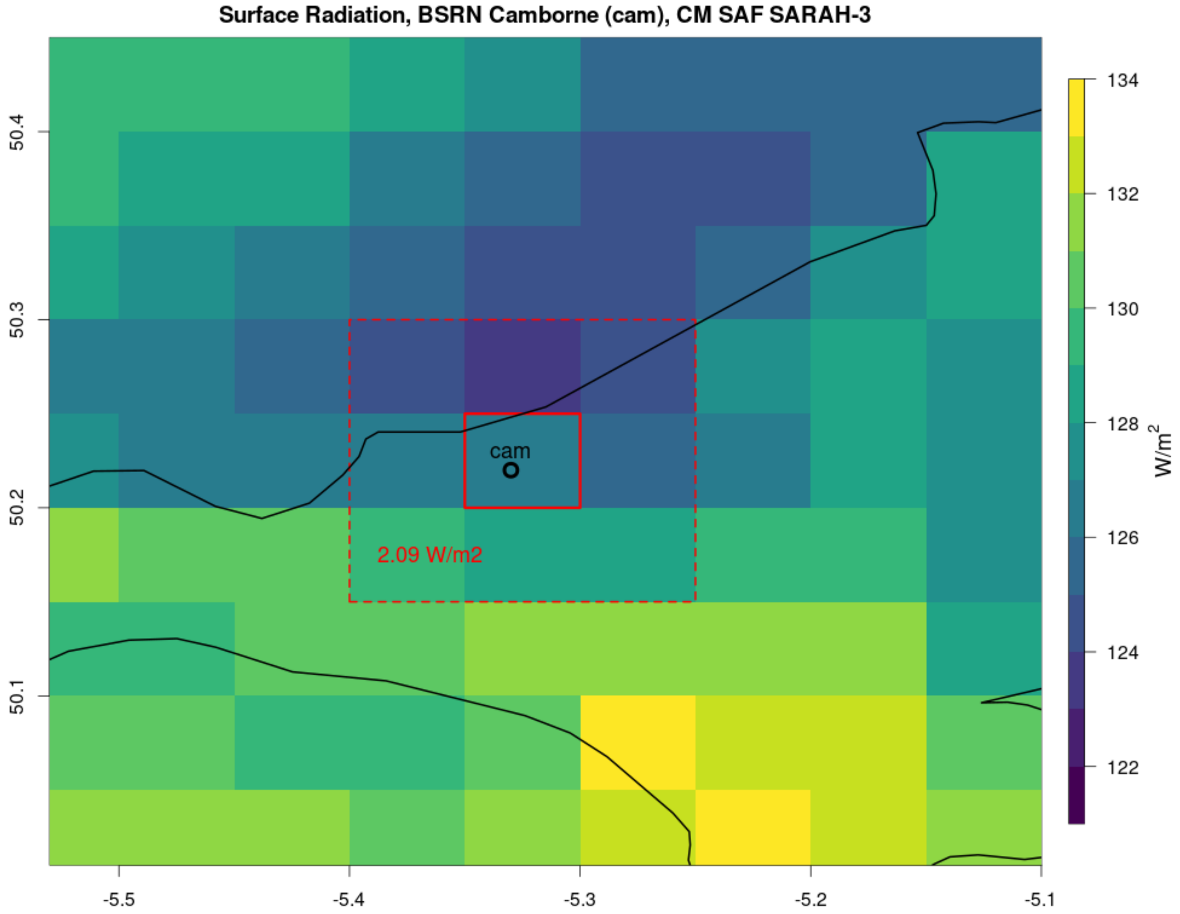
Budapest, Hungary



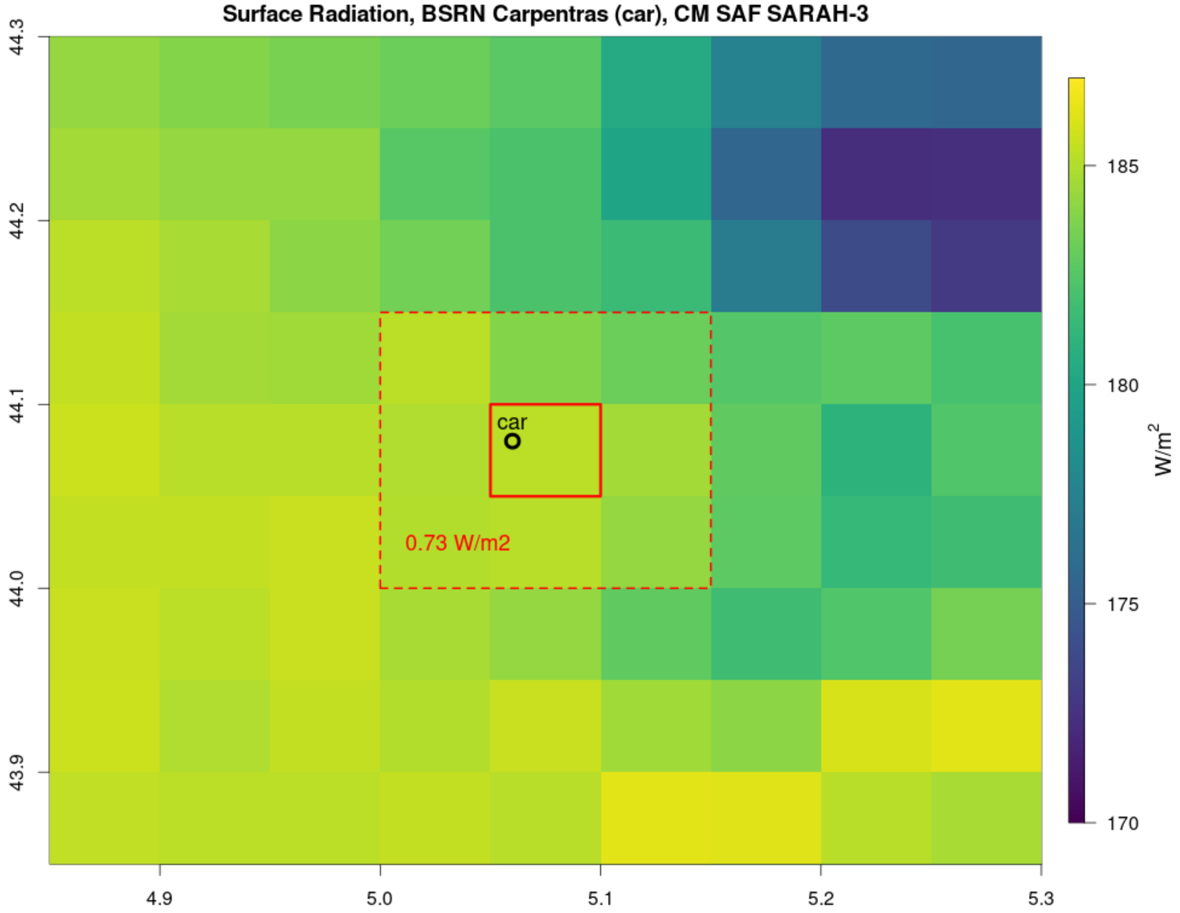
Cabauw, The Netherlands



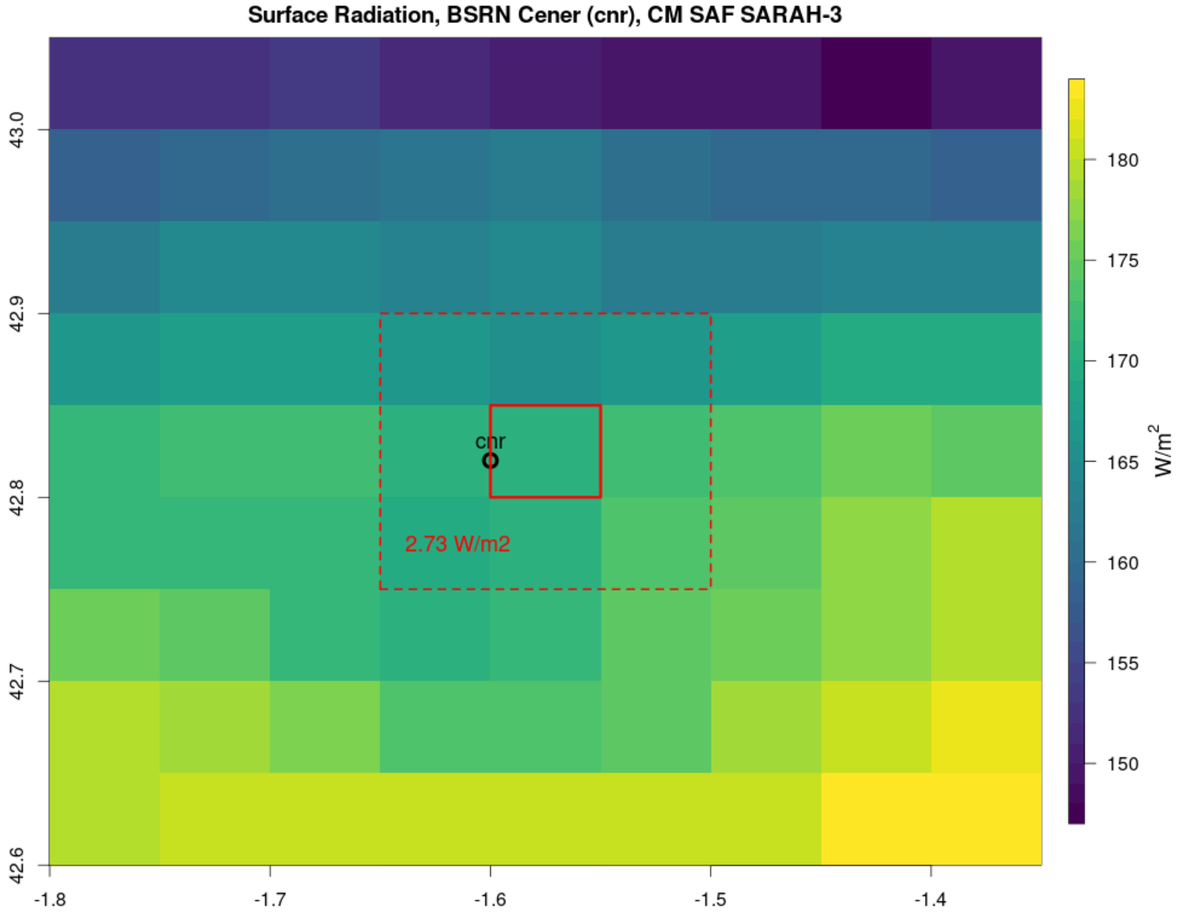
Camborne, UK


Surface Radiation, BSRN Camborne (cam), CM SAF SARAH-3
50.4
50.3
50.2
50.1
-5.5
-5.4
-5.3
-5.2
-5.1
cam
2.09 W/m2
134
132
130
128
126
124
122
W/m2

