EUMETSAT Satellite Application Facility on Climate Monitoring

Validation Report

Meteosat Solar Surface Radiation and Effective Cloud Albedo Climate Data Record

SARAH-2.1 climate data records

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Effective Cloud Albedo (CAL)	**CM-23082 / CM-23085**
Surface Incoming Shortwave Radiation (SIS)	**CM-23202 / CM-23205**
Surface Direct Irradiance (SDI)	**CM-23291 / CM-23295**
Spectral Resolved Irradiance (SRI)	**CM-23241 / CM-23245**
Sunshine Duration (SDU)	**CM-23282 / CM-23283**

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Applicable Documents

Reference	Title	Code
AD 1	CM SAF Product Requirement Document	SAF/CM/DWD/PRD/2.9

Reference Documents

Reference	Title	Code
RD 1	Algorithm Theoretical Baseline Document (ATBD) Meteosat Solar Surface Irradiance and effective Cloud Albedo Climate Data records SARAH-2.1	SAF/CM/DWD/ATBD/METEOSAT/HEL v 2.2
RD 2	Product User Manual Meteosat Climate Data Records of Surface Radiation SARAH-2.1	SAF/CM/DWD/PUM/METEOSAT/HEL V 2.1
RD 3	Requirements Review 2.1 document	SAF/CM/CDOP2/DWD/RR21 version 1.1

Executive Summary

The new Solar Radiation Data record – Heliosat Version 2.1 (SARAH-2.1) consists of the Solar Surface Irradiance (SIS), two Surface Direct Irradiance (SDI) parameters, the Spectrally Resolved Irradiance (SRI), the Effective Cloud Albedo (CAL) and the Sunshine Duration (SDU) and covers the time period 1983-2017. SARAH-2.1 is based on data from the MVIRI and SEVIRI instruments on board the Meteosat satellite series (from Meteosat-2 to Meteosat-10). All SARAH-2.1 parameters are validated and the results are shown in this report. The SARAH-2.1 climate data record is the temporal extension of the SARAH-2 climate data record. SARAH-2.1 is closing the gap between the former SARAH-2 and the new regularly updated SEVIRI Interim Climate Data Record of radiation parameters.

The radiation parameters of SARAH-2.1 have been validated using ground based observations from the Baseline Surface Radiation Network (BSRN) as a reference. The Spectrally Resolved Irradiance (SRI) has been validated using ground measurements from Ispra (Italy). 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 means of 8/15 W/m² for SIS, 10/20 W/m² for SID and 15/25 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 mean absolute differences of the monthly mean SIS and the SDI parameters are 5.2 W/m^2 and 7.7 W/m^2 (for SID) / 16.4 W/m^2 (for DNI), respectively, which is well below or, in the case of DNI, close to the respective target accuracies of 8 W/m^2 (SIS), 10 W/m^2 (SID) and 16 W/m² (for DNI). Moreover, about 96 %, 93 % and 84 % of the monthly mean absolute differences are below the target / 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 well below 20 h.
The daily mean SIS data have a mean absolute difference of 11.7 W/m², which is below the target accuracy of 15 W/m². The mean absolute difference of the daily mean direct, and direct normal radiation (SID and DNI) is 17.1 and 33.1 W/m^2, respectively, which is also below its threshold values. The daily sums of the sunshine duration have a mean absolute deviation of about 90 min. The target / threshold accuracy is therefore achieved for monthly and daily means / sums.
A small negative decadal trend of -0.8±0.4 W/m^2/decade in the bias between the satellite-derived data record and surface irradiance observations in Europe has been found, indicating a stability of the surface radiation data records within the target accuracy of 2 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 validation of the spectral resolved irradiance climate data record (SRI) in Ispra, Italy, documents an accuracy of the monthly mean values of <0.03 W/m^2/nm for wavelength below 1000 nm and an even better accuracy for larger wavelengths.

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 35 year long (1983-2017) continuous surface radiation climate data record based on observations from the Meteosat First and Second Generation satellites: Surface Solar Radiation Data record – Heliosat Version 2.1 (SARAH-2.1).
The Digital Object Identifier (DOI) of this SARAH-2.1 data record (1983-2017) is 10.5676/EUM_SAF_CM/SARAH/V002_01 and includes the SARAH-2 data record (1983-2015) (DOI: 10.5676/EUM_SAF_CM/SARAH/V002).

SARAH-2.1 contains climate data records of the surface incoming solar radiation (SIS), the surface incoming direct radiation (SDI), spectrally resolved radiation (SRI), the effective cloud albedo (CAL) and the sunshine duration ((Müller et al., 2015, Kothe et al., 2017). The validation of these CDRs is 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 2-10) are used. The SIS, SDI and SRI 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). The effective cloud albedo is used as input for the Mesoscale Atmospheric Global Irradiance Code (MAGIC), which calculates the clear sky radiation and considers the effect of the effective cloud albedo on the irradiance. MAGIC is a sophisticated eigenvector look-up table method (Mueller et al. 2009). Heliosat is extended by addition of a self-calibration method accounting for changes in the satellites (switches, degradation) and a modification in the determination of the surface albedo. 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 and SDI 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 radiation 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.

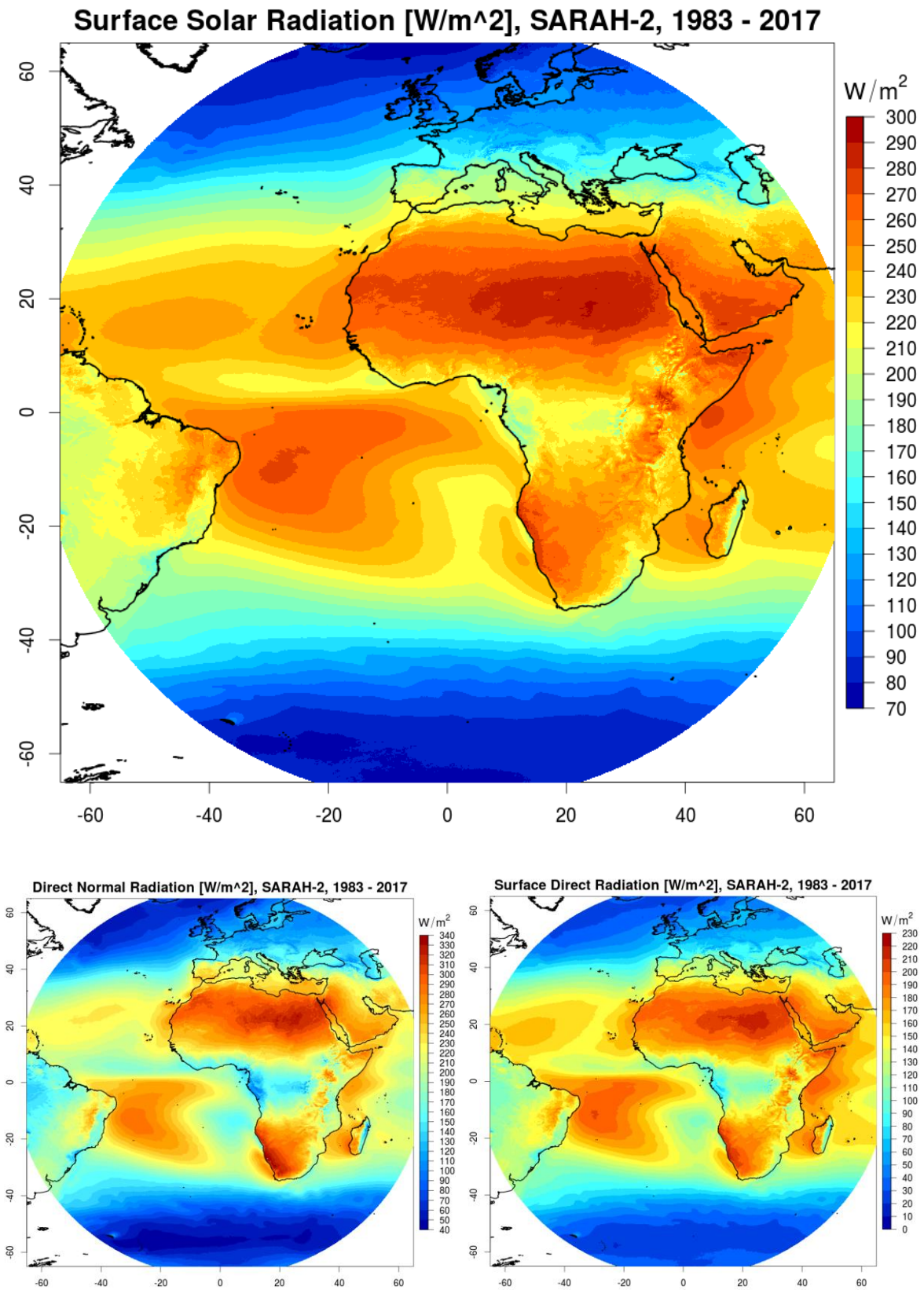


Figure 2-1: Multiyear means of SIS (top), and of the SDI Parameters DNI (bottom left) and SID (bottom right) for the SARAH-2.1 climate data record (1983-2017)

3 Validation procedure

3.1 Validation data

The validation of the new SARAH-2.1 data records for the surface incoming solar radiation (SIS) and 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). 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 15 stations are located mainly in the Northern Hemisphere but they cover the main climatic regions and they span a substantial part (1992-2017) 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. Ground observations of spectrally resolved radiation are very rare. For the SRI validation a station record of Ispra is used.
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 the SARAH data record.

Station	Country	Code	Latitude [°N]	Longitude [°E]	Elevation [m]	Data since
Cabauw	Netherlands	Cab	51.97	4.93	0	1.2.2005
Camborne	UK	Cam	50.22	-5.32	88	1.1.2001
Carpentras	France	Car	44.05	5.03	100	1.8.1996
Cener	Spain	Cnr	42.82	-1.60	471	1.7.2009
De Aar	South Africa	Daa	-30.67	23.99	1287	1.5.2000
Florianopolis	Brasil	Flo	-27.53	-48.52	11	1.6.1994
Gobabeb	Namibia	Gob	-23.56	15.04	407	1.5.2012
Lerwick	UK	Ler	60.13	-1.18	84	1.1.2001
Lindenberg	Germany	Lin	52.21	14.12	125	1.9.1994
Palaiseu Cedec	France	Pal	48.71	2.21	156	1.6.2003
Payerne	Switzerland	Pay	46.81	6.94° E	491	1.9.1992
Sede Boger	Israel	Sbo	30.9	34.78	500	1.1.2003
Solar Village	Saudi Arabia	Sov	24.91	46.41	650	1.8.1998
Tamanrasset	Algeria	Tam	22.78	5.51	1385	1.3.2000
Toravere	Estonia	Tor	58.25	26.46	70	1.1.1999

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.

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 2016 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-2.1.

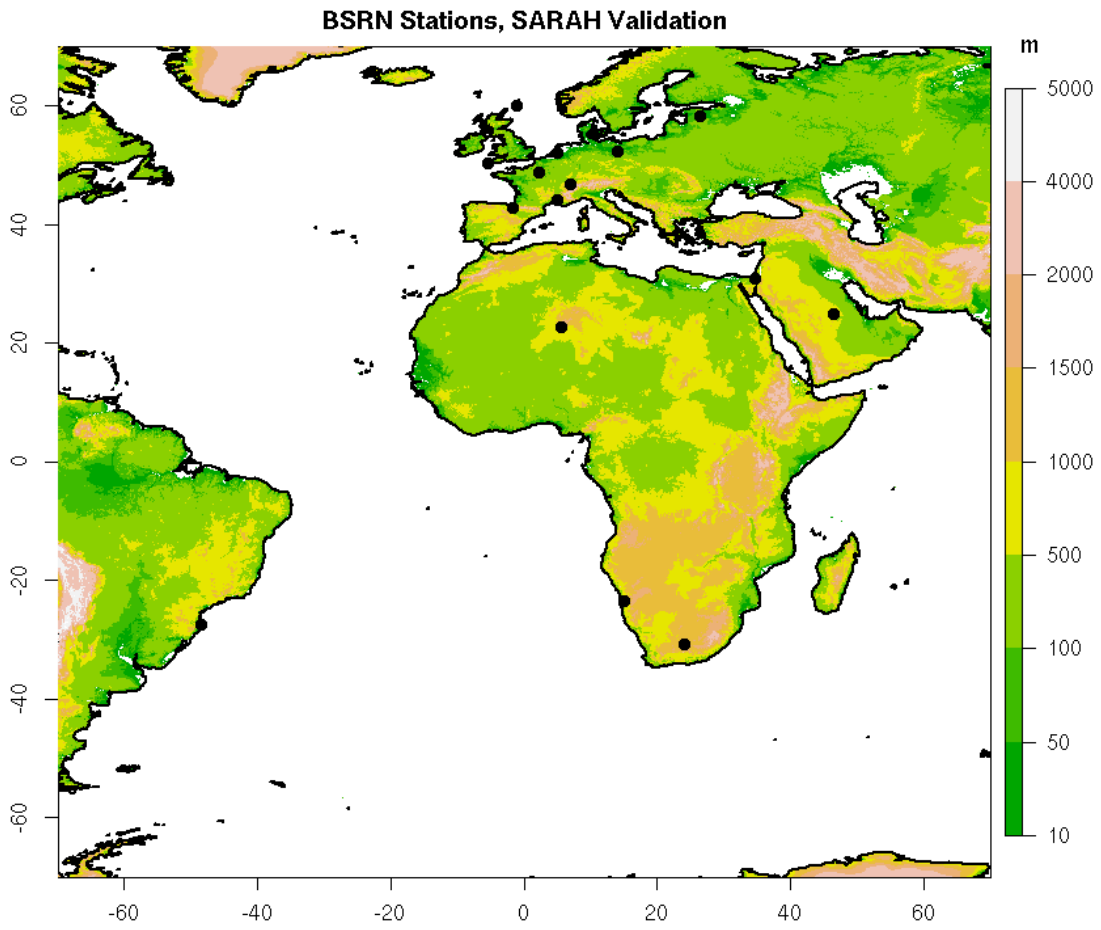


Figure 3-1: Location of the BSRN stations used for the validation. Black dots are the locations of the stations. The underlying map shows the topography.

The validation thresholds as defined in the Requirements Review 2.1 Document [RD 3] and CM SAF CDOP Product Requirements Document [AD 1] for SIS, SDI (SID, DNI), SRI and CAL are listed in Table 3-2. 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 and 10 W/m^2 for the SDI parameters.

Only very limited reference measurements are available to validate the spectral resolved surface irradiance (SRI). Measurements of the surface spectral irradiance are rare and not easily available; the calculation of monthly means often is impossible due to the reduced sampling frequency and the short time period of the measurements. The only accessible and available measurements of the spectral irradiance in the relevant region have been performed at the EU Joint Research Center (EU JRC) in Ispra, Italy from February 2009 to June 2010. The measurements were obtained over the range of 400 – 2500 nm in steps of 2 nm and in intervals of about 30 min; each measurement is a result of a spectral scan lasting about 6 min. More information on these measurements is available in Norton et al. (2015). Based on these data monthly means of the spectral resolved irradiance have been derived for each spectral band. The calculation of monthly means based on 30-min instantaneous measurements is associated with enhanced uncertainty, which need to be taken into account

when interpreting the comparison between the surface and the satellite measurements. To reduce the uncertainty it was required for the calculation of the monthly averages that more than 20 daily means were available for that month; daily means were only derived if more than 10 observations covering at least 75 % of the daylight hours were available. In total, 12 monthly means of the spectral irradiance between March 2009 and April 2010 (May and November 2009 were missing) have been derived and will be used in the validation.

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 some 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.

Table 3-2: Accuracy [W/m2] (SDU: [h]) and decadal stability [W/m2/decade] (SDU: [h/dec]) requirements (threshold (Thr), target (Tar) and optimal (Opt)) for monthly and daily averaged data from the SARAH-2 data record (SIS, SDI, SRI, CAL, SDU); *the accuracy value has been weighted with the relative contribution to the broadband spectra;

	SIS [W/m^2]			SID [W/m^2]			DNI [W/m^2]			SRI [W/m^2]*			CAL			SDU [h]		
accuracy	Th	Ta	Op	Th	Ta	Op	Th	Ta	Op	Th	Ta	Op	Thr	Tar	Opt	Th	Ta	Op
monthly	15	8	5	15	10	8	20	15	12	15	10	8	0.15	0.1	0.08	30	20	10
daily	20	15	12	25	20	15	30	25	20	/	/	/	0.2	0.15	0.1	2.0	1.5	1.0
stability	3	1	0.5	5	3	2	5	3	2	/	/	/	0.08	0.06	0.03	0.8	0.5	0.3

3.2 Data record used for evaluation

In addition to the validation with surface measurements from the BSRN archive, the quality of the CM SAF SARAH-2.1 data record is evaluated against the quality of the first release of the CM SAF surface radiation data based on the MVIRI measurements only, available from 1983 to 2005 (Posselt et al. 2011; Posselt et al. 2012). This data record has been widely used and evaluated by numerous users much beyond the validation activities conducted by the CM SAF (e. g., Bojanowski et al. 2014; Hagemann et al. 2013; Sanchez-Lorenzo et al. 2013,). Further, the predecessor of the new SARAH-2.1 data record, SARAH, is used for comparisons (see Müller et al. 2015). An extensive analysis of temporal variability and trends of the global radiation (SIS) from SARAH-2 has been performed by Pfeifroth et al., 2018.

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. Bias and standard deviation alone do not provide sufficient information of the climate quality of a data record. 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-2.1) 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.

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

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.

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

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:

$$\text{StMAD} = \frac{1}{nstation}\sum_{k=1}^{nstation} MAD_{station}(k)$$

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.

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

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).

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

4 Validation results

In this section the validation results of the new SARAH-2.1 climate data record are presented. This includes the Surface Incoming Solar Radiation (SIS), the surface incoming direct irradiance (SDI) parameters SID and DNI, the Spectral resolved radiation (SRI) and the effective cloud albedo, CAL. For the evaluation of the quality of the SARAH-2.1 data record, also comparisons with its predecessors SARAH-1 and SARAH-2 surface radiation data records are included.
For the comparison with the BSRN data the daily and monthly means from the SARAH-2.1 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 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. In addition to the results presented in this section, also more figures containing additional results for each individual station are given in the Appendix. These provide additional insights in the differences over time for the different locations.
The statistical quantities used to define the accuracy of the variable are the mean absolute difference and the fraction of month above limit. 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 should be below the threshold / target accuracy plus the uncertainty of the surface measurements.

4.1 Surface Incoming Solar radiation: SIS

Monthly means

The results of the validation of the monthly mean SARAH-2.1 SIS data record are summarized in Table 4-1. It shows that the mean absolute difference (MAD) of the data record of 5.16 W/m^2 is better than the requested limit for the target accuracy of 8 W/m^2 and is close to the optimal accuracy requirement of 5 W/m^2. In total only about 5 % of the monthly mean data exceed the target 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 0.92.
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 to document the continuous improvement.

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 target accuracy. The target value to determine the fraction of months that exceed the target is shown in brackets.

SIS	N_{mon}	Bias [W/m^2]	MAD [W/m^2]	SD [W/m^2]	StMAD [W/m^2]	AC	$Frac_{mon}$ > target accuracy [%]
SARAH-2.1	2453	1.59	5.19	6.96	5.31	0.92	5.5 (>13 W/m^2)
SARAH-2	1909	2.03	5.13	6.66	5.20	0.93	5.3 (>13 W/m^2)
SARAH	1672	1.27	5.46	7.34		0.92	5.6 (>15 W/m^2)
MVIRI	878	4.24	7.76	8.23		0.89	10.71 (>15 W/m^2)

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. As already shown in Table 4-1 the new SARAH-2.1 surface radiation data record is overall an improvement relative to its predecessors.

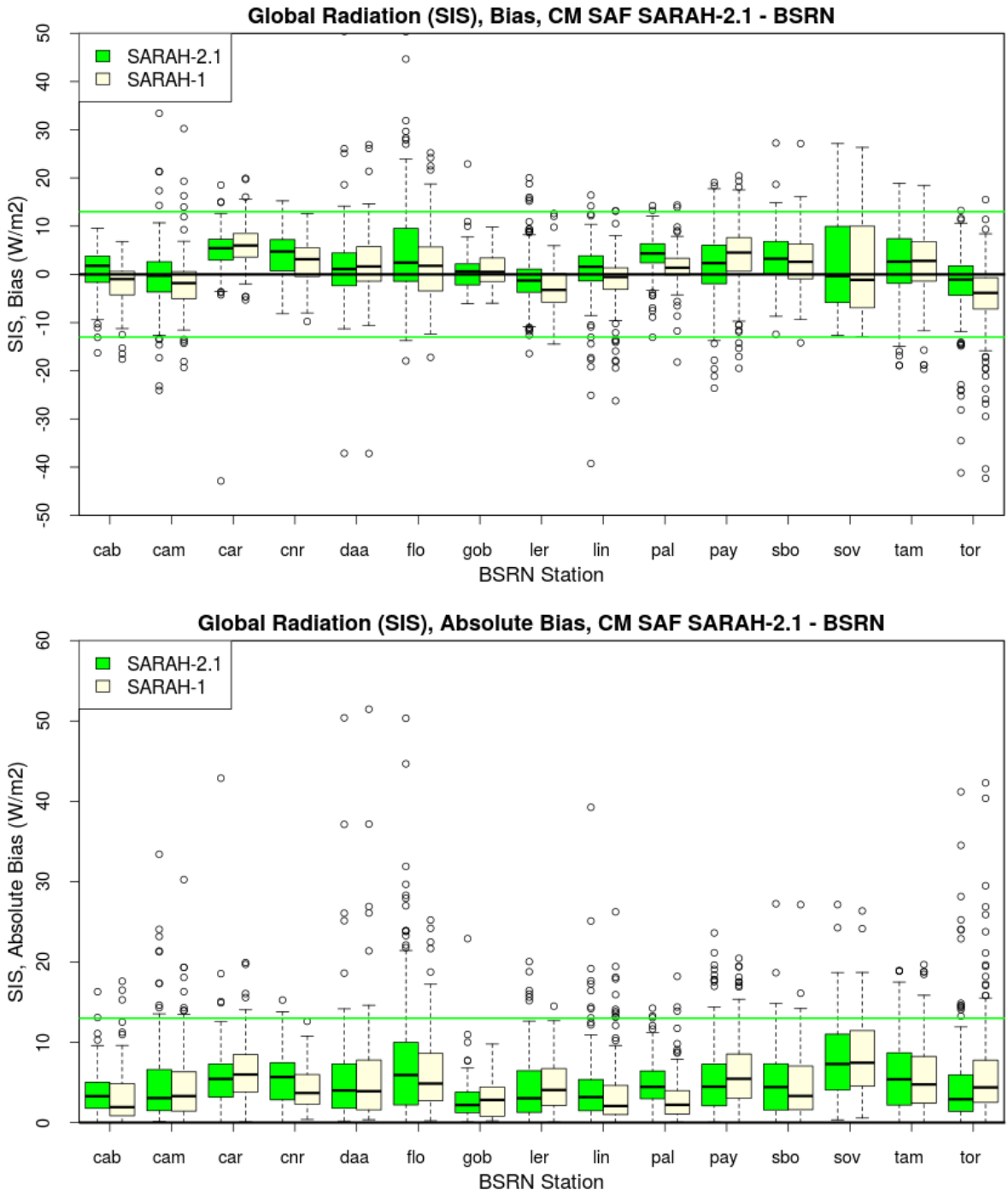


Figure 4-1: (Top) Bias and (bottom) absolute bias (MAD: mean absolute difference) between the monthly mean BSRN surface measurements and the (green) SARAH-2.1 SIS data record and the (yellow) SARAH-1 SIS data record for each considered BSRN station. The green lines indicate the target value of 13 W/m^2.

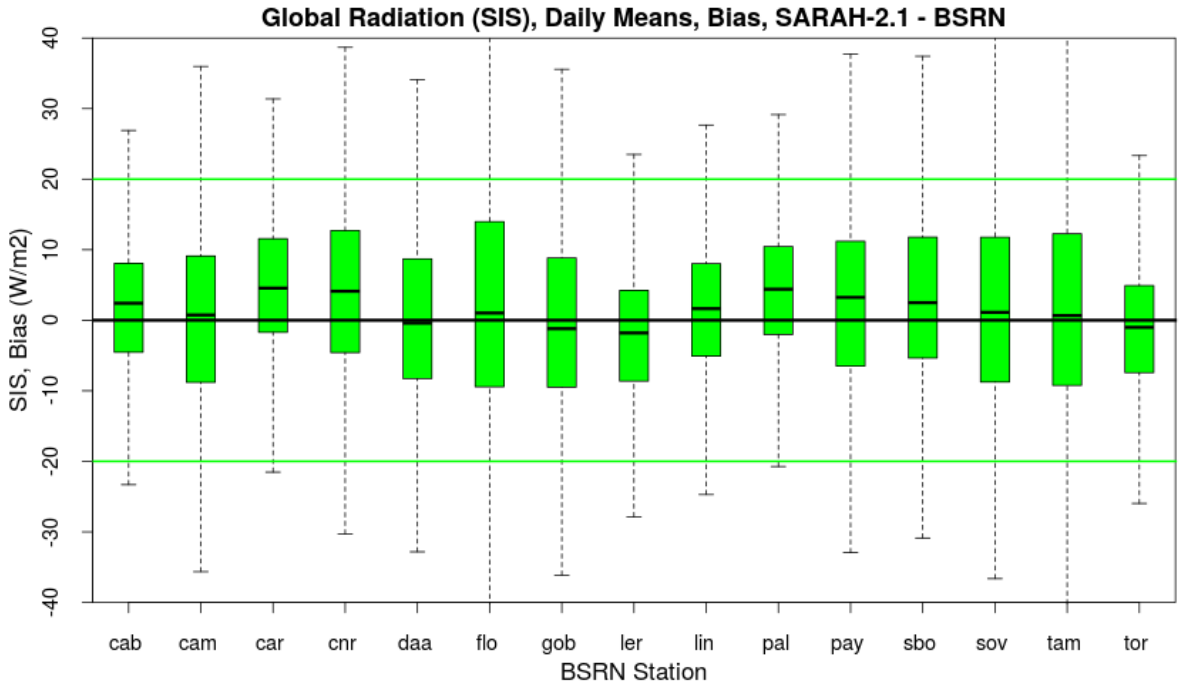
Daily means

Table 4-2 provides the validation result for the daily means of the new SARAH-2.1 SIS data record, the SARAH-2 data record and the previous CM SAF climate data records 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-2.1 SIS daily mean data record (i. e., 11.7 W/m^2) is well below the target value of 20 W/m² and even below the optimal accuracy of 12 W/m^2 (neglecting station uncertainty). Nearly 83 % of the MAD values meet the accuracy requirement. Thus, the accuracy requirement is overall fulfilled for the daily means. As for the monthly mean validation, the SARAH-2.1 SIS data record shows improved performance compared to the SARAH-1 SIS data record, beside for the bias. The bias is slightly higher for SARAH-2.1 (and SARAH-2), which is a consequence of the improved temporal stability achieved (see Section 6).

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 target accuracy. The target value to determine the fraction of days that exceed the target is shown in brackets.

SIS	N_{day}	Bias [W/m^2]	MAD [W/m^2]	SD [W/m^2]	StMAD [W/m^2]	AC	$Frac_{day}$ > target accuracy [%]
SARAH-2.1	72087	1.51	11.70	17.2	11.92	0.95	16.8 (>20 W/m^2)
SARAH-2	57128	1.74	11.78	17.2	11.96	0.95	16.9 (>20 W/m^2)
SARAH	48605	1.12	12.1	17.9		0.95	11.3 (>25 W/m^2)
MVIRI	29790	4.41	15.05	23.36		0.92	16.3 (>25 W/m^2)

The bias and the MAD of the SIS daily mean from the SARAH-2.1 data record for the individual BSRN stations are shown in Figure 4-2. Generally, the CM SAF SARAH-2.1 SIS performs well at all stations with mean absolute difference values well below the target value; at nearly all stations the bias is below the target value for well over 75 % of the daily mean values.



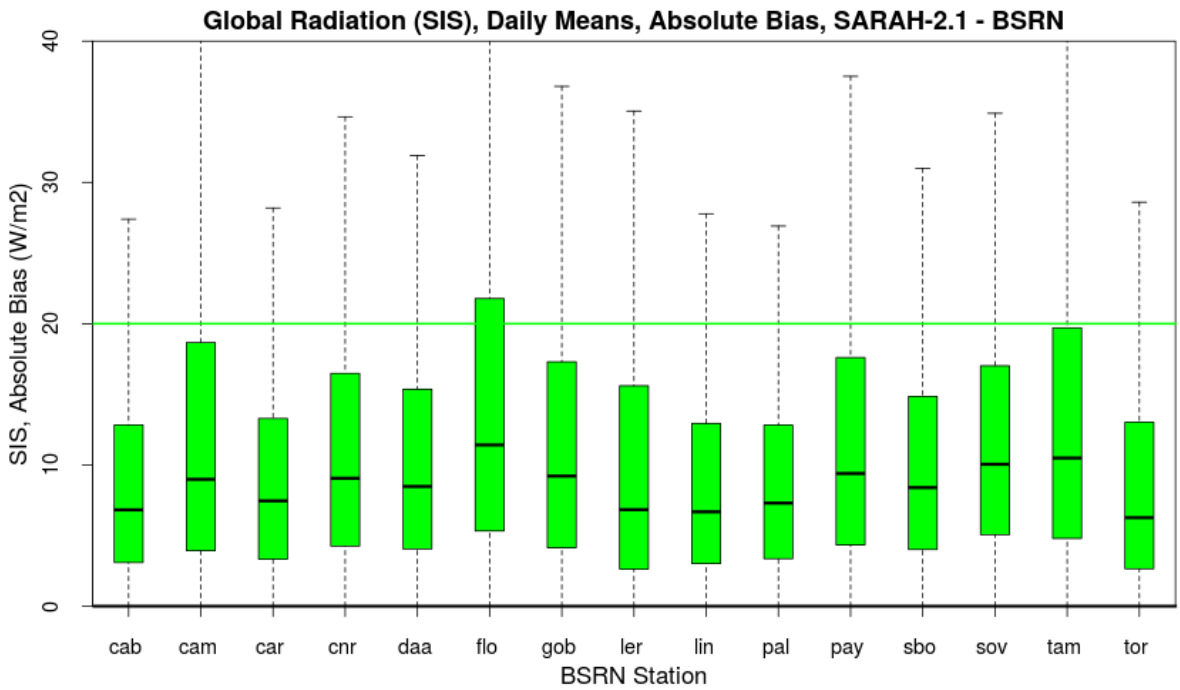


Figure 4-2: (Top) Bias and (bottom) absolute bias for the comparison of daily mean SIS between the BSRN stations and the SARAH-2.1 Surface radiation data record. No outliers are shown here. The green lines indicate the target accuracy for the SIS daily means.

4.2 Surface Direct radiation (SDI) parameters

This section presents the validation results of the SARAH 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)

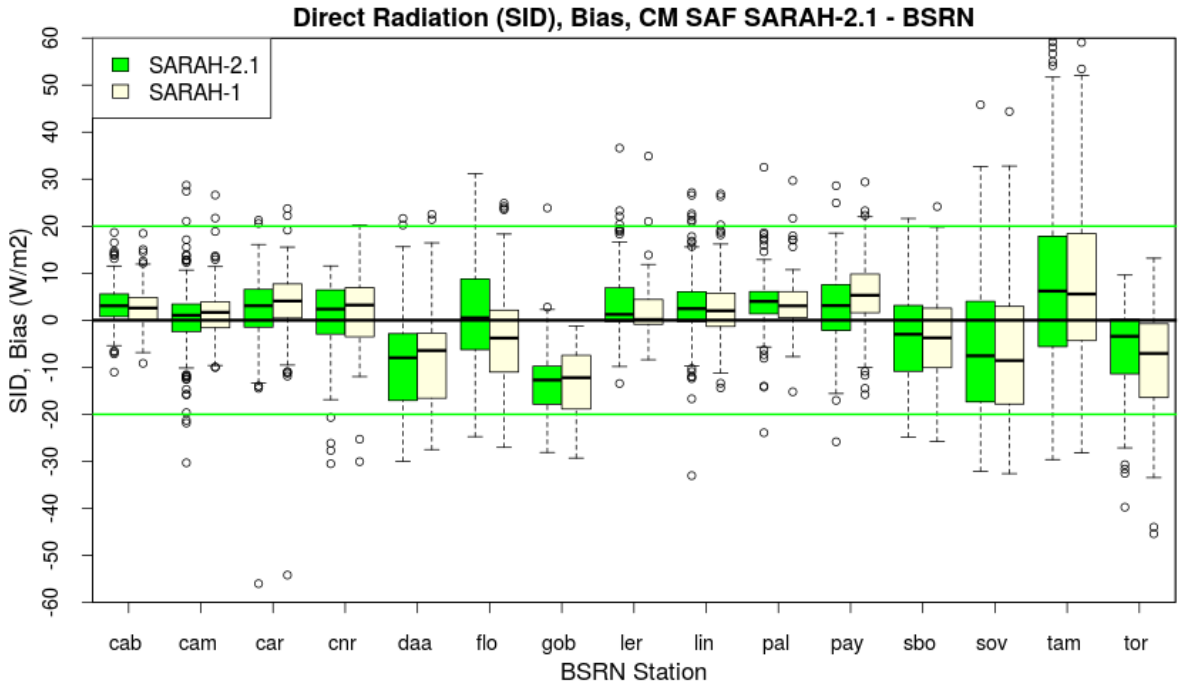
Monthly means

Table 4-3 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 0.87 W/m^2 is found in the SARAH-2.1 SID data. The mean absolute difference is 7.8 W/m^2 and hence below the target accuracy of 10 W/m^2. The standard deviation is larger for the direct radiation than for global radiation (11.3 W/m^2 compared to 7 W/m^2). Only 8% 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 0.89.

Table 4-3: 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 target accuracy. The target value to determine the fraction of months that exceed the target is shown in brackets.

SID	N_{mon}	Bias [W/m^2]	MAD [W/m^2]	SD [W/m^2]	StMAD [W/m^2]	AC	$Frac_{mon}$ > 20 W/m^2 [%]
SARAH-2.1	2347	0.87	7.8	11.3	8,70	0.89	7.7
SARAH-2	1828	1.36	7.8	11.2	8.58	0.90	7.5
SARAH	1587	0.98	8.2	11.6		0.89	8.4
MVIRI	805	0.89	11.0	15.67		0.83	15.4

For comparison with the previous versions of the CM SAF surface radiation data record, Table 4-3 also shows the results of the validation of the surface direct radiation (SID) for SARAH-2, SARAH and the CM SAF MVIRI data records. Here the improvement of the new data record of the direct surface solar radiation is visible.
The results for the individual BSRN stations are shown in Figure 4-3. For the SID parameter the target accuracy is achieved at all used BSRN station. Figure 4-3 also presents the bias and the absolute bias of the monthly means of SID from SARAH-2.1 and from SARAH-1 data record for each station. Overall the SARAH-2.1 shows a comparable quality for SID at the individual BSRN stations compared to SARAH-1. However on average the mean absolute deviation has improved to a value of 7.8 W/m^2. The largest improvement is found at the Toravere station (see Figure 4-3) that is located at the border of the Meteosat field of view. This improvement is likely a result of the improvement treatment of radiation at high satellite zenith angles, meaning when the satellite views towards the borders of the field of view.