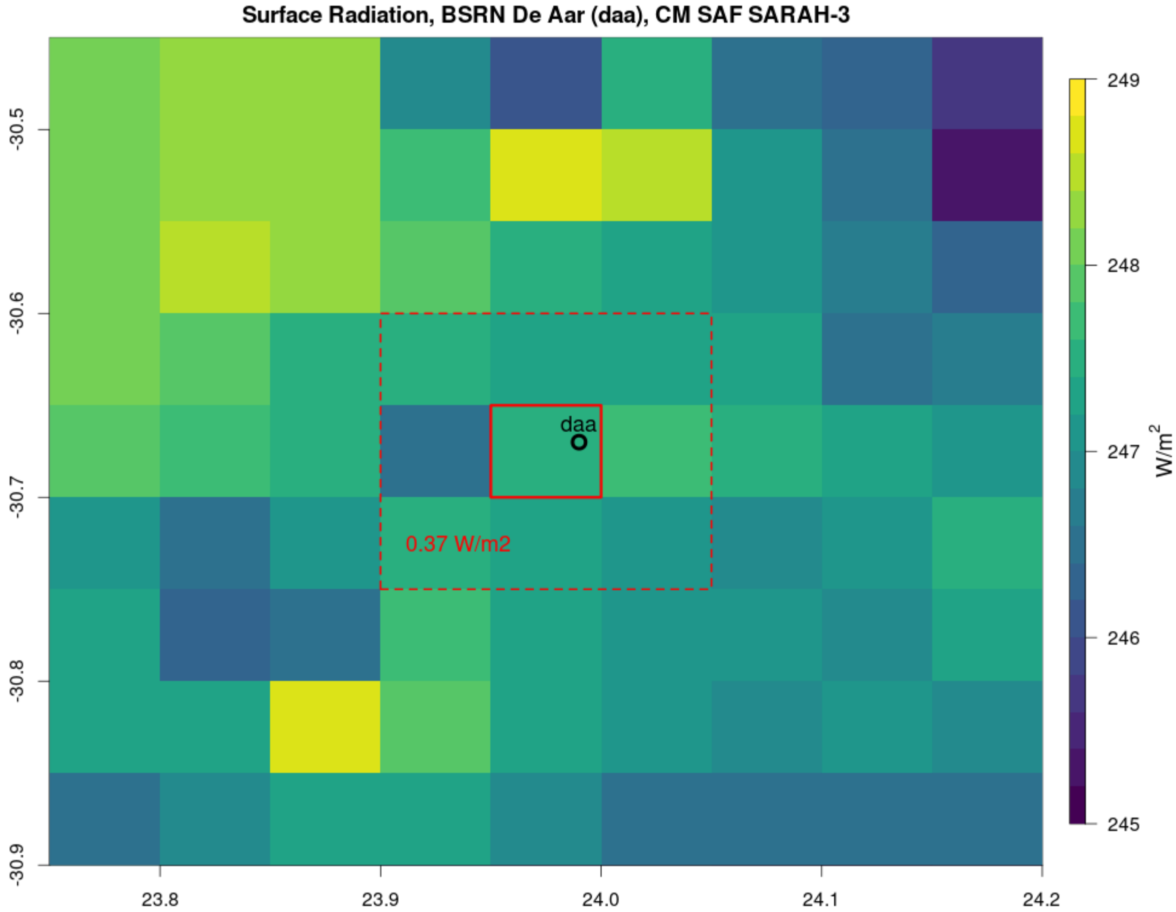
Carpentras, France



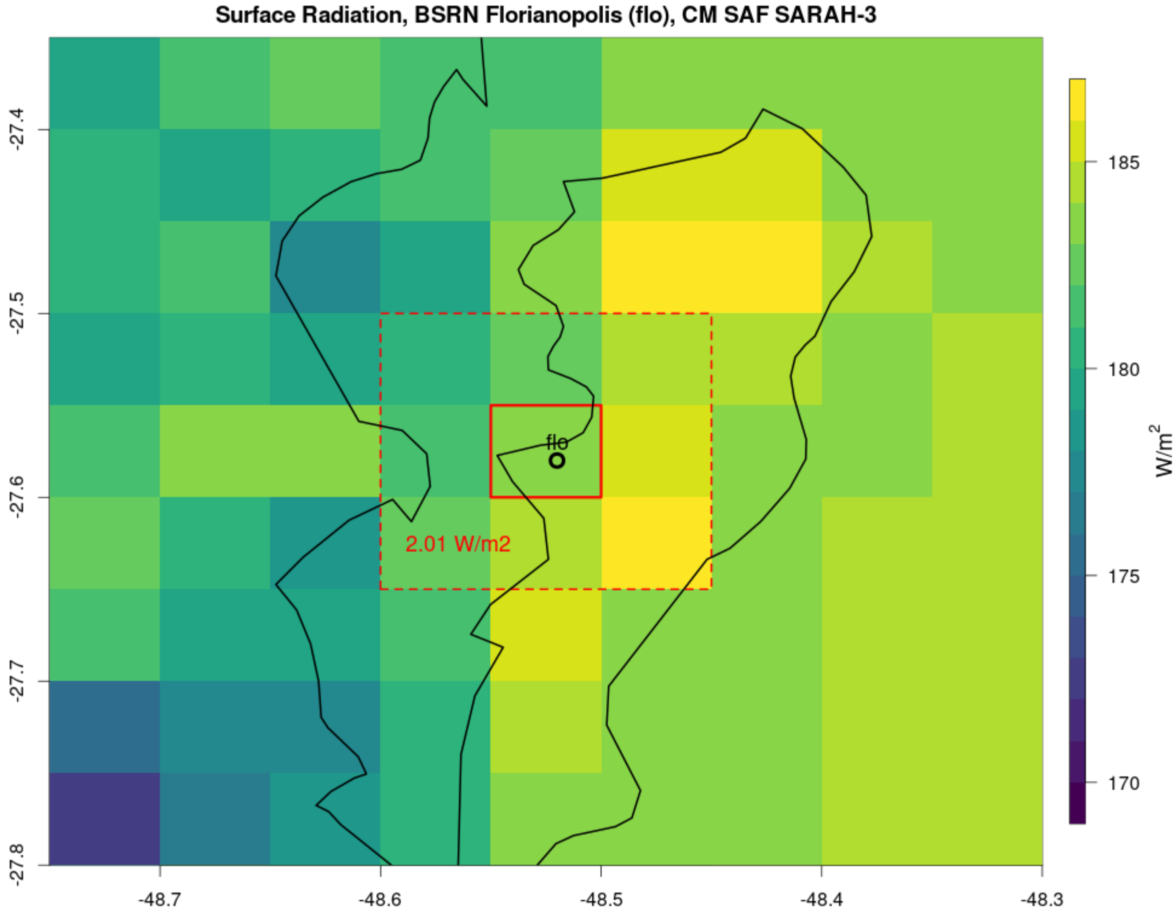
Cener, Spain


Surface Radiation, BSRN Cener (cnr), CM SAF SARAH-3
cnr
2.73 W/m2
43.0
42.9
42.8
42.7
42.6
-1.8
-1.7
-1.6
-1.5
-1.4
180
175
170
165
160
155
150
W/m2