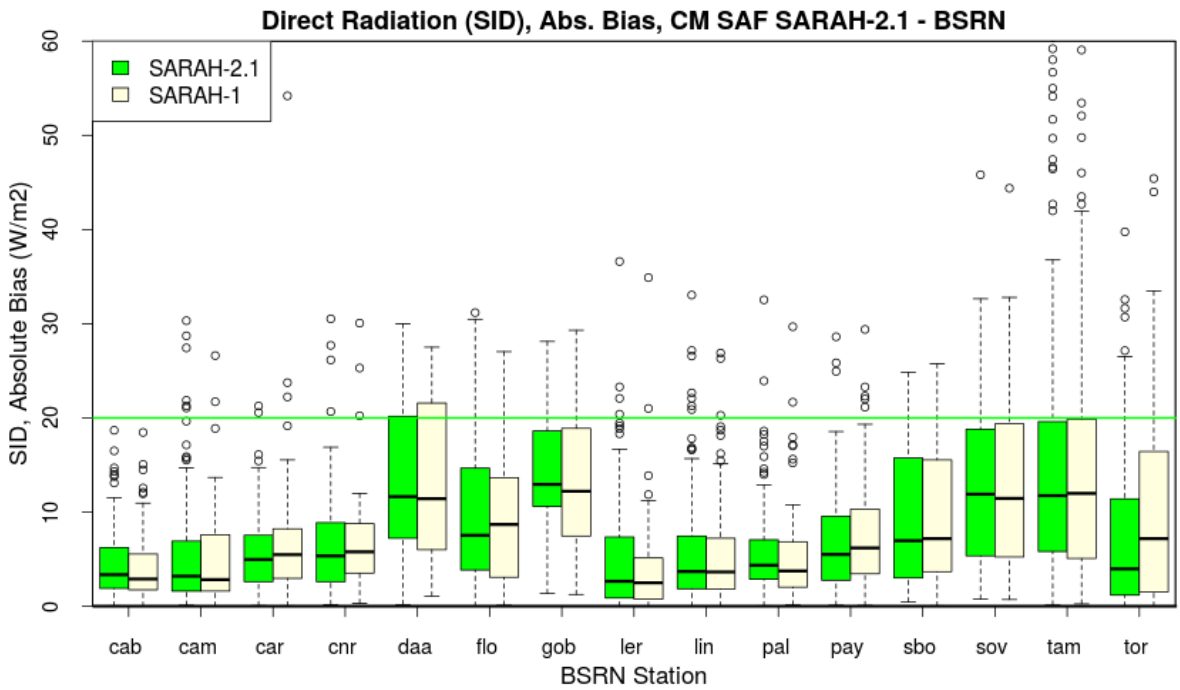


Figure 4-3: (Top) Bias and (bottom) absolute bias (MAD: mean absolute difference) between the monthly mean BSRN surface measurements and the (green) SARAH-2.1 SID data record, and the (yellow) SARAH-1 SID data record for each considered BSRN station. The solid green line indicates the target value of 20 W/m^2 for SID.

Daily means

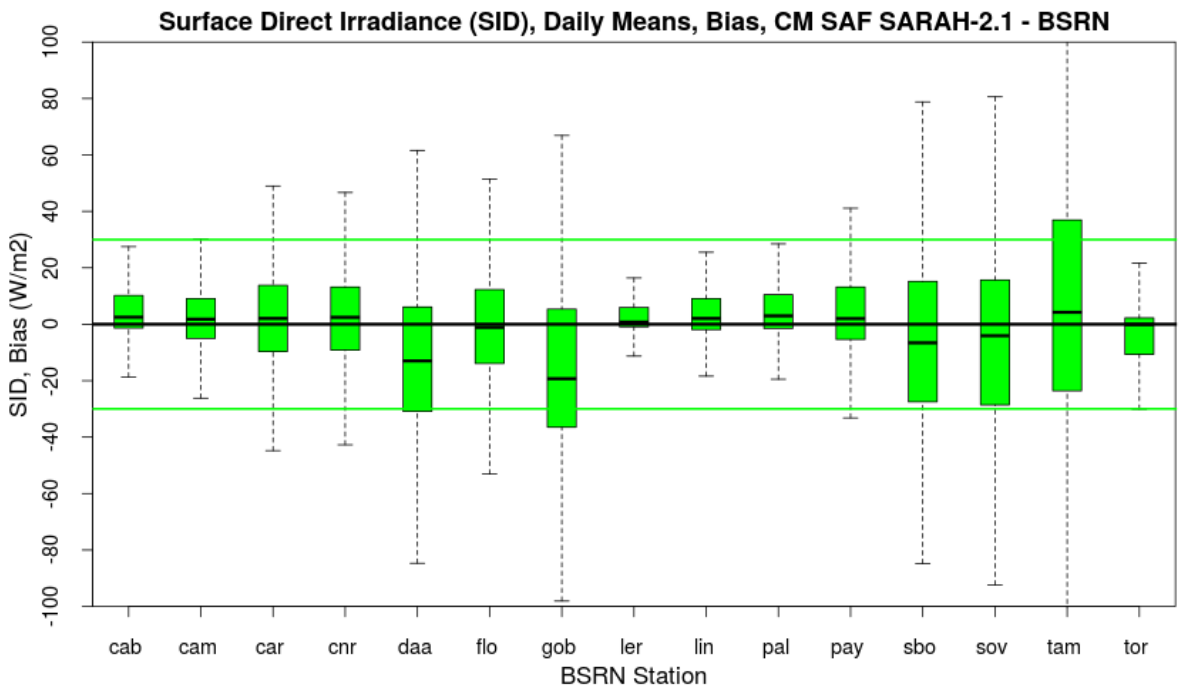
The validation results for the daily means of the CM SAF SARAH-2.1 SID data record are shown in Table 4-4. The mean absolute difference of SID is larger than for the daily mean SIS data record (17.2 W/m^2 compared to 11.7 W/m^2), but well below the target accuracy of 20 W/m^2. As for SIS, also the daily mean SID shows a larger spread than the corresponding

monthly means. For comparison with the CM SAF SARAH-1 surface radiation data record, the evaluation results for the surface direct irradiance (SID) from the SARAH-1 data record are also reported in Table 4-4. As for SIS, SARAH-2.1 shows an overall improvement compared to the SARAH-1 data record. Results for SARAH-2.1 and SARAH-2 are, as expected, comparable.

Table 4-4: Results of the comparison between the daily mean surface solar direct radiation derived from BSRN measurements and the SARAH-2.1 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 two SARAH-2.1 predecessors 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/m^2]**	**MAD [W/m^2]**	**SD [W/m^2]**	**StMAD [W/m^2]**	**AC**	**$Frac_{day}$ > 30 W/m^2 [%]**
SARAH-2.1	65697	0.79	17.2	25.9	18.85	0.92	19.3
SARAH-2	51929	0.89	17.6	26.2	18.76	0.92	19.8
SARAH	43549	0.77	17.9	26.6		0.92	20.5
MVIRI	26614	0.74	20.73	31.74		0.89	23.42

The results for the individual stations shown in Figure 4-4, show similar features as for the monthly mean SID data. Large mean absolute differences are found at the mostly sunny, cloud free desert stations of Gobabeb and Tamanrasset. For most other stations, the majority of daily mean values of SID are below the target accuracy.



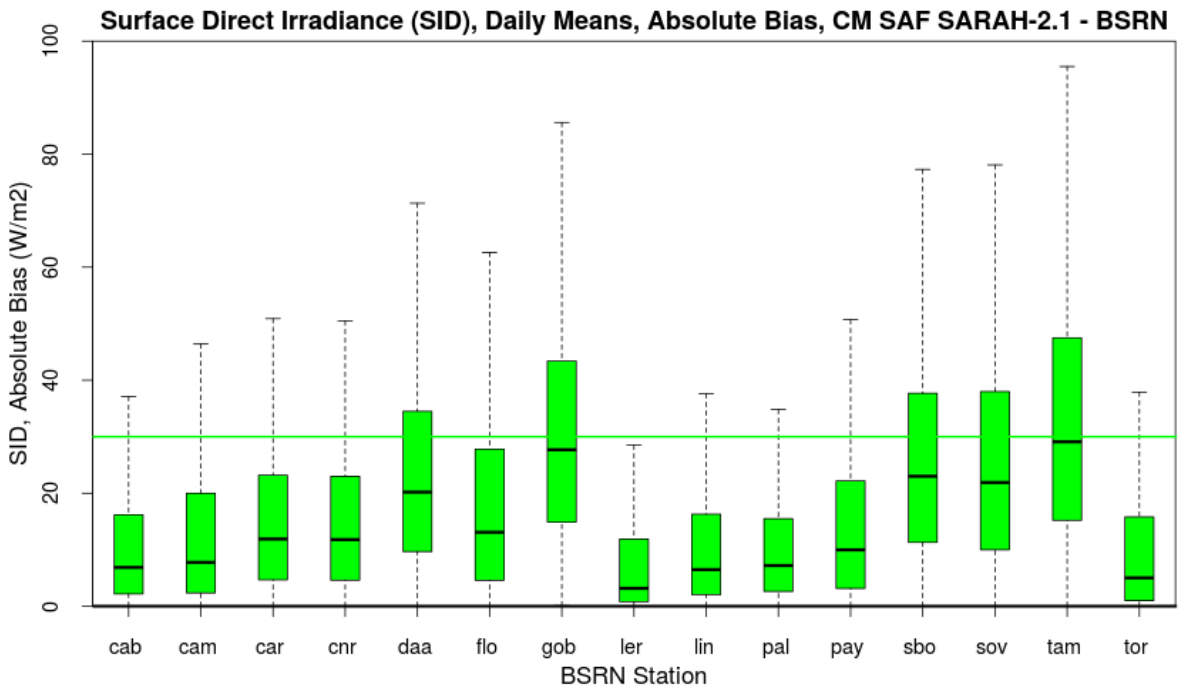


Figure 4-4: (Top) Bias and (bottom) absolute bias for the comparison of daily mean SID data between the BSRN stations and the SARAH-2.1 Surface radiation data record. No outliers are shown here.

4.2.2 Surface Direct Normal Radiation (DNI)

Monthly means

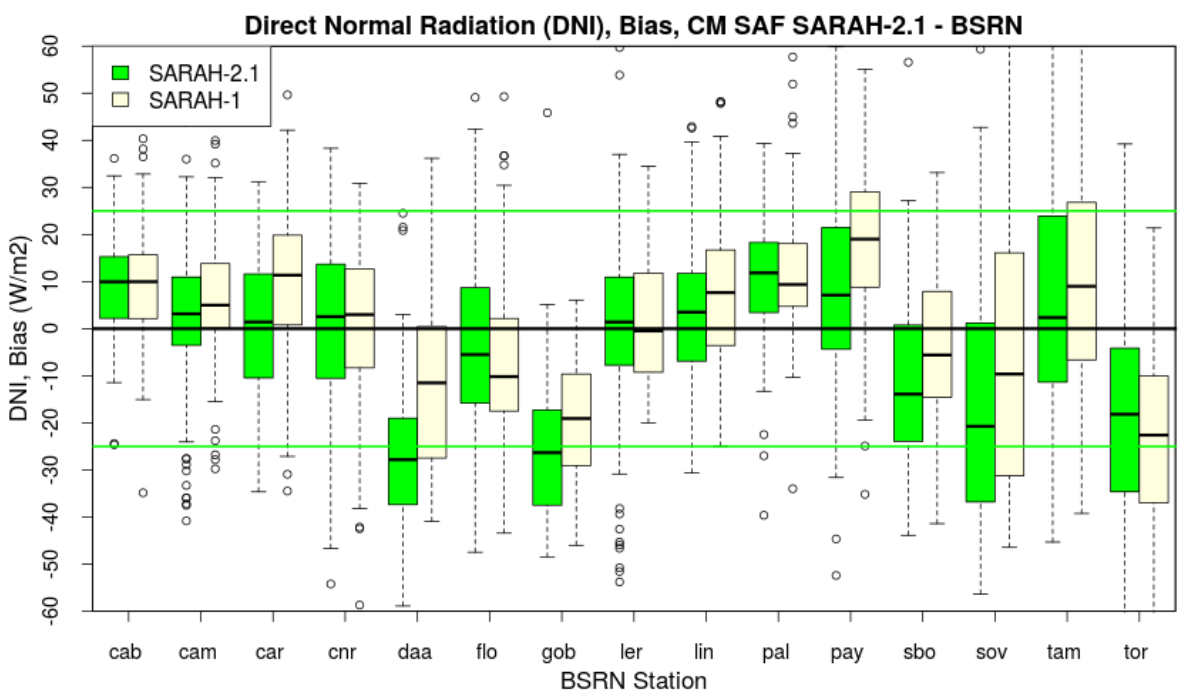
Table 4-5 shows the validation results of the monthly mean direct normal surface radiation (DNI) from the new CM SAF SARAH-2.1 surface radiation data record compared to the observations from the BSRN measurements. A small negative bias of -1.82 W/m^2 is found in

the SARAH-2.1 DNI data record. The mean absolute difference is 16.4 W/m^2, i.e., close to the target accuracy of 15 W/m^2 and well below the threshold accuracy of 20 W/m^2. The standard deviation and, thus, the spread is larger for DNI than for SID (21.5 W/m^2 compared to 11.3 W/m^2). More than 85 % of the monthly mean values are better than the target accuracy value including measurement uncertainty. The anomaly correlation reaches a value of 0.88.

Table 4-5: Results of the comparison between the monthly mean surface solar direct normal radiation derived from BSRN measurements and the SARAH-2.1 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 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	$Frac_{mon}$ > 30 W/m^2 [%]
SARAH-2.1	2263	-1.82	16.4	21.9	17.97	0.88	14.7
SARAH-2	1794	-0.89	16.4	21.9	17.75	0.88	14.4
SARAH-1	1541	3.25	17.5	22.9		0.87	16.4

For comparison with the previous versions of the CM SAF surface radiation data record, Table 4-5 also shows the results of the validation of the direct normal radiation (DNI) for the SARAH-2 and SARAH-1 data records.



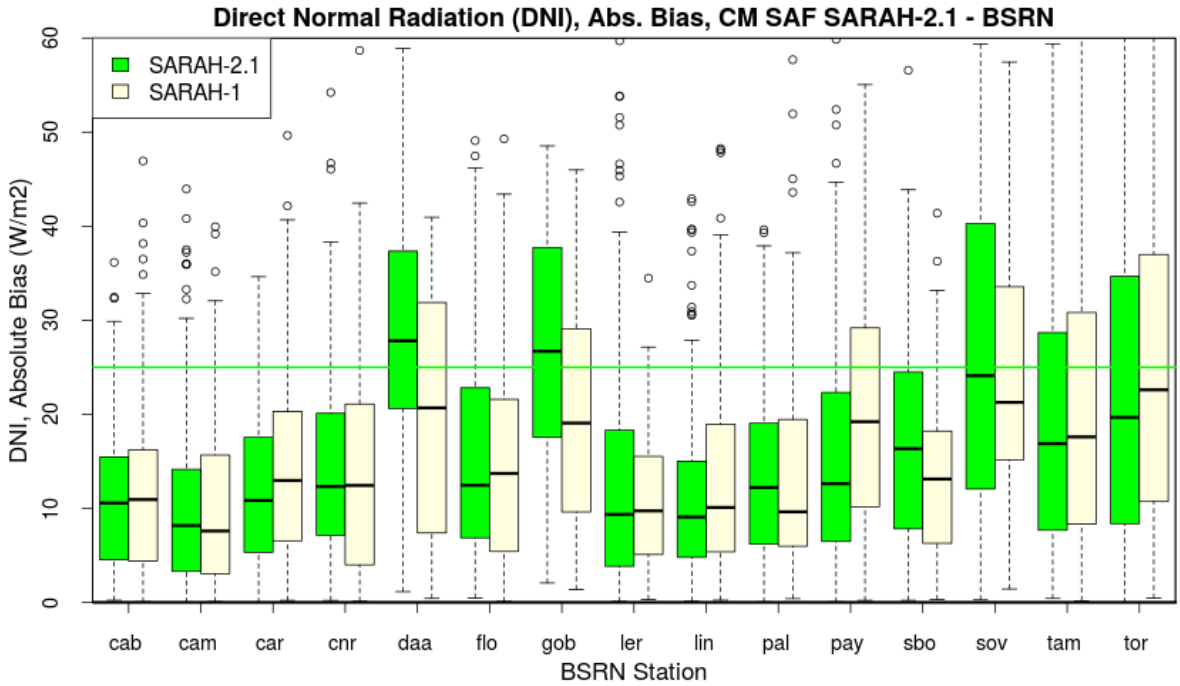


Figure 4-5: (Top) Bias and (bottom) absolute bias (MAD: mean absolute difference) between the monthly mean BSRN surface measurements and the (green) SARAH-2.1 DNI data record, and the (yellow) SARAH-1 DNI data record for each considered BSRN station. The solid green line indicates the target value of 30 W/m^2 for DNI.

The results for the individual BSRN stations are shown in Figure 4-5. At the stations of De Aar and Gobabeb more than 50% of the DNI monthly means do not fulfill the target value requirement (green line in Figure 4-5). As for SID, the SARAH-2 data record shows lower accuracies, in absolute terms, for desert stations with high radiation values; However in relative terms the deviations are not as different for these locations compared to the other stations.

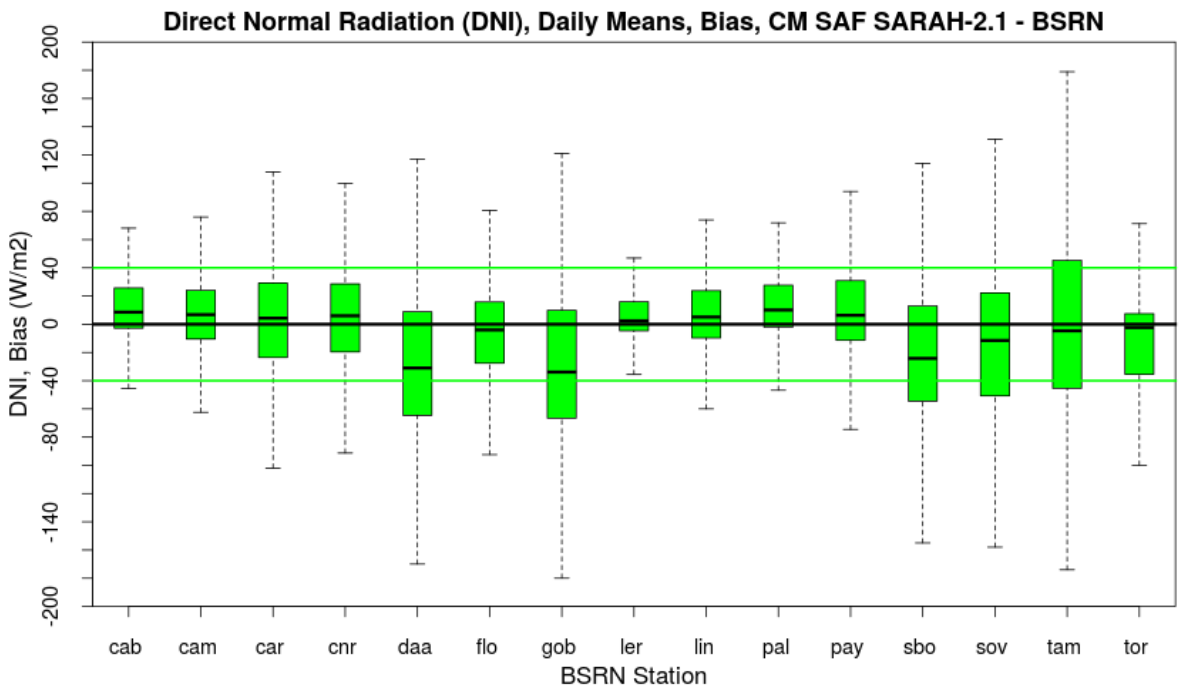
Daily means

The validation results for the daily means of the DNI of SARAH-2.1 are shown in Table 4-6. The mean absolute difference is slightly larger than for the daily mean SID data record (33.4 W/m^2 compared to 17.2 W/m^2), but well below the threshold value of 40 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-1 surface radiation data record, the evaluation results for the surface direct normal irradiance (DNI) from the SARAH-1 data record are also reported in Table 4-6. As for SIS, the improved performance of SARAH-2.1 compared to the SARAH-1 data record can be seen.