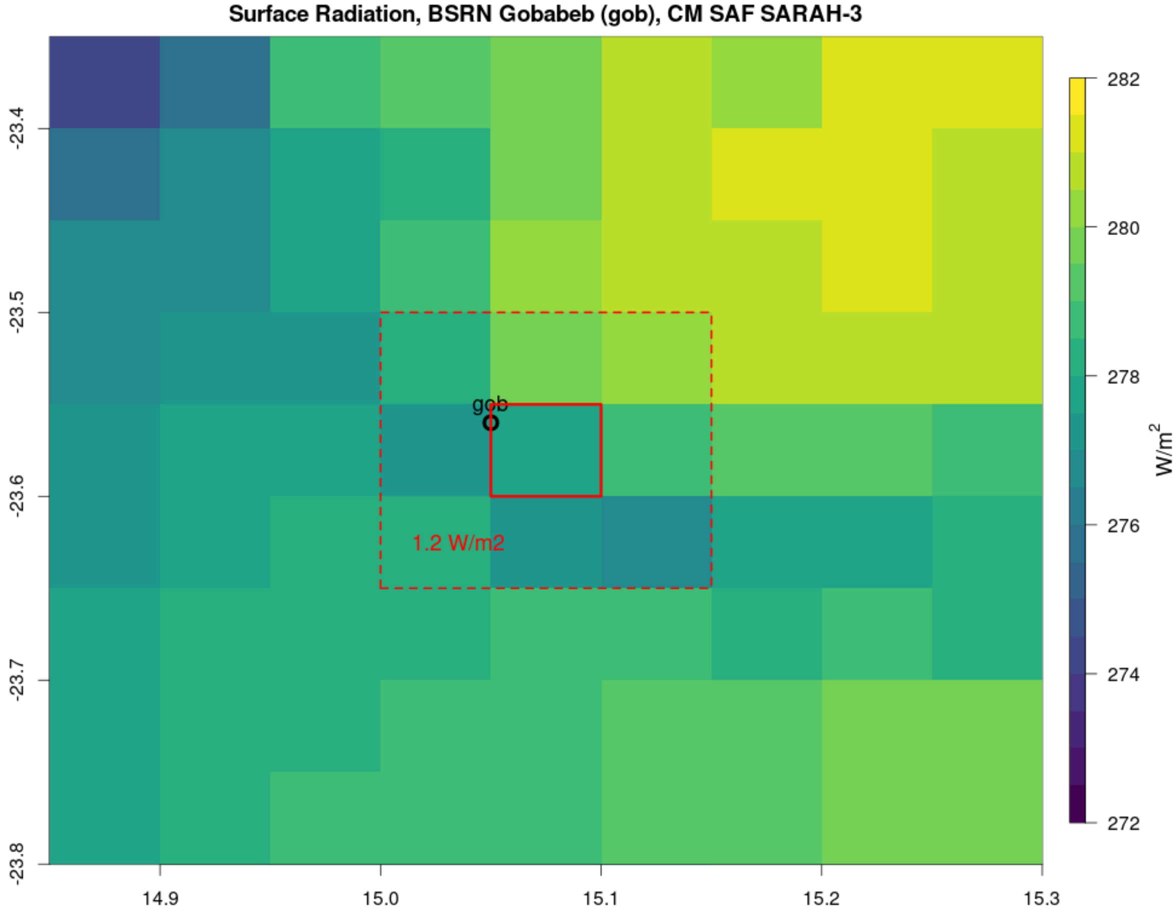
De Aar, South Africa



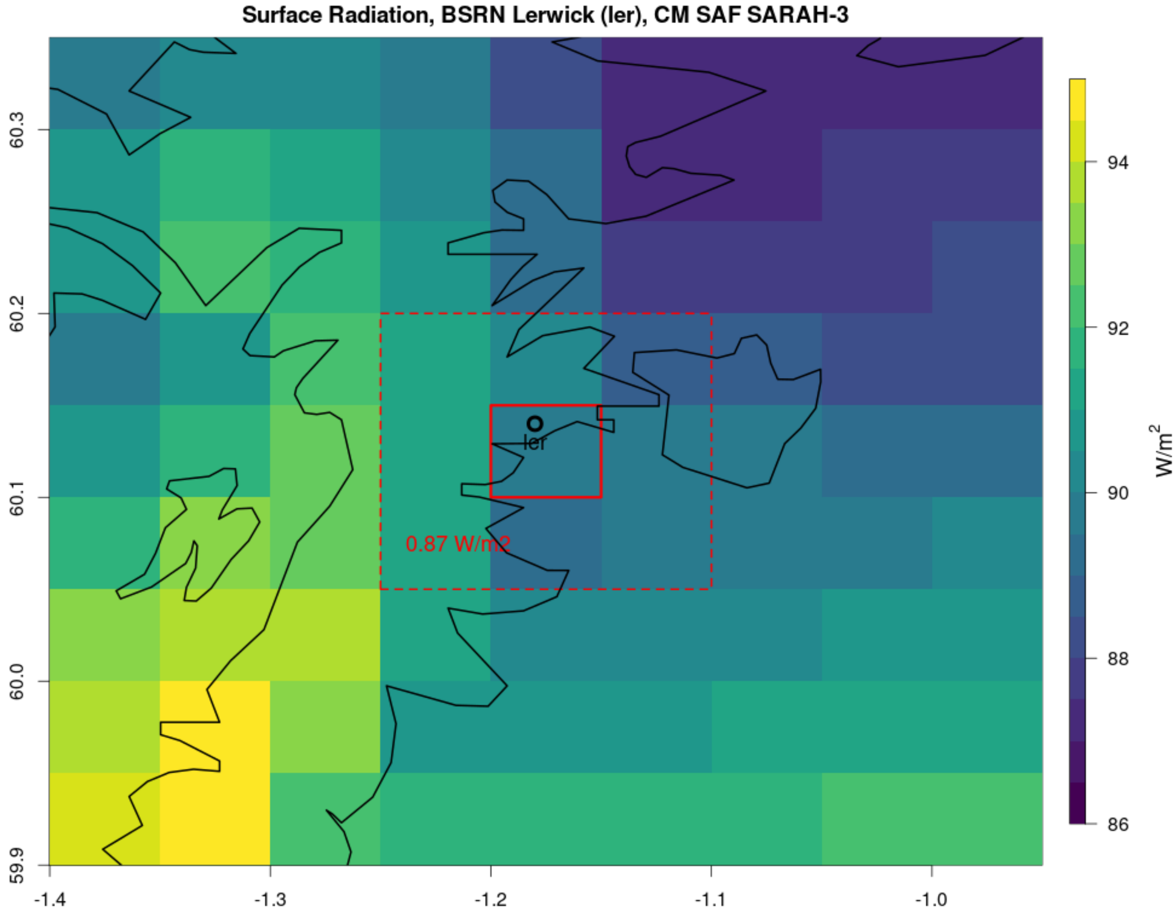
Florianopolis, Brasil



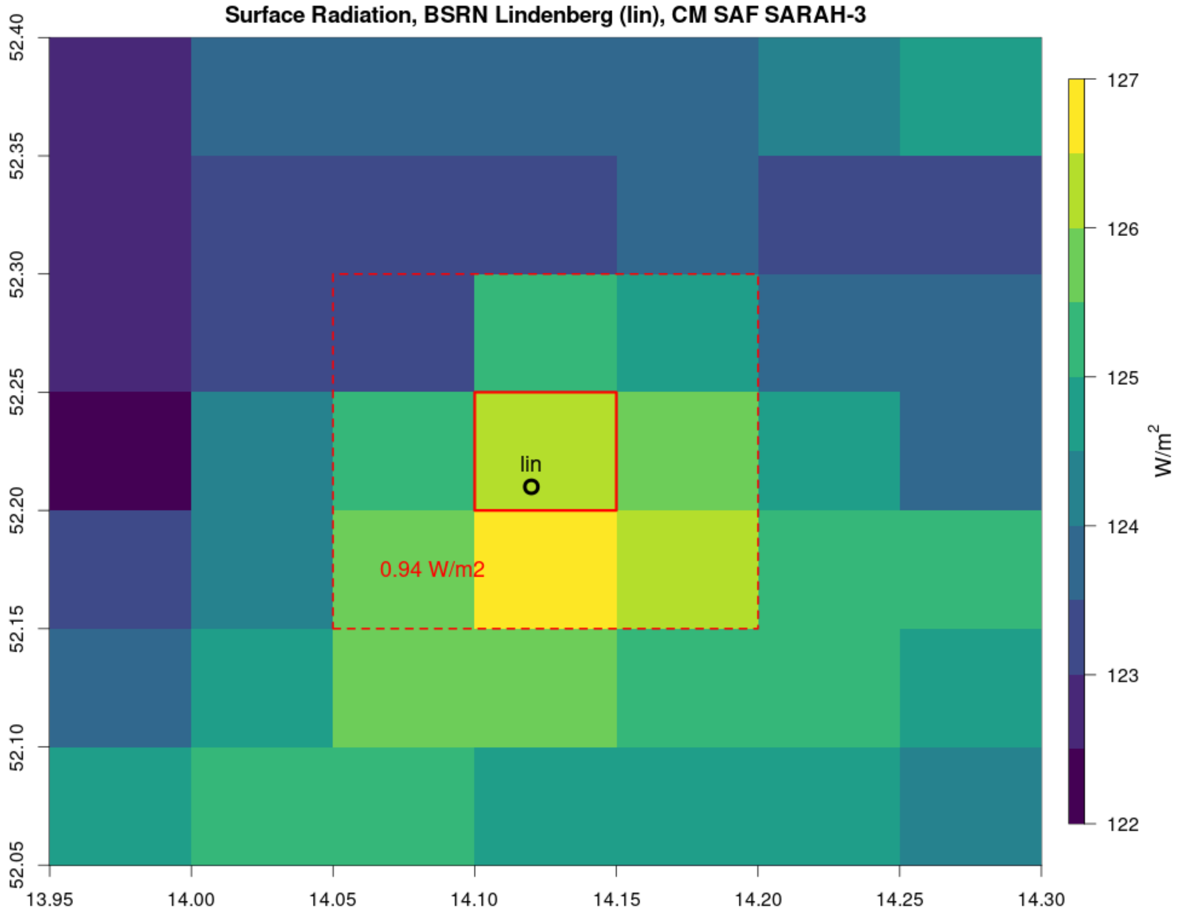
Gobabeb, Namibia