Table 4-6: Results of the comparison between the daily mean surface solar direct normal radiation derived from BSRN measurements and the SARAH-2.1 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 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	$Frac_{day}$ > 40 W/m^2 [%]
SARAH-2.1	60528	-0.82	33.4	46.8	35.71	0.91	32.3
SARAH-2	49075	-0.81	33.4	46.8	35.45	0.91	32.4
SARAH	41253	3.8	34.0	48.4		0.91	32.8

The results for the individual stations are shown in Figure 4-6. The validation results at the individual BSRN stations show the same features as for the monthly mean DNI data. Exceptionally large mean absolute differences are found at the mostly sunny, cloud free desert stations of Gobabeb and Tamanrasset. For most other stations, more than 50 % of the daily mean bias difference of DNI is within the target accuracy value including measurement uncertainty. The relative MAD measures for the desert stations of Gobabeb and De Aar are in the order of 15 %. At those dessert stations the bias is clearly negative in the order of -20 to -30 W/m^2. This negative might be partly explainable by the circumsolar radiation affecting surface measurements of the direct radiation (Blanc et al., 2014)



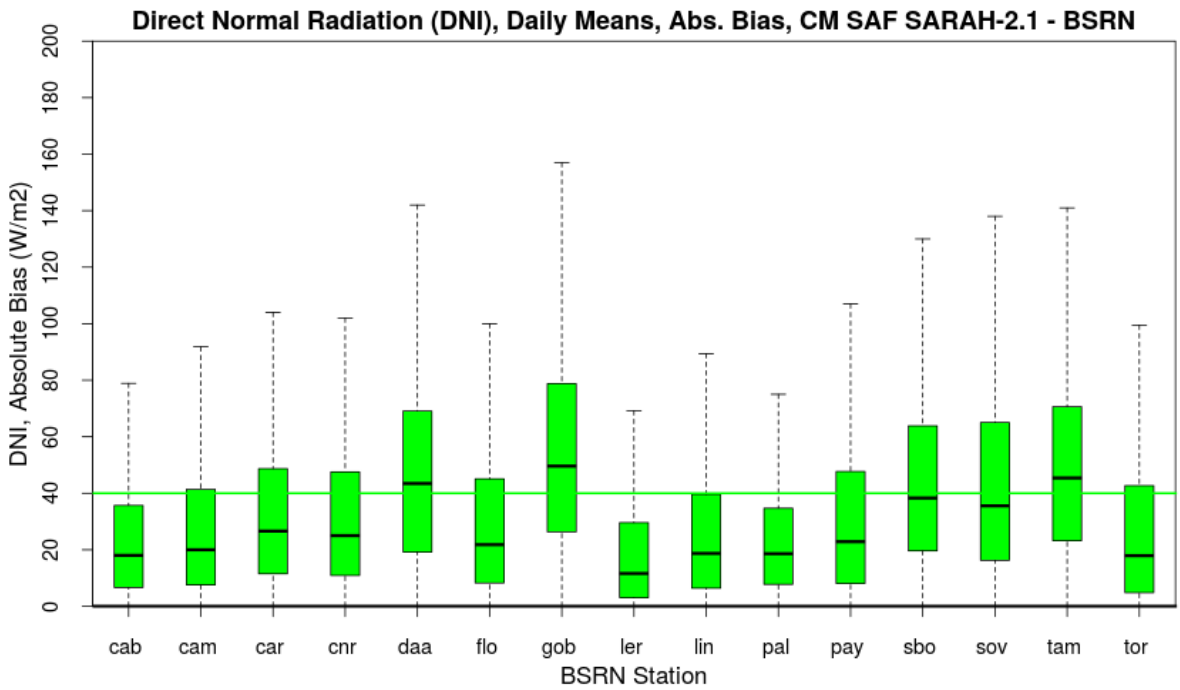


Figure 4-6: (Top) Bias and (bottom) absolute bias for the comparison of daily mean DNI between the BSRN stations and the SARAH-2.1 climate data record. No outliers are shown here.

4.3 Spectral Resolved Irradiance SRI

The spectral resolved irradiance (SRI) is based on the same satellite retrieval method as the SIS and SDI data records (Mueller et al., 2015). However, in the case of the spectral resolved irradiance the full spectral information used in the retrieval is contained in the climate data record. To limit the data amount only monthly means data are generated, validated, and provided. For the validation of the monthly mean SRI data record only reference data from Ispa, Italy, are available (Norton et al., 2015).

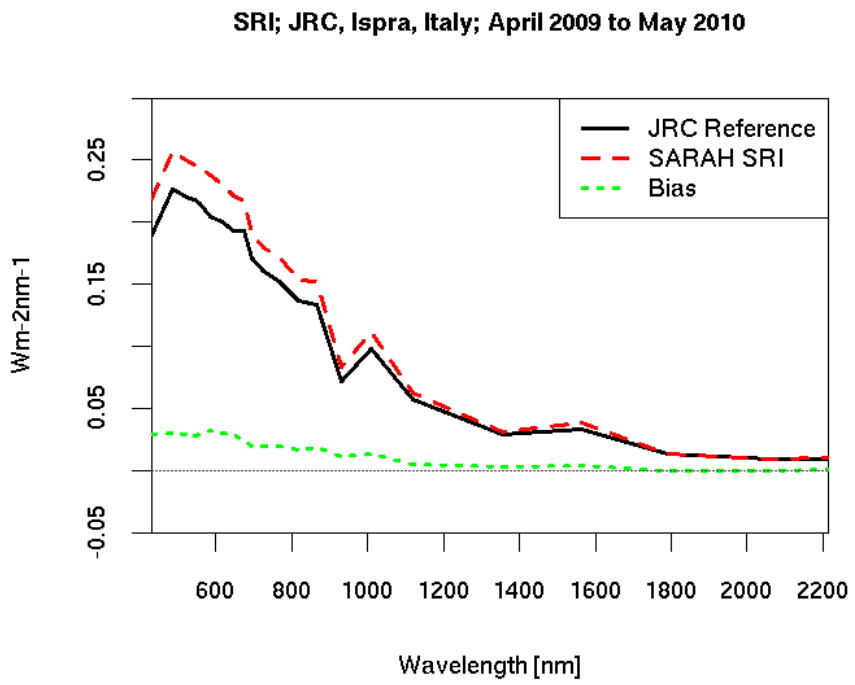


Figure 4-7: Mean Spectral Irradiance from April 2009 to May 2010 in Ispra, Italy, based on surface measurements (black line) and the SARAH-2.1 SRI data record (red dashed). The dotted green line represents the bias.

Figure 4-7 presents the mean spectral irradiance between April 2009 and May 2010 in Ispra, Italy, based on surface reference measurements and the SARAH-2.1 SRI data record as well as the bias between both data records. Overall there is a small overestimation of the SARAH-2.1 SRI data record compared to the surface reference measurements, which is consistent with an overestimation of about 15 W/m^2 of the SARAH-2.1 SIS when compared to surface measurements of the global radiation at Ispra. The bias at around 500 nm is about 0.03 $Wm^{-2}nm^{-1}$ and decreases with increasing wavelength. The general shape of the spectral irradiance, incl. the decreased irradiance in the water vapor absorption bands between 800 and 1000 nm, is well represented in the satellite-derived data record.

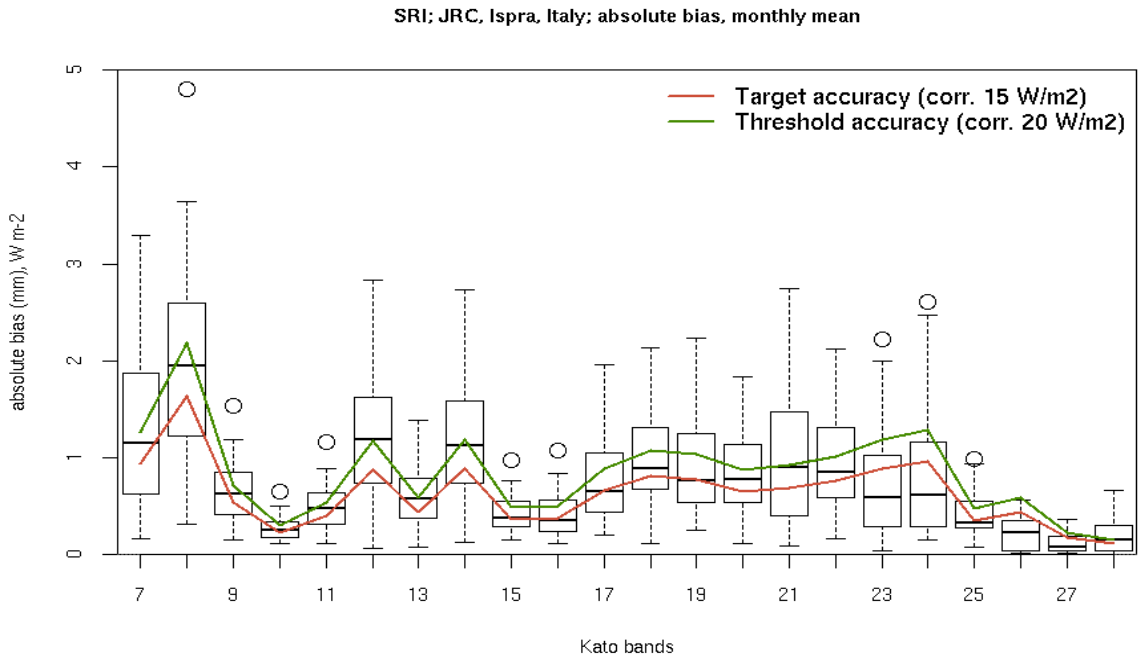


Figure 4-8: Boxplot of the absolute bias of the monthly means for each Kato band. The red / green line represent the target / threshold accuracy per spectral band based on their contributon to the total irradiance.

Figure 4-8 presents the statistics of the absolute bias for each spectral band for the 12 month of available reference data between March 2009 and April 2010 (May and November 2009 are missing). The median of the absolute bias is below or equal to the threshold accuracy for all Kato bands. The absolute bias increases with higher irradiance during summertime, which might explain some of the higher deviations between the SRI data record and the reference observations.
The target and threshold accuracy are derived for each Kato band considering the relative contribution of each band to the total irradiance and taken into account an uncertainty of the reference data of 5 W/m^2, based on the BSRN standards. However, as mentioned in Section 3.1, the calculation of the monthy averages from the surface measurents likely introduces a higher uncertainty in the monthly aveages due to the reduced temporal sampling. Overall it can be concluded that the SRI data record is in accordance with the requirements at this station.

4.4 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 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 predominantly 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. The overall SIS mean absolute difference consists of the mean absolute difference for cloudy and for clear sky. Hence, Figure 4-9 shows the maximum error in the effective cloud albedo, which would only be given for a mean absolute difference of zero in the clear sky irradiance. 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

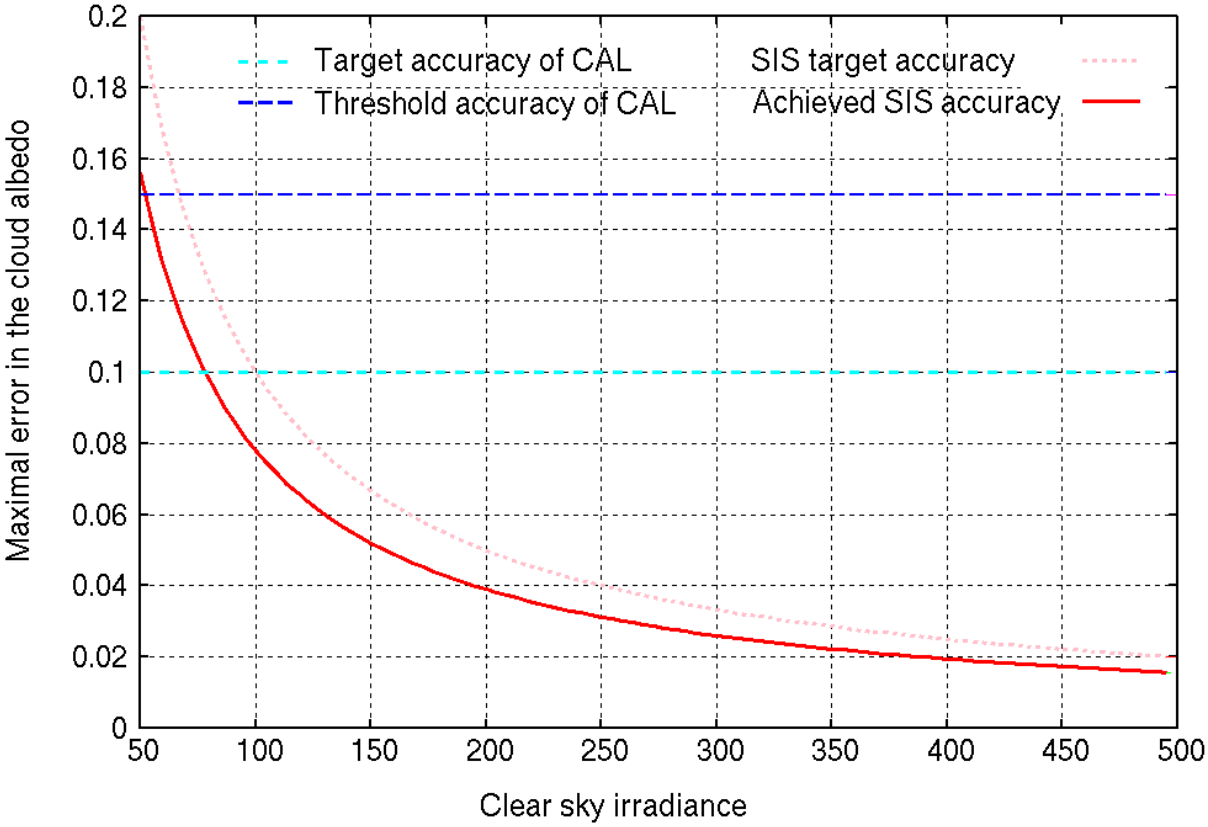


Figure 4-9: Maximum error of the monthly mean effective cloud albedo in dependency of the clear sky irradiance based on the derived SIS accuracy. The target accuracy is 10 W/m². For the achieved SIS accuracy the mean absolute difference given in Table 4-1 has been used.

Figure 4-9 shows that values above the target accuracy of 0.1 only occur for clear sky irradiances below 70 W/m². Values above the threshold accuracy of 0.15 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. This method does not provide information whether the target accuracy is fulfilled during the winter period (+/-1.5 month period around the respective winter solstice), see Figure 4-10. 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.

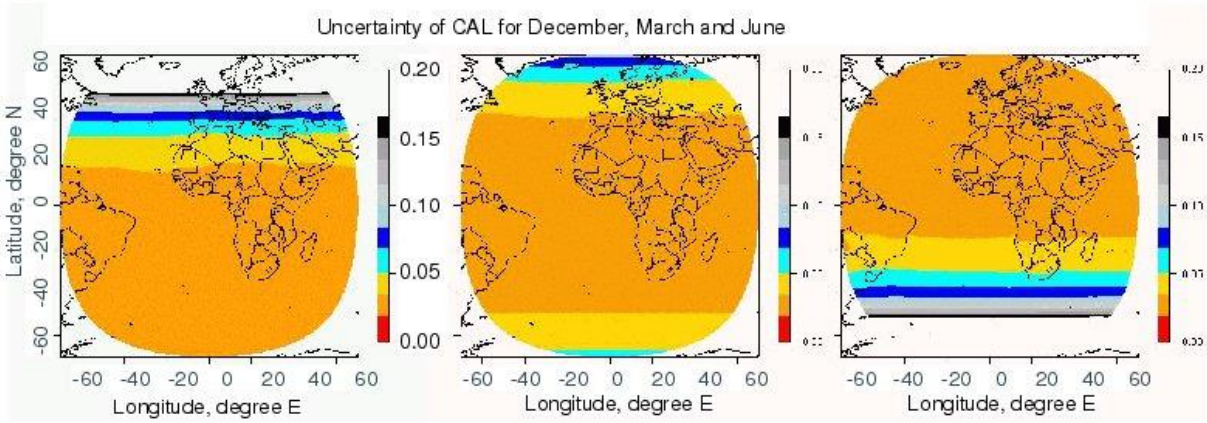


Figure 4-10: Uncertainty of the effective cloud albedo for winter, spring and summer months. The applied method fails to provide the accuracy of the method for the white regions followed by the black colored "border".

Daily means

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

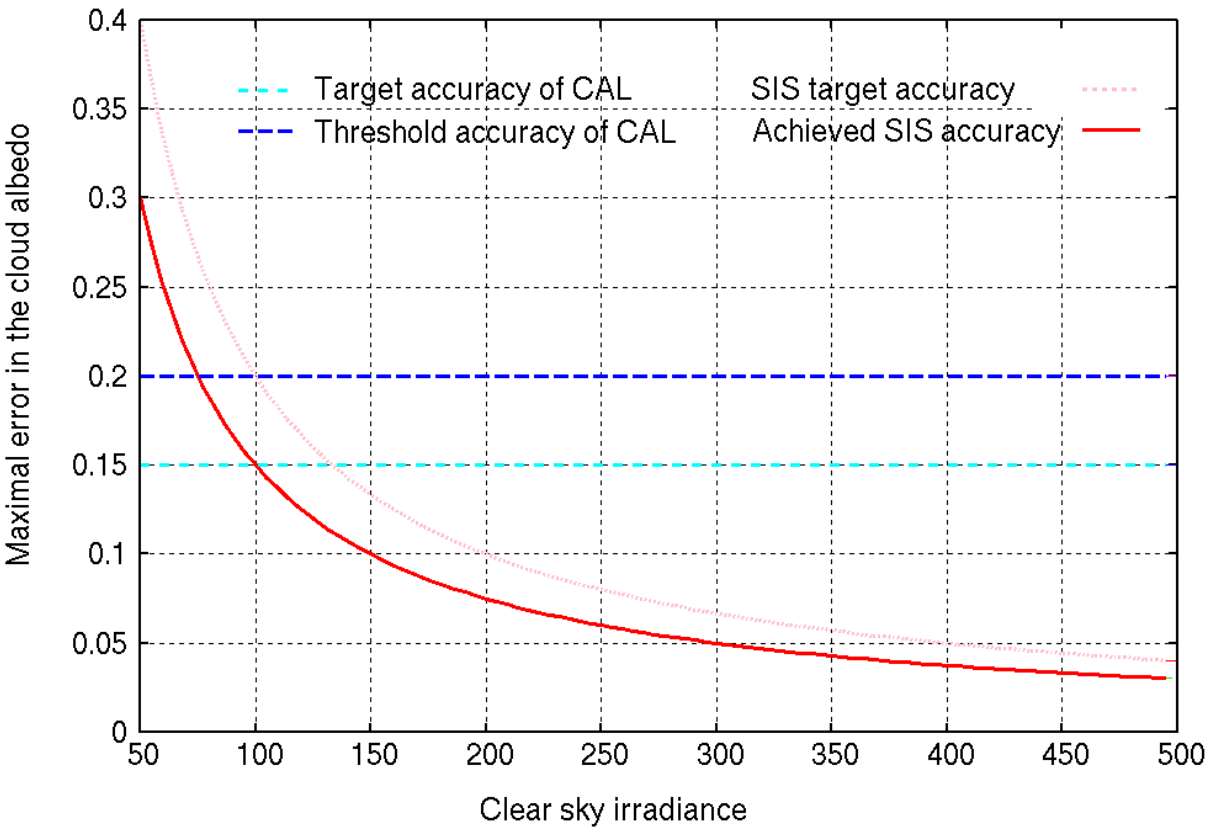


Figure 4-11: Maximal error of the effective cloud albedo (daily mean) for different clear sky irradiance values based on the derived SIS accuracy for daily means. The target accuracy is 20 W/m². For the achieved SIS accuracy the mean absolute difference given in Table 4-2 has been used.

In Figure 4-11 it is shown that values above the target accuracy of 0.15 only occur for clear sky irradiances below 100 W/m². Values above the threshold accuracy of 0.2 only occur for clear sky irradiances below 75 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 3) 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.

4.5 Sunshine Duration (SDU)

Monthly means

Table 4-7 shows the validation results of sunshine duration (SDU) monthly sums from the new CM SAF SARAH-2.1 and SARAH-2 surface radiation data set compared to the observations from CLIMAT measurements. A positive bias of 8.5h is found in the SARAH-2.1 SDU data set. The mean absolute difference is 16.6h and therefore within the target accuracy of 20h. Considering the uncertainty of the surface measurement, the target accuracy requirement is fulfilled. The standard deviation and, thus, the spread is 21.3h. More than 86% of the monthly sum values are better than the threshold accuracy value including measurement uncertainty. The anomaly correlation reaches a good value of 0.88.

Table 4-7: Results of the comparison between the sunshine duration monthly sums derived from CLIMAT station data and the SARAH-2.1 and SARAH-2 SDU sunshine duration data set.

SDU	N_{mon}	Bias [h]	MAD [h]	SD [h]	AC	$Frac_{mon}$ > 30 h [%]
SARAH-2.1	137811	8.45	16.6	21.3	0.88	13.7
SARAH-2	117373	7.23	18.7	24.3	0.84	18.5

The Figs. 4-12 and 4-13 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 cloud fields, which might be underestimated by satellite-retrievals. This might lead to an overestimation of sunshine duration in these regions. But, as Fig. 4-14 shows, most MAD values are within the threshold accuracy.

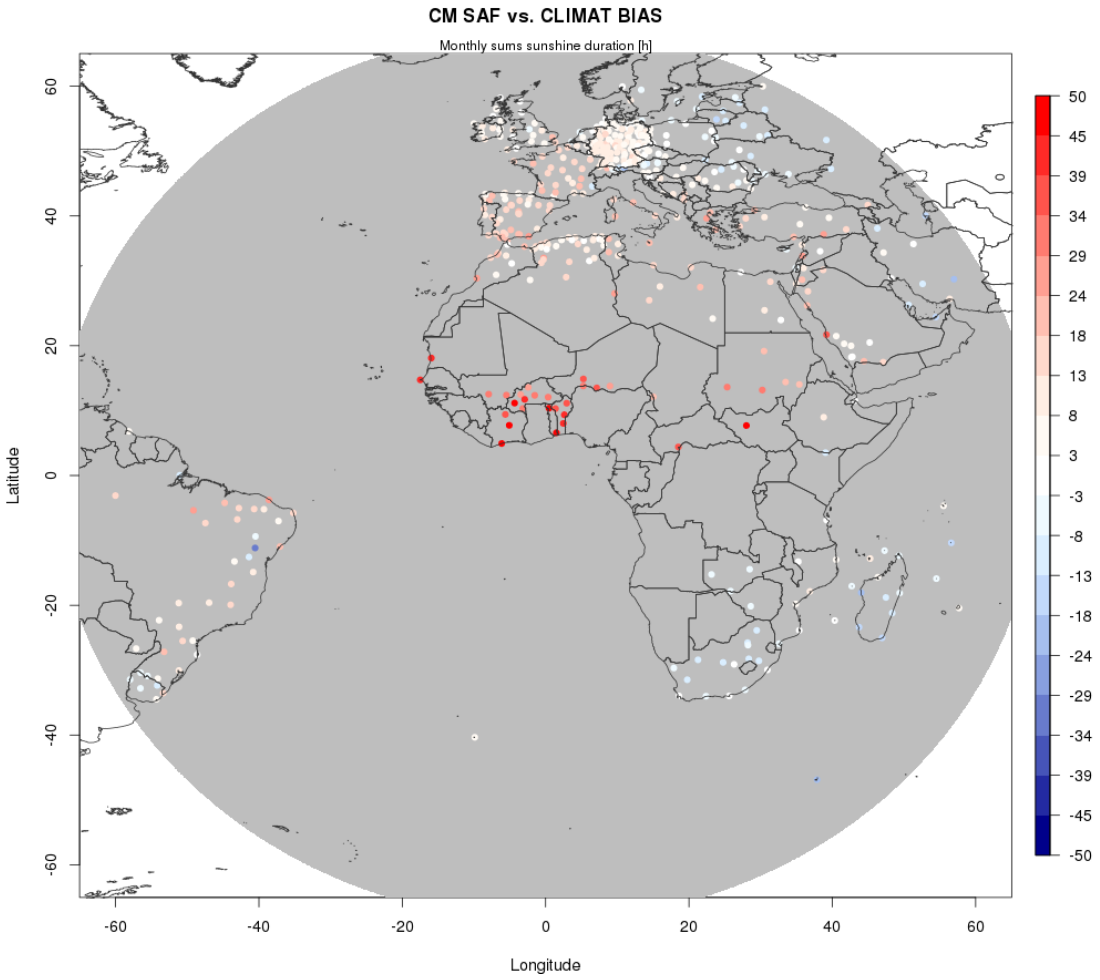


Figure 4-12: Bias for the comparison of sunshine duration monthly sums of CLIMAT station data and SARAH-2.1 SDU.

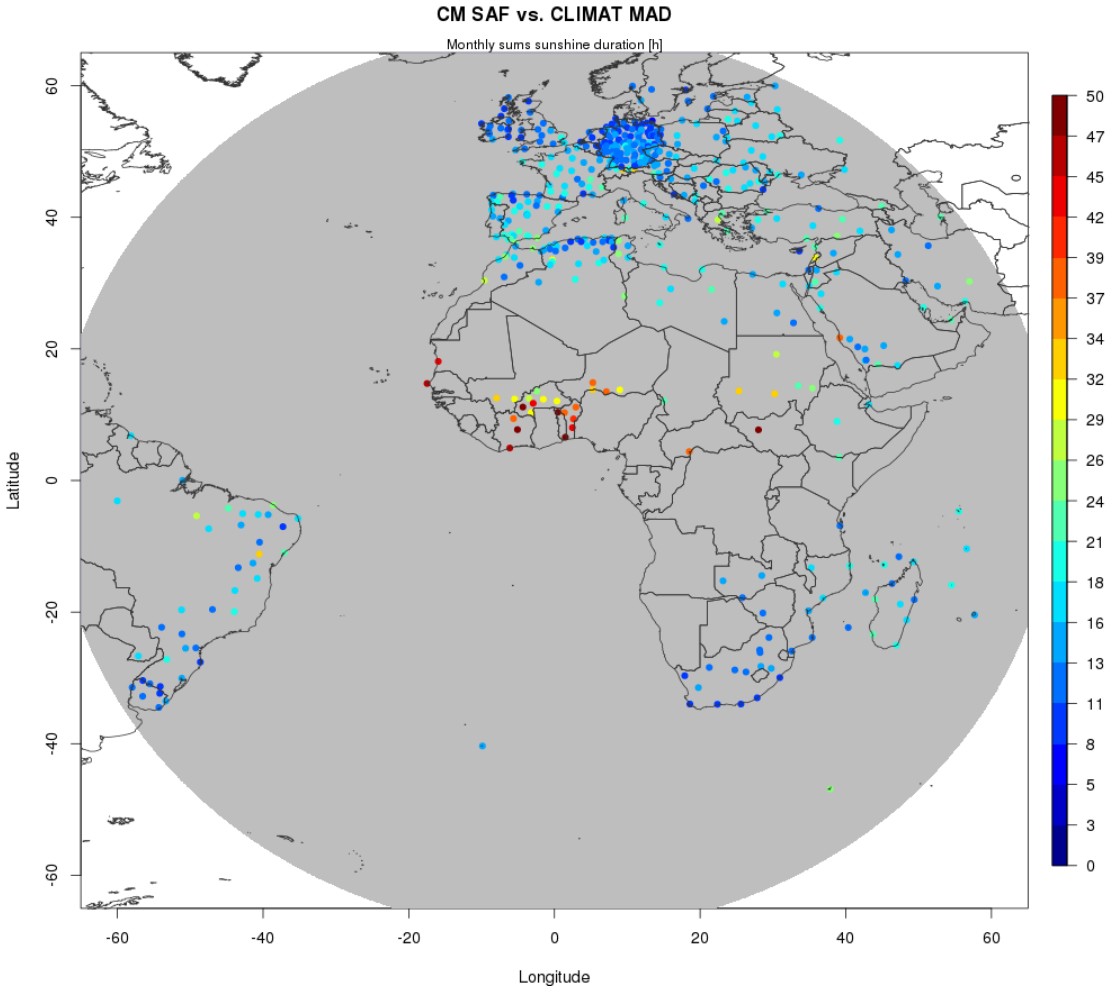


Figure 4-13: Mean absolute difference (MAD) for the comparison of sunshine duration monthly sums of CLIMAT station data and SARAH-2.1 SDU.

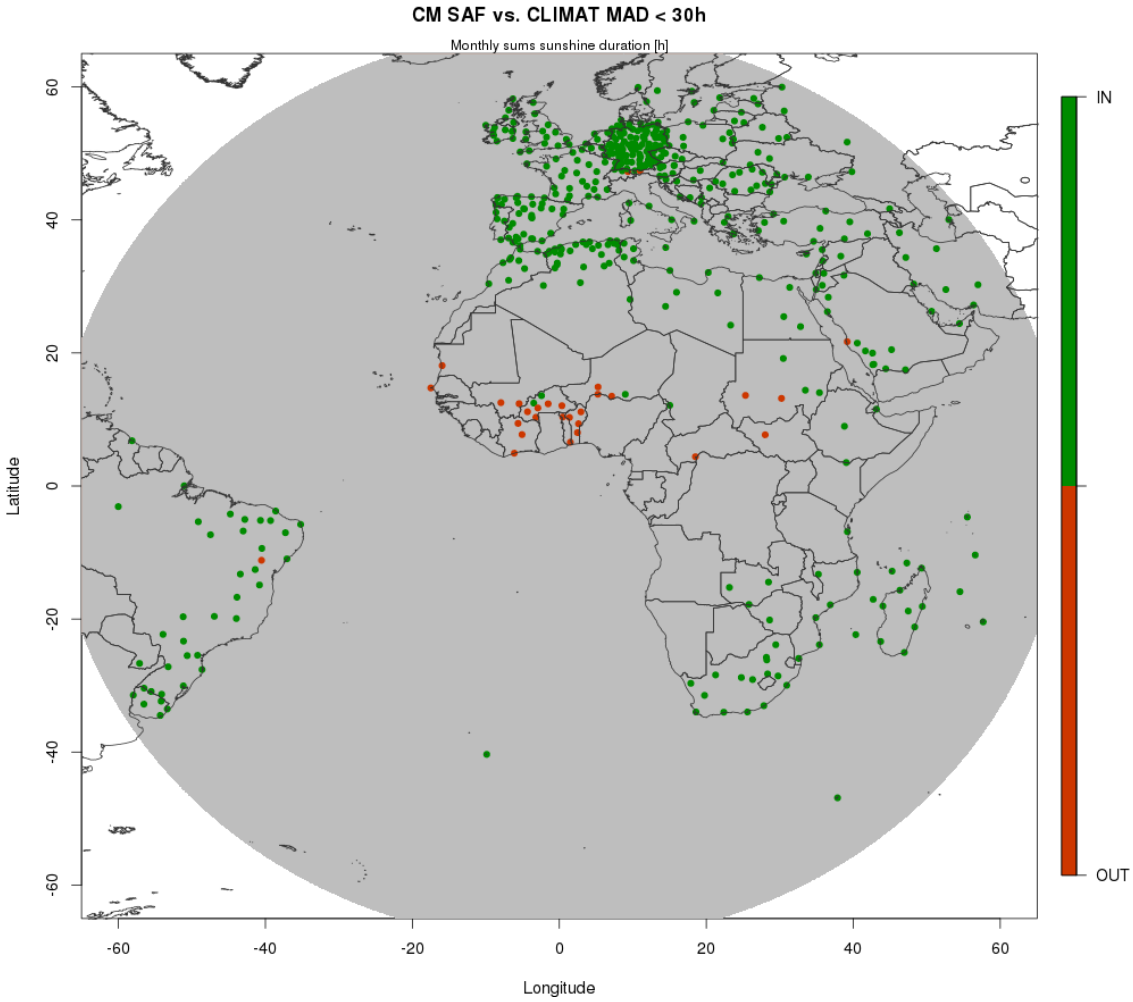


Figure 4-14: Stations matching the threshold accuracy (MAD < 30h) for the comparison of sunshine duration monthly sums of CLIMAT station data and SARAH-2.1 SDU.

Daily means

Table 4-8 shows the validation results of the sunshine duration (SDU) daily sums from the new CM SAF SARAH-2.1 surface radiation data set compared to the observations from the ECA&D measurements. A positive bias of 0.37 h is found in the SARAH-2.1 SDU data set. The mean absolute difference is 1.01 h and therefore better than the target accuracy of 1.5 h. The standard deviation and, thus, the spread is 1.45 h. More than 77 % of the monthly sum values are better than the threshold accuracy value including measurement uncertainty. The anomaly correlation reaches a good value of 0.93.

Table 4-8: Results of the comparison between the sunshine duration daily sums derived from ECA&D station data and the SARAH-2.1 and SARAH-2 SDU sunshine duration data sets.

SDU	N_{day}	Bias [h]	MAD [h]	SD [h]	AC	$Frac_{day}$ > 1.5 h [%]
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 Figs. 4-15 and 4-16 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 and the Canaries. Especially at stations, which are located on mountains, the sunshine duration tend to be overestimated by SARAH-2.1 SDU. But, as Fig. 4-17 shows, most MAD values are within the target accuracy.

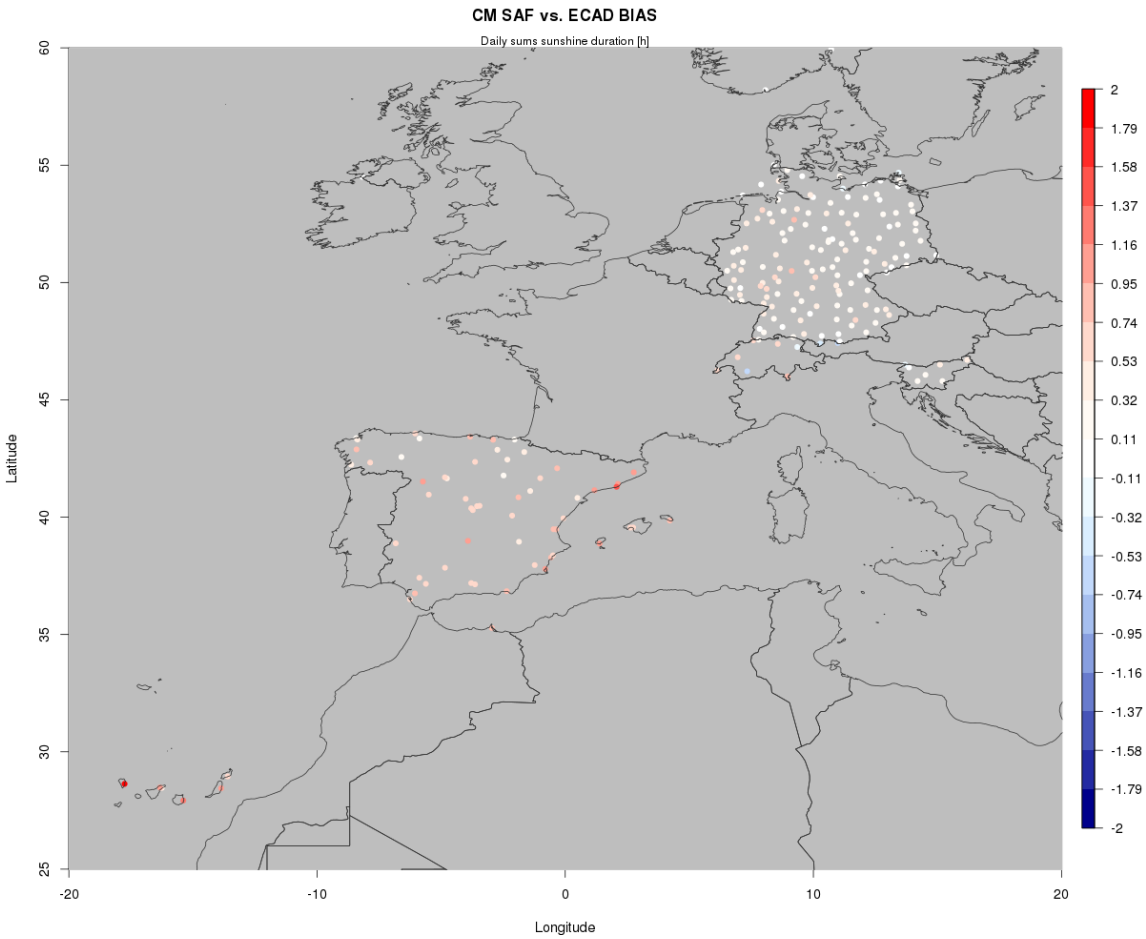


Figure 4-15: Bias for the comparison of sunshine duration daily sums of ECA&D station data and SARAH-2.1 SDU.