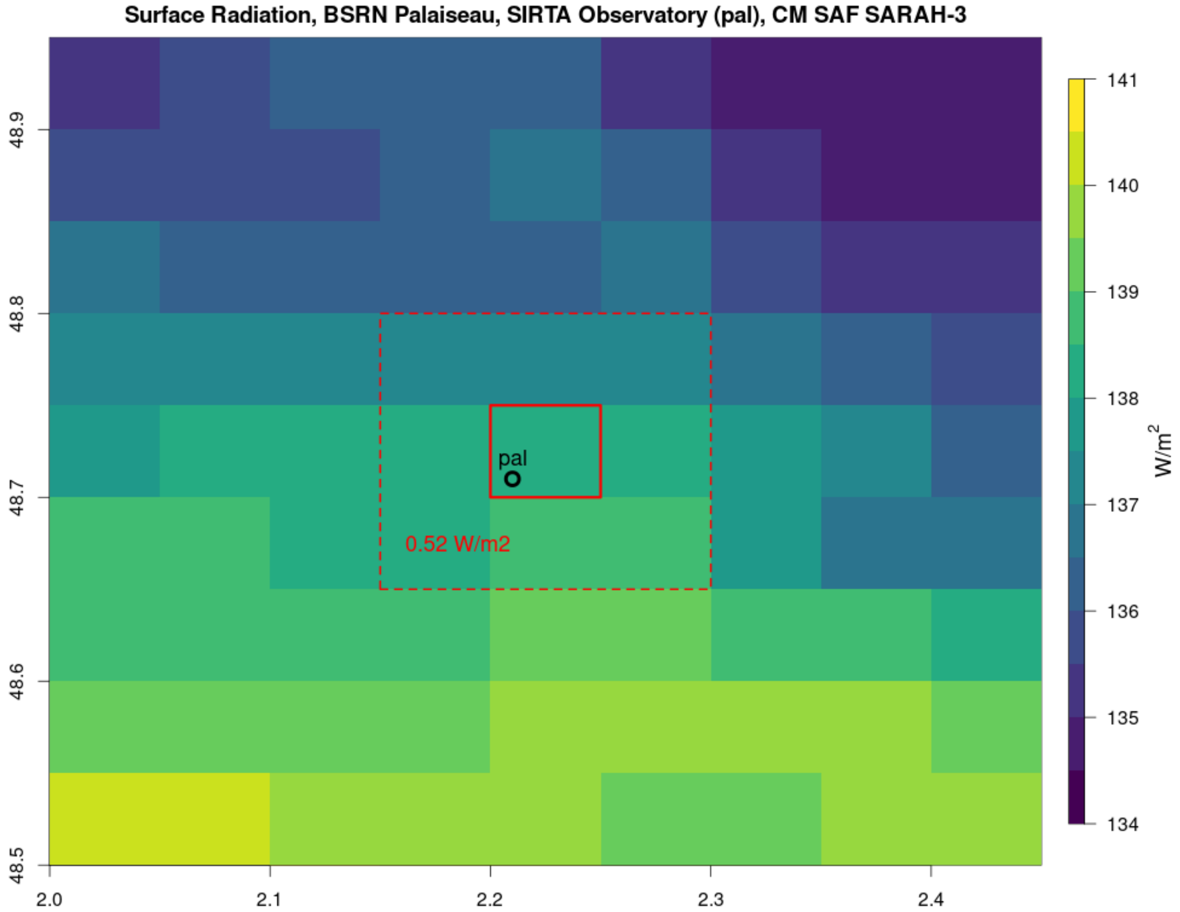
Lerwick, UK


Surface Radiation, BSRN Lerwick (ler), CM SAF SARAH-3
ler
0.87 W/m2
60.3
60.2
60.1
60.0
59.9
-1.4
-1.3
-1.2
-1.1
-1.0
94
92
90
88
86
W/m²

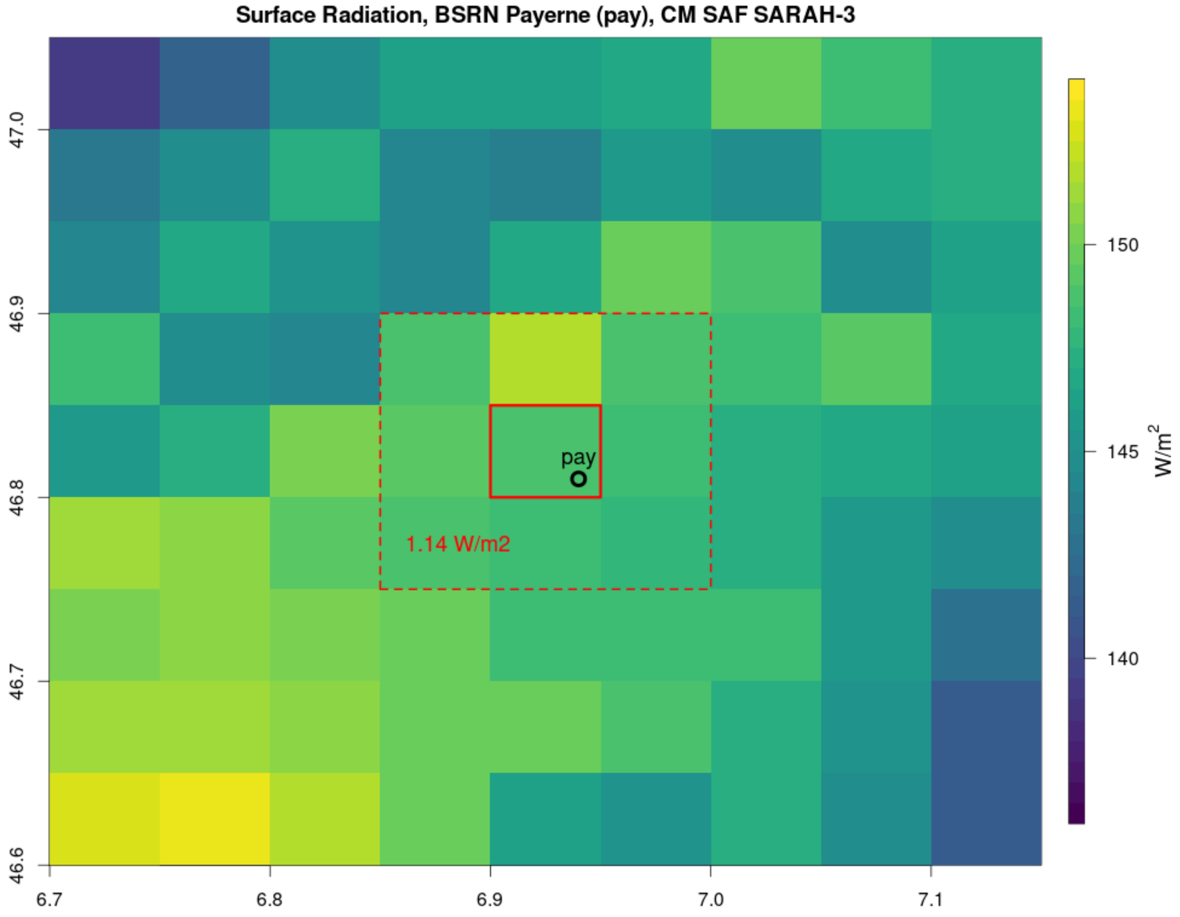
Lindenberg, Germany



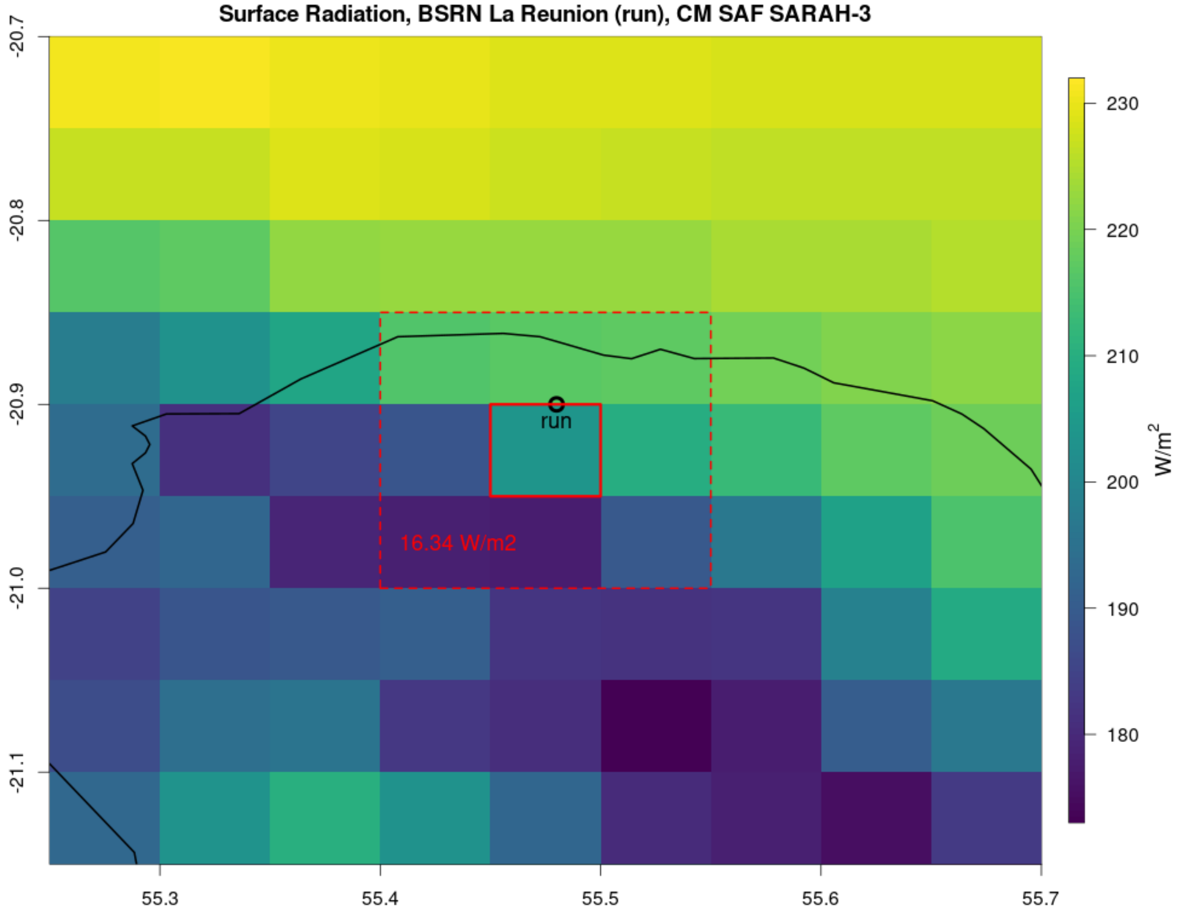
Palaiseau Cedec, France