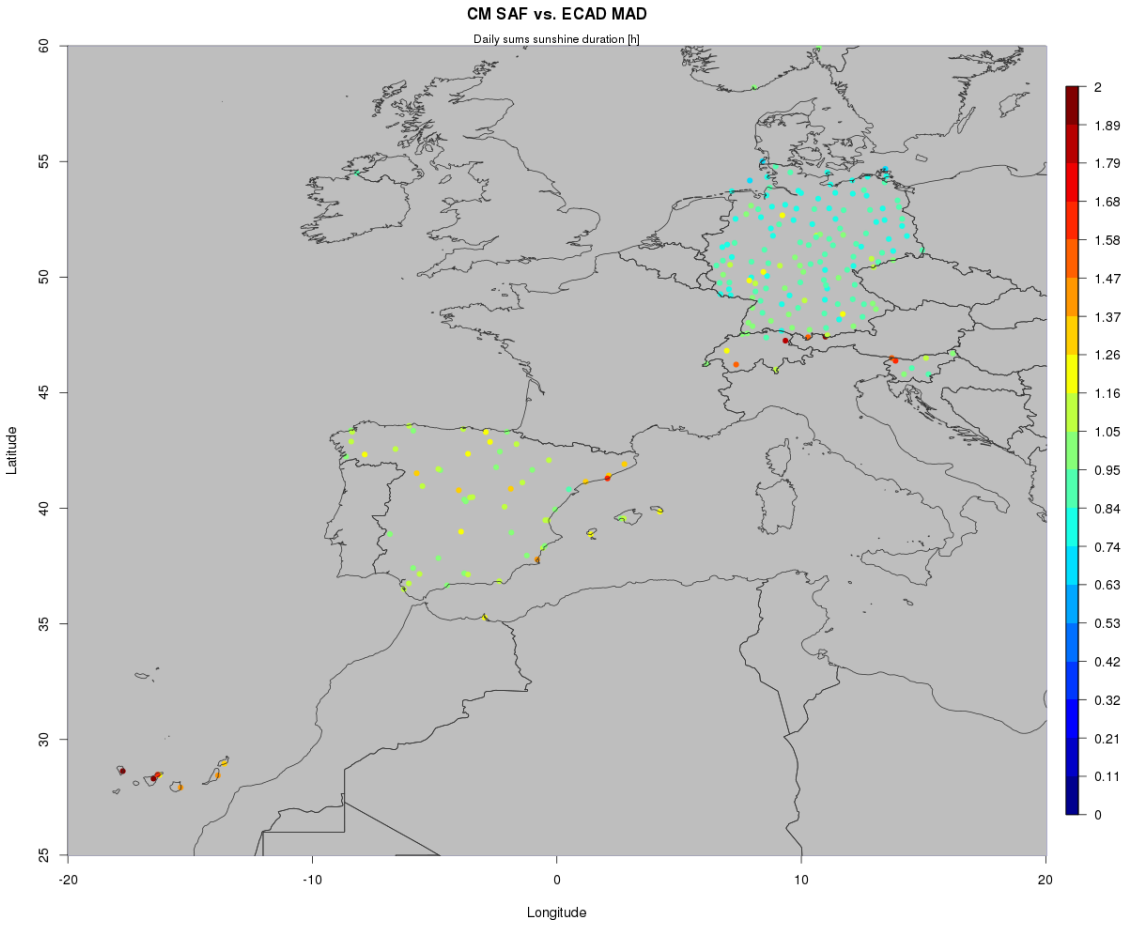


Figure 4-16: Mean absolute difference (MAD) for the comparison of sunshine duration daily sums of ECA&D station data and SARAH-2.1 SDU.

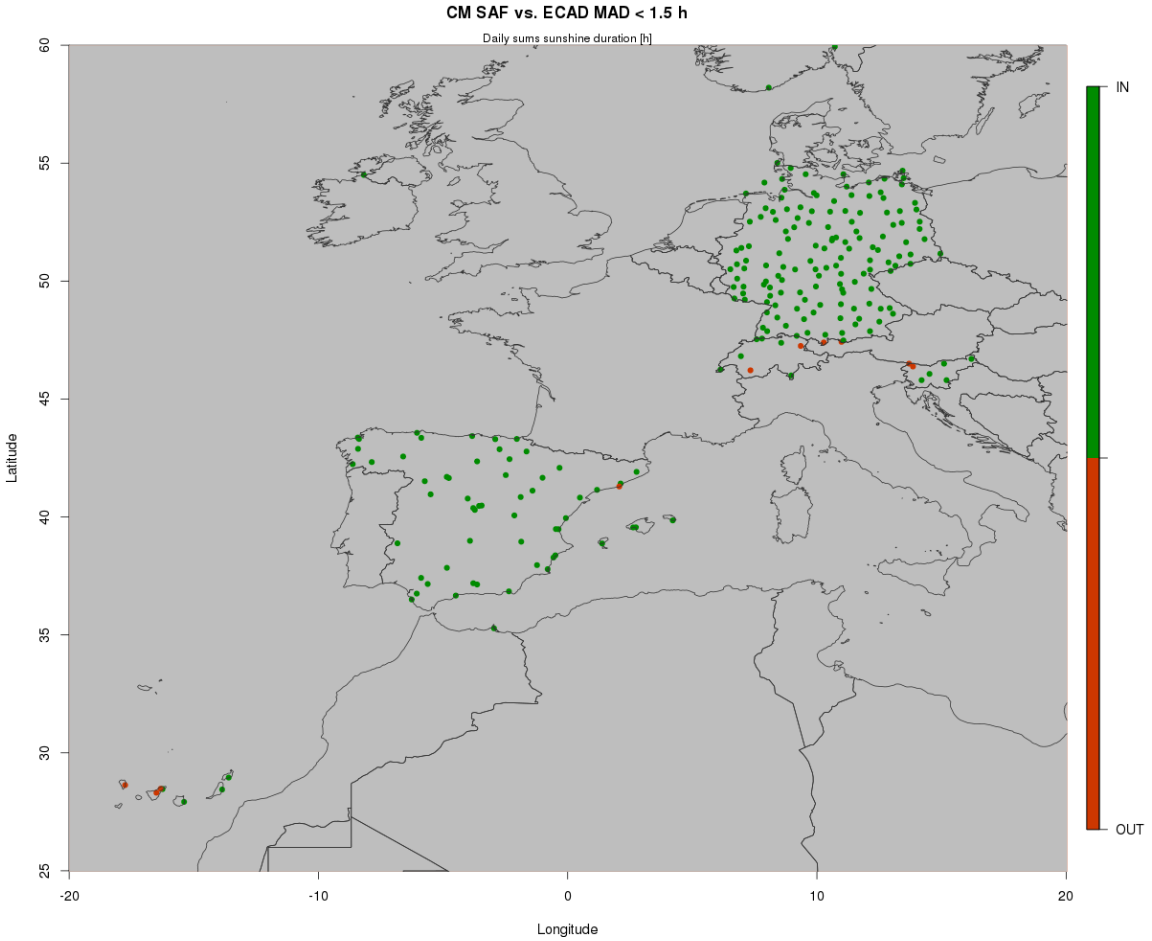


Figure 4-17: Stations matching the target accuracy (MAD < 1.5h) *for the comparison of sunshine duration monthly sums of CLIMAT station data and SARAH-2.1 SDU.*

5 Influence of downscaled water vapor input

The water vapor input from the ERA-Interim reanalysis is downscaled based on a topographic correction [RD 1]. This means that the spatial resolution of the water vapor is increased and that changes of water vapor amount mostly occur in topographic rough terrain, where the native ERA-Interim topography is different from the actual topographic height. The topograhic downscaling may result in a an increase of water vapor if the actual topograhy is lower than in the reanalysis or in an decrease, if the actual topography is lower than the real one.

The mean influence of the downscaled water vapor on the clear-sky global radiation for Europe is shown in Figure 5-1. The Alps, Pyrenees and other mountaineous areas cleary seen as regions with increased radiation, while other areas, especially valleys like the Po-valley, show reduced clear-sky radiation.

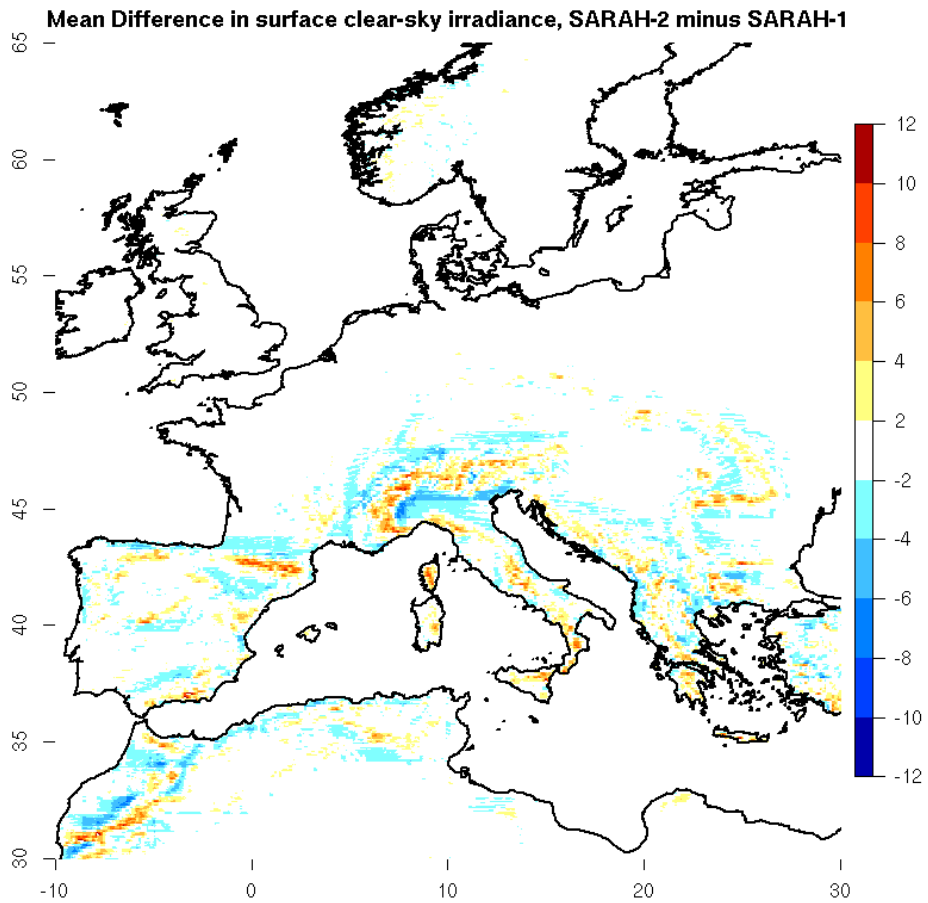


Figure 5-1: Influence of downscaled water vapor input on clear-sky radiation. The mean difference of SARAH-2 minus SARAH-1 clear-sky radiation is shown in W/m^2.

The influence of the downscaled water vapor on the global radiation SIS is shown in Figure 5-2 for June 2006. The general bahavior is similar to the influence on the clear-sky radition. Again mountaineous areas mostly show higher values in SARAH-2 than in SARAH-1 and in some valleys the opposite is the case. SARAH-2 and SARAH-2.1 behave similar in terms of the water vapor effect.

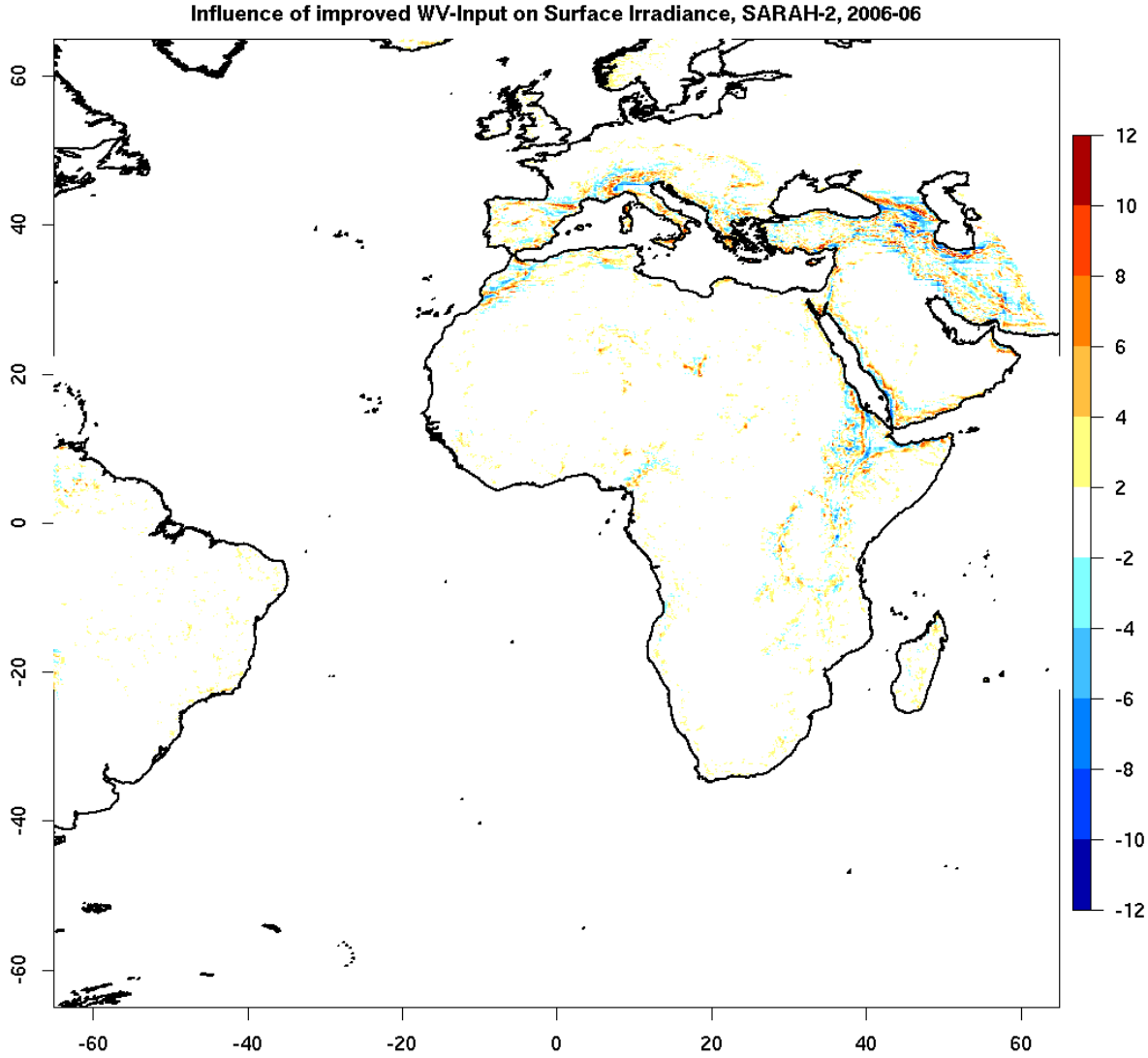


Figure 5-2: Influence of downscaled water vapor on SIS in W/m^2 for the monthly mean of 2006-06 on the full METEOSAT-disk. As in Figure 5-1, the difference SARAH-2 minus SARAH-1 is shown.

Overall the influence of the new water wapor input on the surface incoming radiation can reach up to ±10 W/m^2.

To further assess the impact of the new integrated water vapor used for the generation of SARAH-2 a validation has been conducted of SARAH and SARAH-2 with surface observations of the global irradiance taken at the Joint Research Centre in Ispra, Italy (8.62°E; 45.82°N). Figure 5-3 presents the multi-annual monthly differences between the surfae irradiance derived from SARAH-2 and the SARAH and from the surface measurememnts in Ispra as well as the difference in the integrated water vapor used in the derivation of SARAH-2 and SARAH. The topographical downscaling results in higher water vapor in Ispra in SARAH-2 with a clear seasonal cycle and a maximum diffence in in July / August. Corresponding to the increase in the integrated water vapor the abolute level of the surface irradiance is smaller in SARAH-2 compared to SARAH. Since the satellite-derived data records overestimate the measured surface irradiance (about 15 W/m^2 for SARAH) the reduced surface irradiance derived for SARAH-2 improves the comparison between SARAH-2 and the surface measurements (see Figure 5-3). The seasonal cylce of the change in the bias follows the seasonal cylce of the difference in water vapor and reduces the bias during

summer in Ispra by more than 5 W/m2, i.e., about 20 %. The overall improvement of the satellite-derived data records in Ispra is on average about 2 W/m^2.
The difference between SARAH and the surface measurements in Ispra (almost 13 W/m^2 for SARAH-2) is rather high compared to the mean bias for all surface stations indicating other factors contributing to the overestimation of the satellite data records in Ispra (e.g, the assumed aerosol loading). Overall the use of the downscaled water vapor data record has a very positve impact on the quality of the satellite-derived surface irradiance.