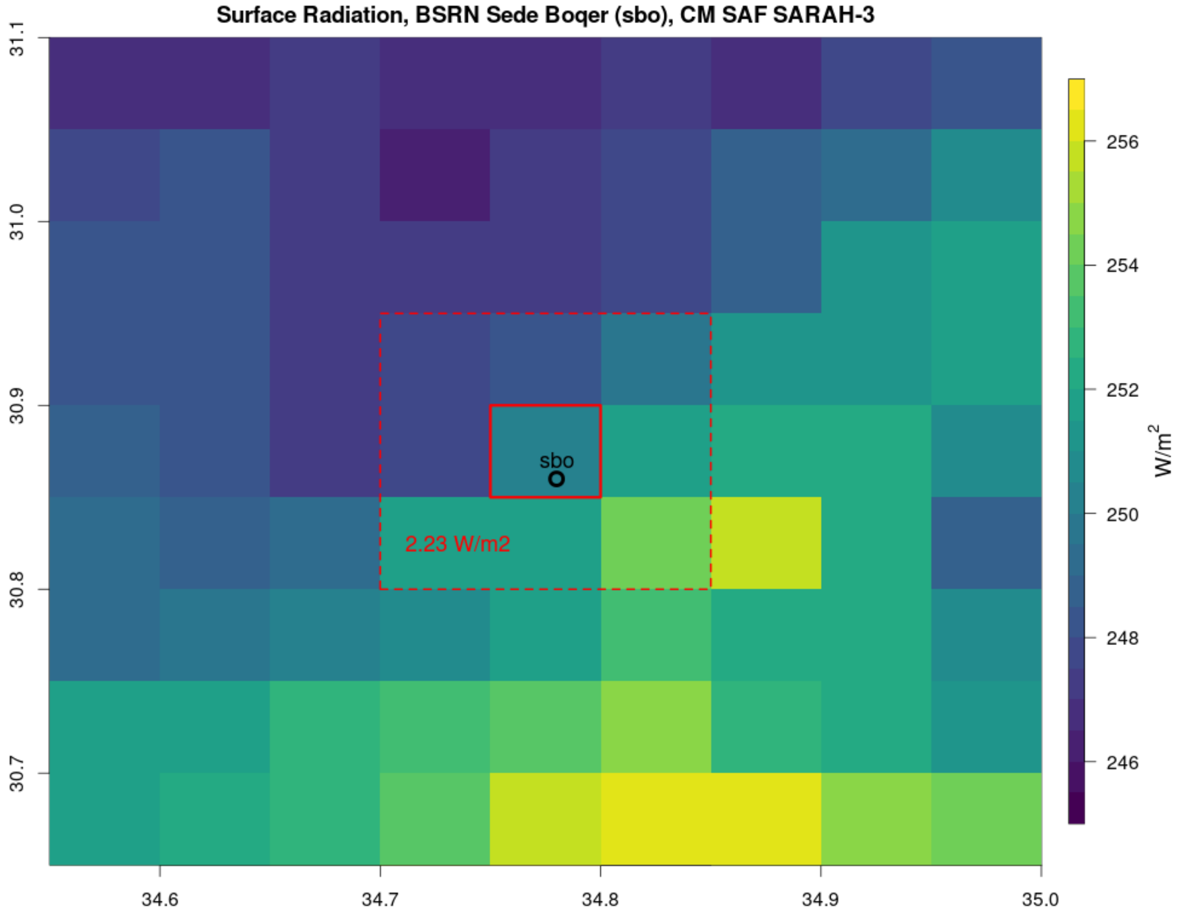
Payerne, Switzerland



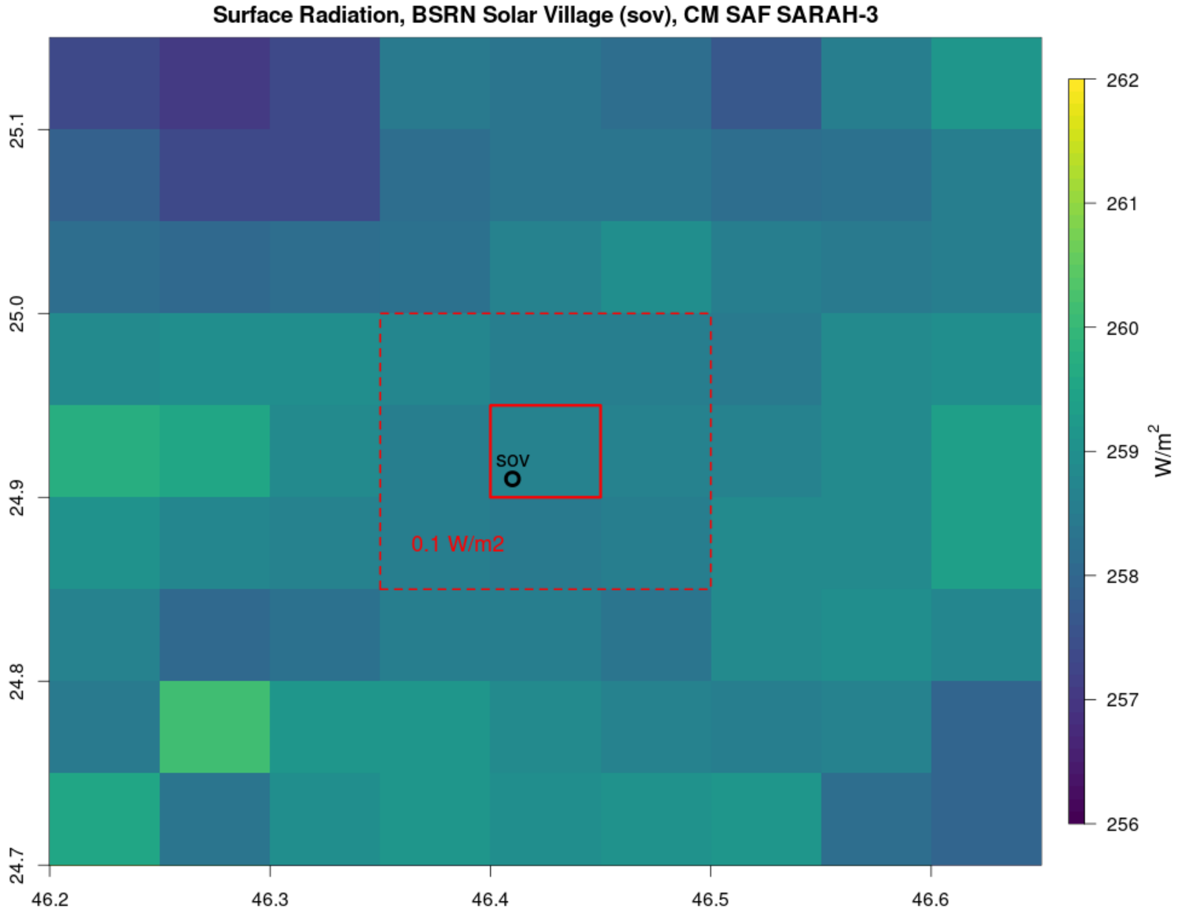
Reunion Island, France



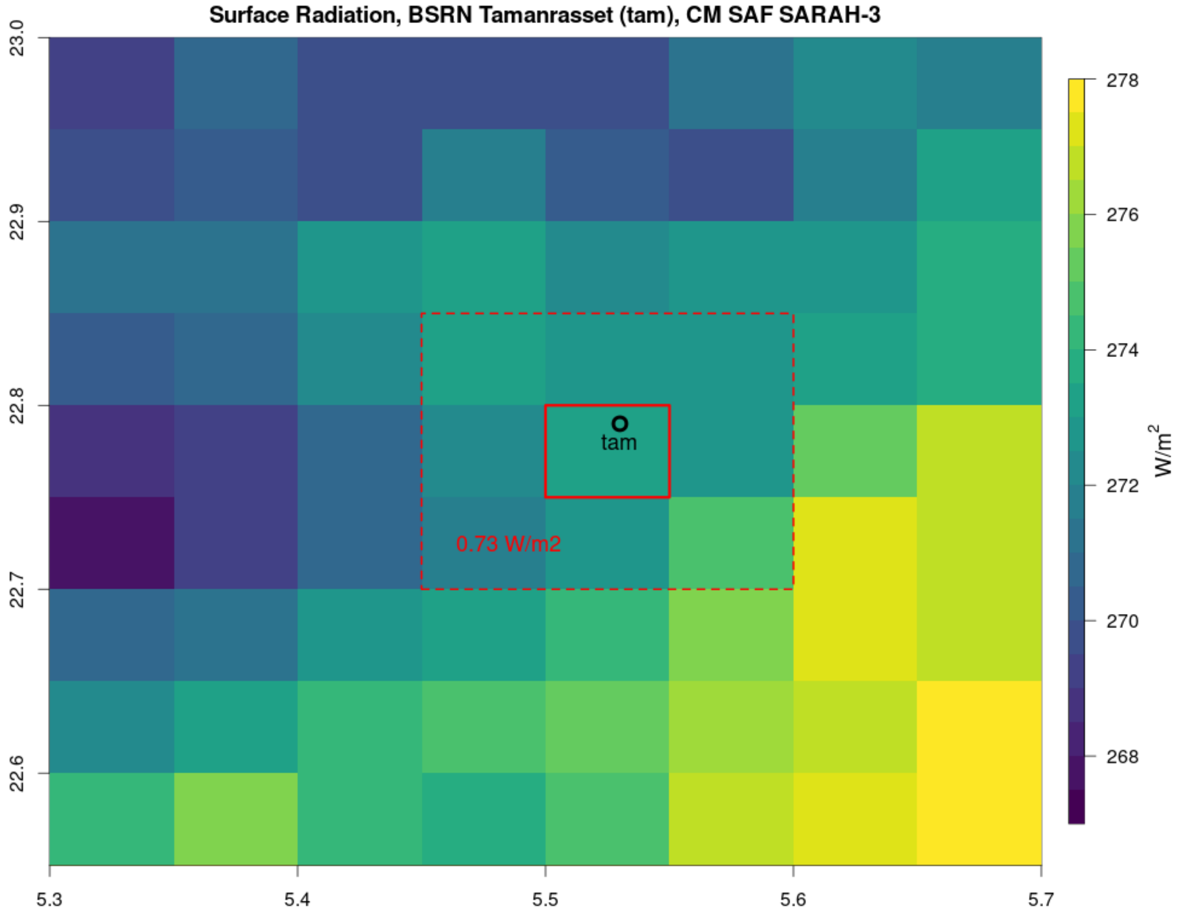
Sede Boqer, Israel



Solar Village, Saudi Arabia



Tamanrasset, Algeria



Toravere, Estonia