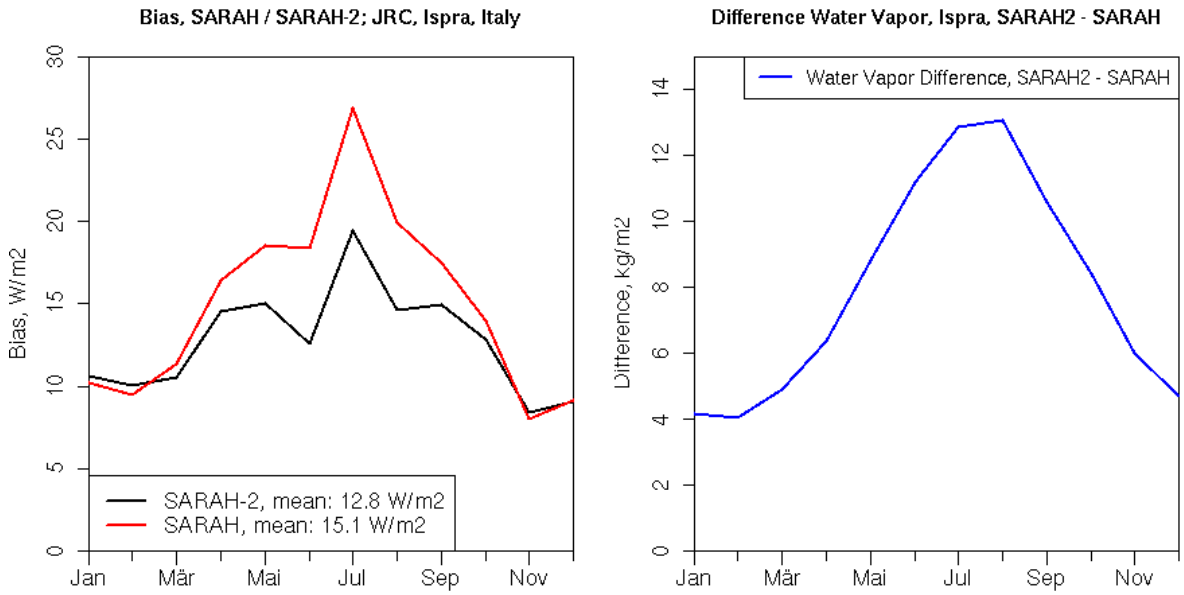


Figure 5-3: Left: Multi-annual monthly mean bias between the SARAH and the SARAH-2 climate data records and the surface irradiance measured at Ispra, Italy. Right: Multip-annual monthly mean difference between the vertically integrated water vapor used for the generation of SARAH-2 and SARAH in Ispra.

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 a 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	31 Dec 2017

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-2.1 data record starting with Meteosat 2 in 1983 until Meteosat 10 in 2017. No obvious steps are present in the time series of the anomaly for the whole time range, pointing to the high stability of the SARAH-2.1 climate data record.

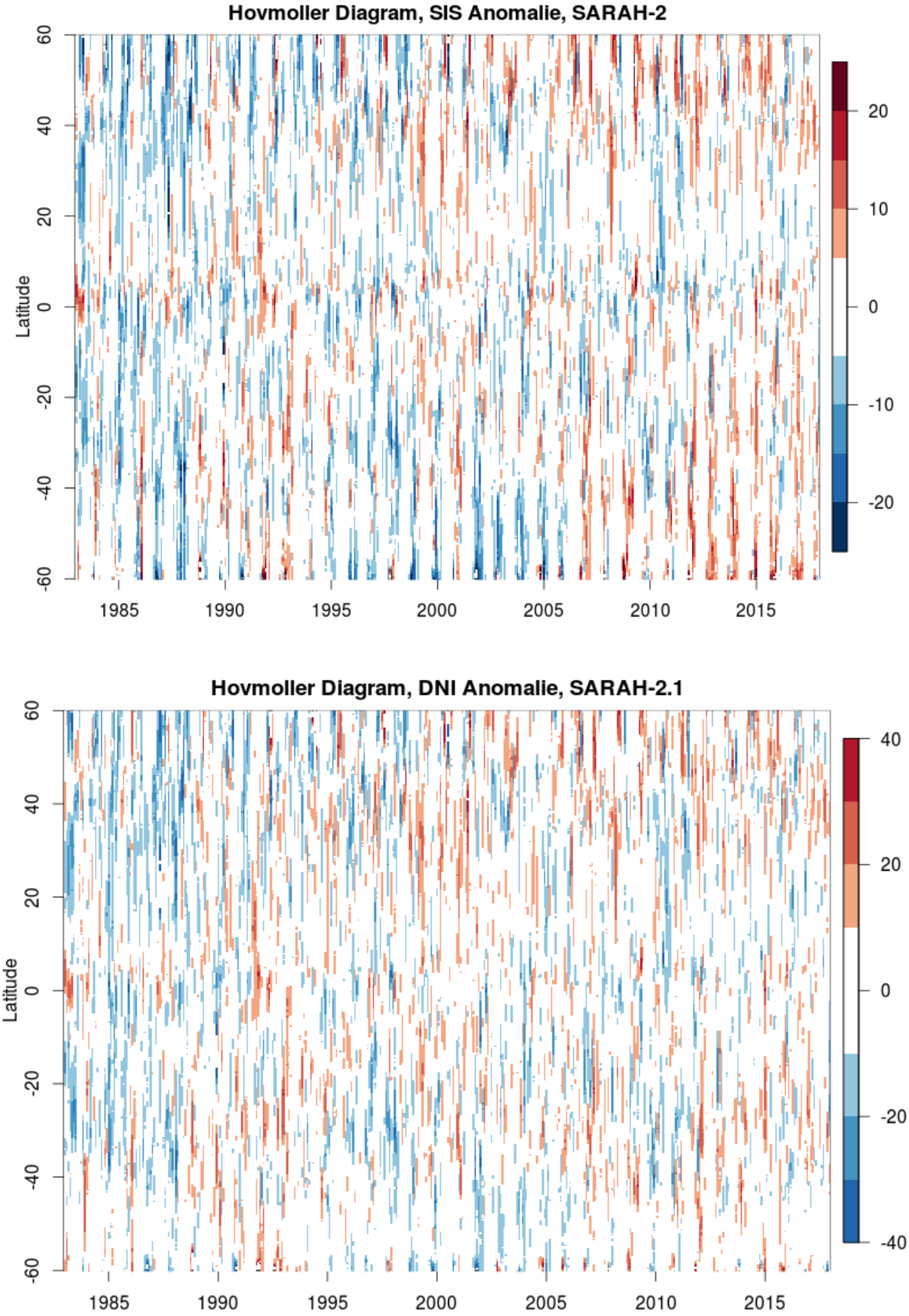


Figure 6-1: Hovmoeller diagrams for the full time period (1983-2017) of the monthly mean anomaly of (top) SIS and (bottom) DNI.

To evaluate and quantify the stability of the SARAH-2.1 data record, surface reference measurements from the GEBA data base 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 data base 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-2.1 SIS data record and the measurements from the GEBA stations. Only stations with more than 95% available monthly means between 1983 and 2016 are considered to avoid artificial shifts in the mean time series due to changes in data availability.
A negative decadal trend of -0.8 ± 0.4 W/m^2/decade of the bias between SARAH-2.1 and GEBA is detected for the time period of 1983 to 2016. This trend is found to be statistically significant, but is well below the CM SAF target accuracy (2 W/m^2/decade). In addition, Figure 6-2 shows the corresponding time series of the bias of the SARAH-1 SIS data record, which exhibits a significant negative trend of -1.7 W/m^2/dec compared to the GEBA surface observations for the time period 1983 to 2016. Overall the stability of the new SARAH-2.1 climate data record is significantly improved, especially due to improvements in the transition from the MVIRI to the SEVIRI time period. More details on the temporal variability and trends can be found in Pfeifroth et al., 2018.

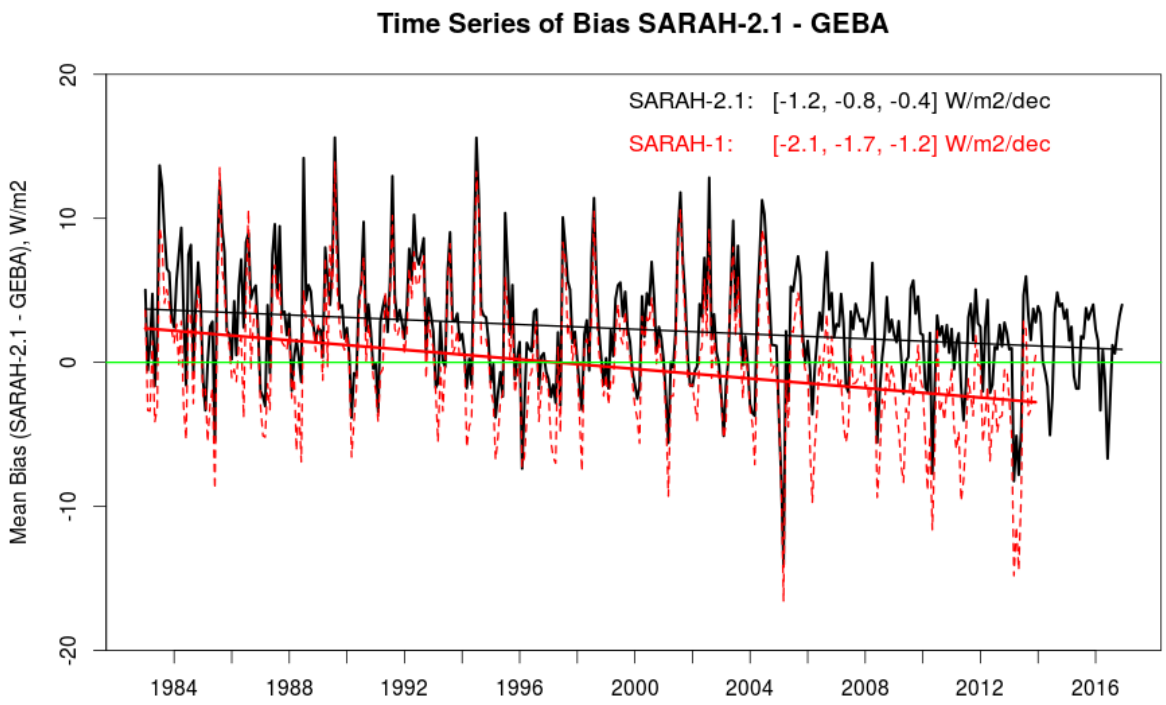


Figure 6-2: Temporal evolution of the normalized differences between the CM SAF SARAH data records and the GEBA data. The green line represents the zero trend line. The black and the red straight lines represent the linear regressions of the time series for the SARAH-1 and SARAH-2.1 global irradiance data records.

7 Conclusion and Recommendation

7.1 Conclusion

The satellite-derived CM SAF SARAH-2.1 climate data record of the surface incoming solar irradiance, direct irradiance, spectral resolved irradiance and effective cloud albedo have been validated by comparison with observations from 15 high-quality ground-based stations of the BSRN network, and by spectrally resolved measurements from Ispra, Italy. The applied validation limit or target 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 BSRN surface measurements.
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. However, there is no physical reason why the accuracy of the climate data record should be significantly lower for this period.
For the surface solar irradiance (SIS) from the SARAH-2.1 data record the mean absolute difference (MAD) of the monthly means (5.16 W/m^2) and the daily means (11.7 W/m^2) is better than the required target accuracy of 8 W/m² and 15 W/m². The validation target is also reached at all considered stations.
For the surface solar direct irradiance (SDI) parameters (SID and DNI), the mean absolute differences (MAD) of the monthly means are 7.7 W/m^2 and 16.1 W/m^2. The MAD values for the daily means are 17.1 W/m^2 and 33.1 W/m^2. These measures are below the required threshold accuracies of 15 W/m² and 20 W/m² for the SID and DNI monthly means, and also below the threshold accuracy of 25 W/m^2 for the SID daily means. The DNI daily mean MAD value is in the range of the threshold accuracy of 30 W/m^2.
The comparison of the CM SAF SARAH-2.1 SIS climate data record with its predecessor CM SAF SARAH-1 shows that the monthly and daily mean SARAH-2.1 SIS has a higher quality than the previous CM SAF Surface radiation data record. This also holds on average for the surface direct irradiance (SDI) parameters. Larger deviations are found for desert stations like Gobabeb and Tamanrasset. Overall the mean bias for SIS is slightly increased in the SARAH-2.1 SIS data record, which is a consequence of its improved stability over time.

The stability of the SARAH-2.1 SIS data record has been validated against European surface measurements from the GEBA database. A small negative linear trend of -0.8 ± 0.4 W/m^2/dec was found, which is below the target stability requirement of 2 W/m^2/decade. Compared to the previous CM SAF SARAH-1 SIS data record the stability over the full time period has increased significantly.

Overall, it is shown that the target / threshold accuracy is achieved for monthly and daily means of the surface incoming solar (SIS) and surface direct irradiance (SDI), respectively, of the CM SAF SARAH-2.1 climate data record. Also for the spectrally resolved irradiance (SRI) and sunshine duration (SDU) the threshold accuracy holds.

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 is 0.15 (threshold), 0.1 (target) and 0.08 (optimal) for periods and regions with a monthly mean clear sky irradiance above 50, 70 W/m² and 150 W/m², respectively. Hence, the requested accuracy is achieved for these cases. For the daily mean CAL the threshold (0.2), the target (0.15) and the optimal (0.1) accuracy is met for daily mean clear sky irradiances above 75, 100 and 150 W/m², respectively.
For lower clear sky irradiance the method fails to provide information whether the target accuracy can be reached. Lower monthly/daily mean clear sky irradiance (<70/100 W/m²)

usually occurs during wintertime above a latitude of +/-55°. The target accuracy might not be reached for these regions and period. Moreover, for slant geometries (border of Heliosat field of view) it is expected that the target accuracy is not met and even higher uncertainties might occur. Higher uncertainties might also occur over bright surface, e. g., snow-covered regions or deserts.

In general for SIS, SDI, SRI and CAL higher uncertainties are expected for regions with long lasting snow cover and desert regions with bright surfaces. 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: Achieved validation results for SARAH-2.1 parameters (SIS, SID, DNI, SRI and CAL).

Product	Summary on mean error (absolute)
SIS: Surface Incoming Solar Radiation.	*Mean Absolute Difference 5 W/m² and 95% of absolute difference values below 8 W/m² (+ uncertainty of ground based measurements) for monthly means and 85% below 15 W/m² for daily means, respectively).*
SID: Surface Incoming Direct Radiation.	*Mean absolute Difference of 11 W/m² and 92.5 % of (monthly) absolute difference values below 10 W/m² (+ uncertainty of ground based measurements) for monthly means.*
DNI: Direct Normal Irradiance at Surface.	*Mean absolute Difference of 16 W/m² and 85 % of (monthly) absolute difference values below 20 W/m² (+ uncertainty of ground based measurements) for monthly means.*
SRI: Spectral Resolved Irradiance.	*Threshold accuracy met at all Kato-bands for the majority of data points validated. The Bias at 500nm is about 0.03 $W/m^{-2}nm^{-1}$.*
CAL: Effective cloud albedo.	*Uncertainty of 0.1 for monthly means and 0.15 for daily respectively.* *Uncertainty of 0.05 and 0.1 respectively for clear sky irradiance monthly means above 150 W/m².* *Bias below 0.15 for hourly means.*
SDU: Sunshine duration.	*Monthly sums of Mean Absolute Difference of 17h and 86% of absolute difference values below 30h (+ uncertainty of ground based measurements) for monthly sums and 77% below 1.5h for daily sums, respectively).*

7.2 Recommendations for future product improvement

- Improvement of atmospheric input

a. Further evaluation of new aerosol climatology/information (e. g. higher temporal/spatial resolution) in order to improve the accuracy of SIS, SDI, and SRI.
b. Using daily means (instead of monthly means) of the integrated water vapour might help to improve the accuracy of the clear sky surface radiation.

- Improvement of algorithms

c. Development and evaluation of methods for the correction of broken clouds effect for the direct beam irradiance.
d. Evaluation of potential improvements in the retrieval of clear sky reflection to minimise cloud contamination.
e. An improved detection of snow and its separation from clouds would substantially help to increase the accuracy of the effective cloud albedo and the surface radiation under snow-covered surface conditions.
f. Detection of cloud shadows. With the classical HELIOSAT, cloud shadows receive a low cloud index value since they are dark, and thus the global radiation for these areas will be at maximum. This could potentially remove some of the remaining bias and spread.

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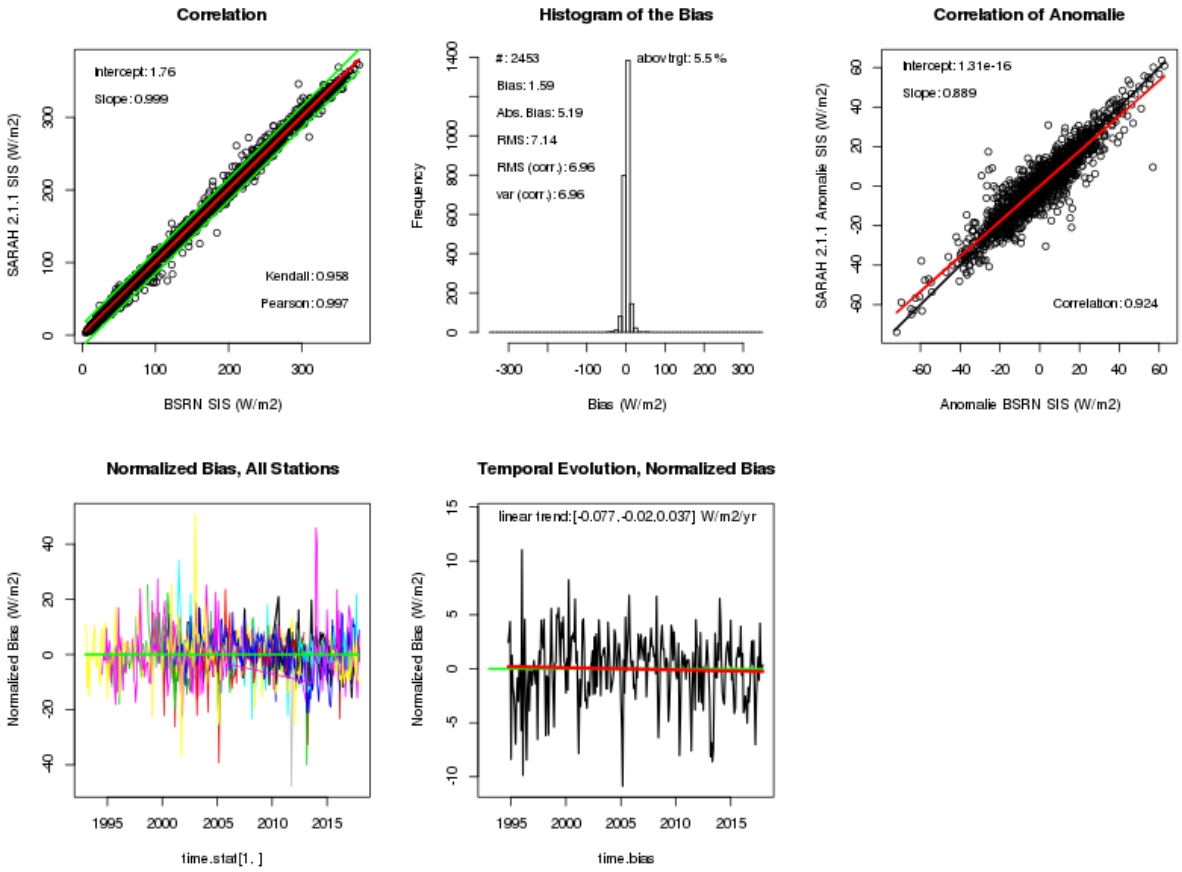
Appendix A: Validation figures of results for all BSRN station

The following figures provide additional validation results for the BSRN stations. The first four figures (composed of five individual plots) present the total validation results for the monthly and daily means of the SARAH-2.1 SIS and SDI parameters, respectively. Shown is the correlation between the SARAH-2.1 and the BSRN measurements, the histogram of the bias, the correlation of the anomalies, the time series of the normalized bias for each station and the temporal evolution of the mean normalized bias.

The subsequent figures present for each BSRN station the comparison of the monthly and daily SIS and SDI parameters (SID and DNI) from the SARAH-2.1 data record and the BSRN observation. Shown are the time series (black: surface observations, red: SARAH-2.1 data record), the mean annual cycle, the correlation, the time series and the histogram of the bias, the correlation of the anomalies, and the temporal evolution of the anomalies, incl. linear trend lines.

Summary Validation Results for SIS

SIS, Monthly means



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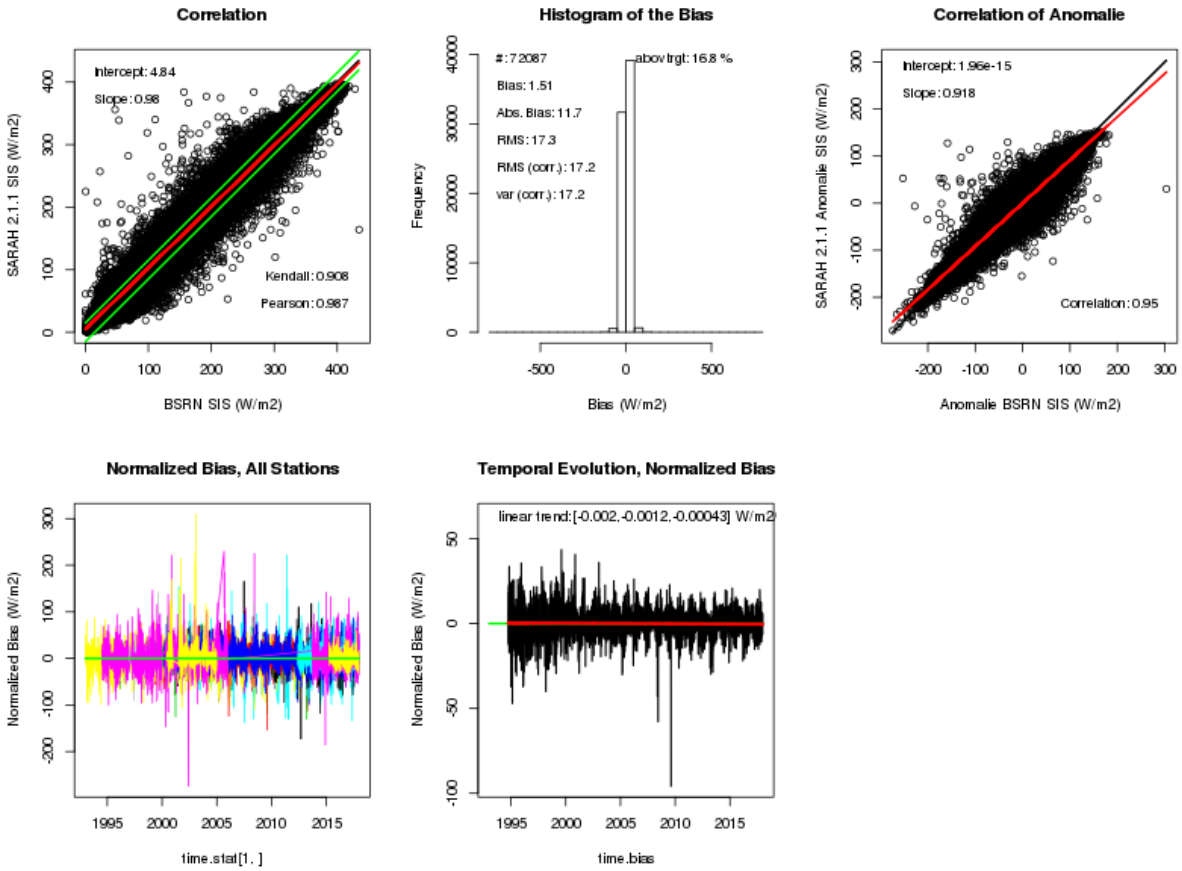
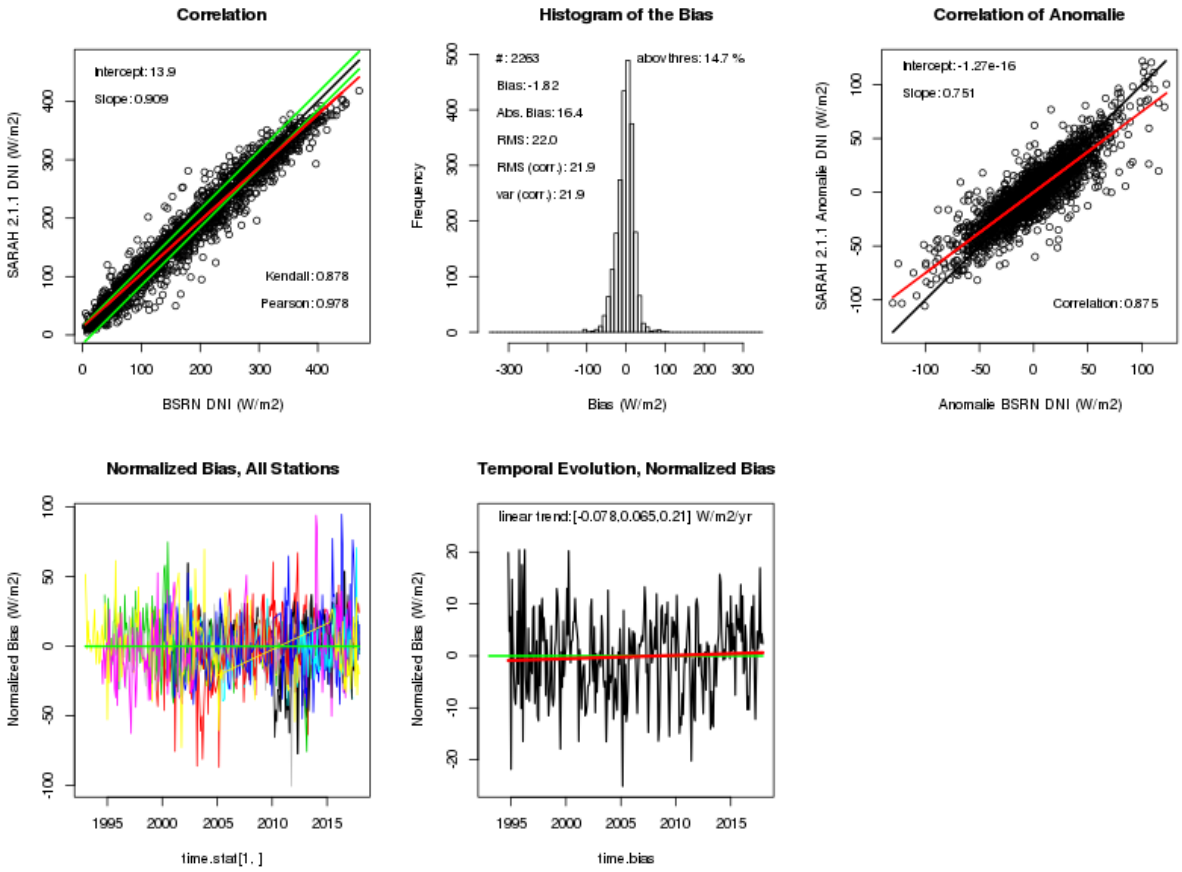
SIS, Daily means

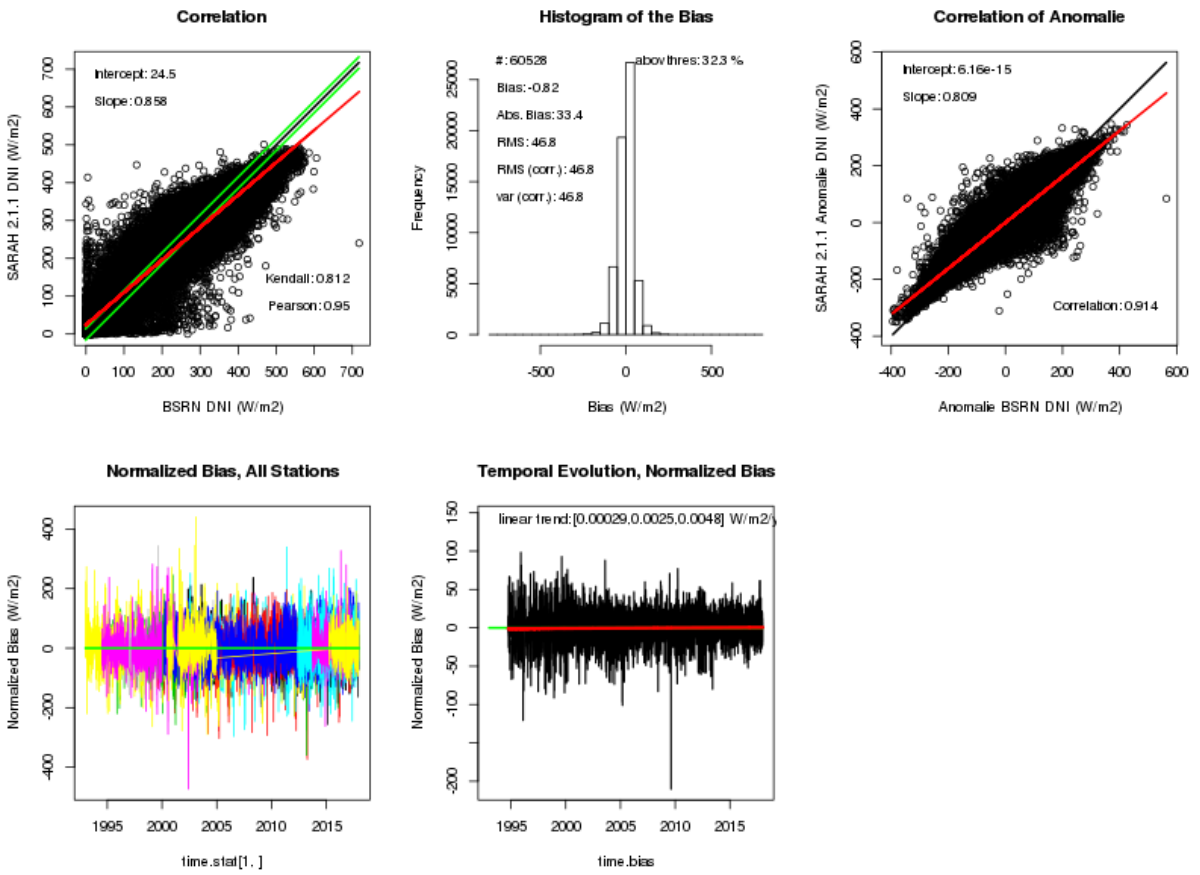


Summary Validation Results for DNI

DNI, Monthly means

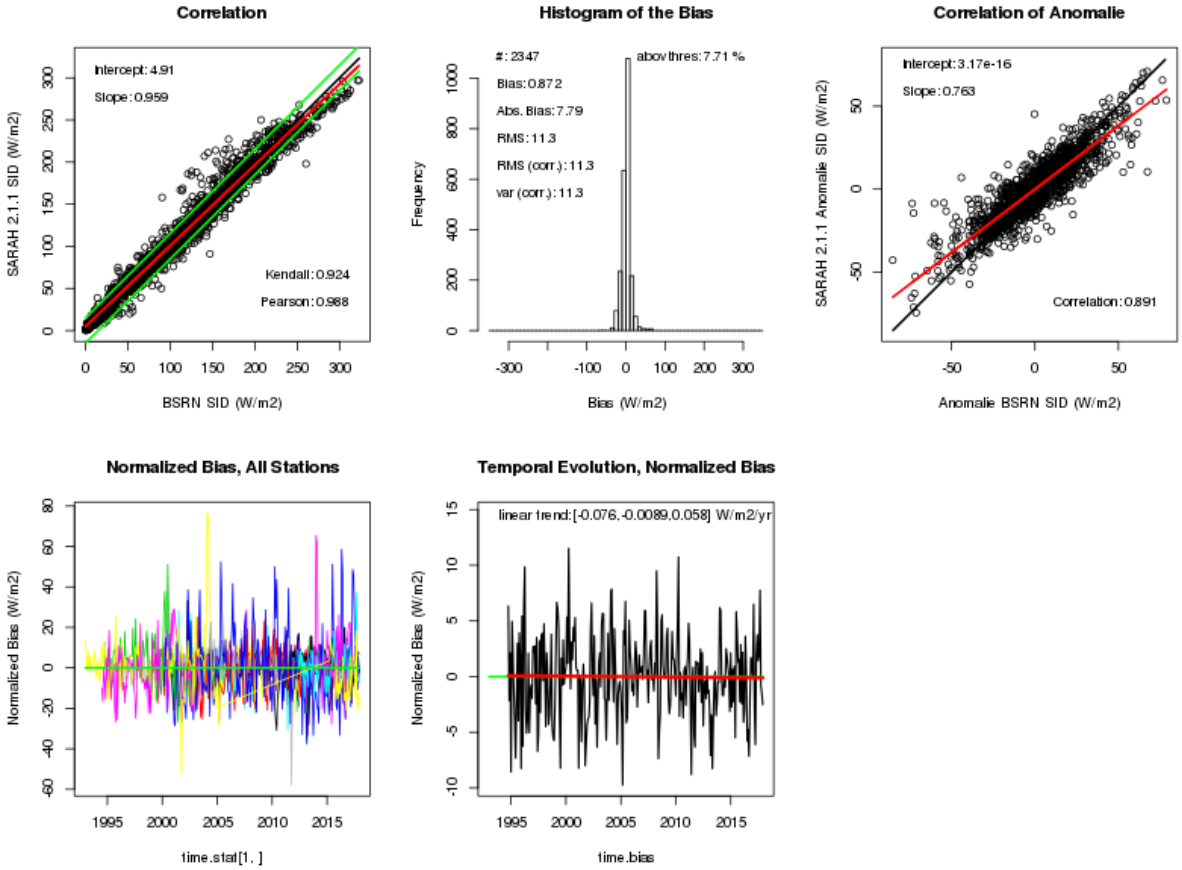


DNI, Daily means

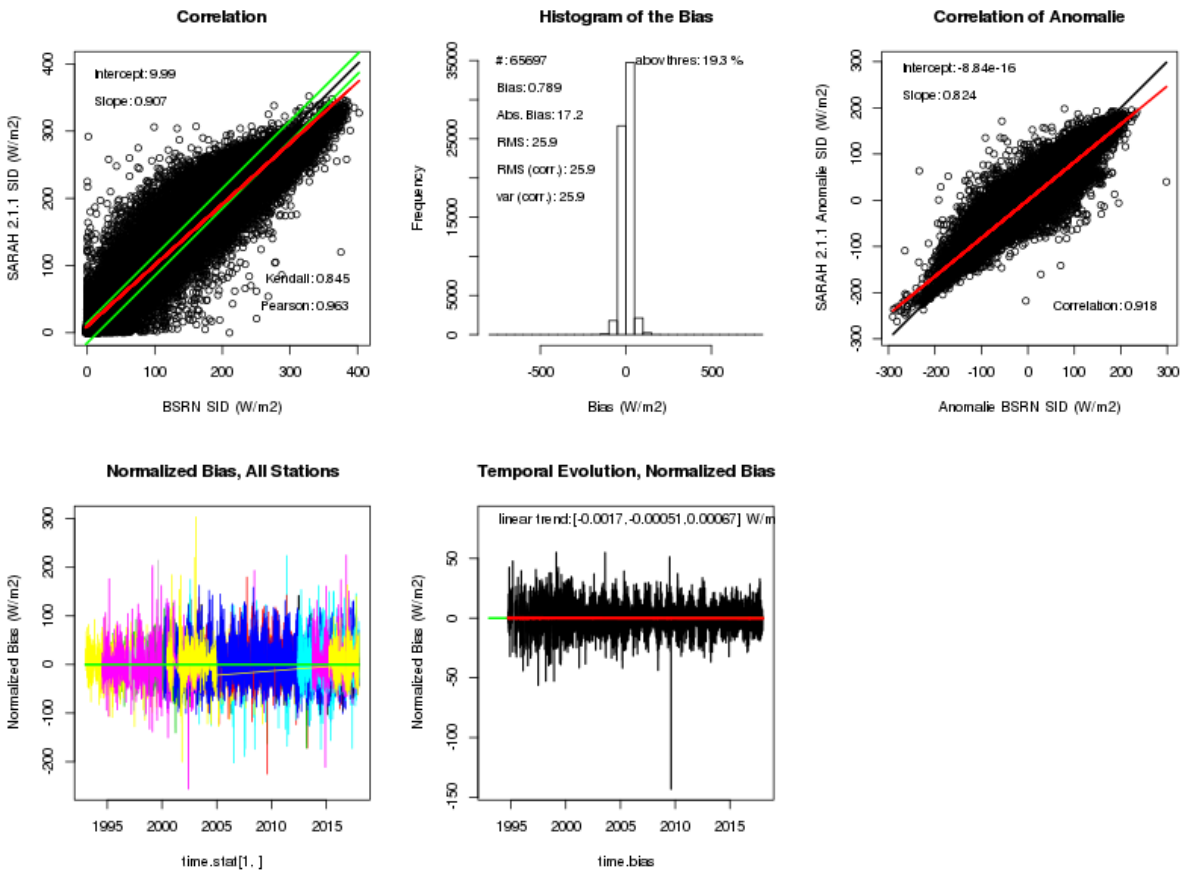


Summary Validation Results for SID

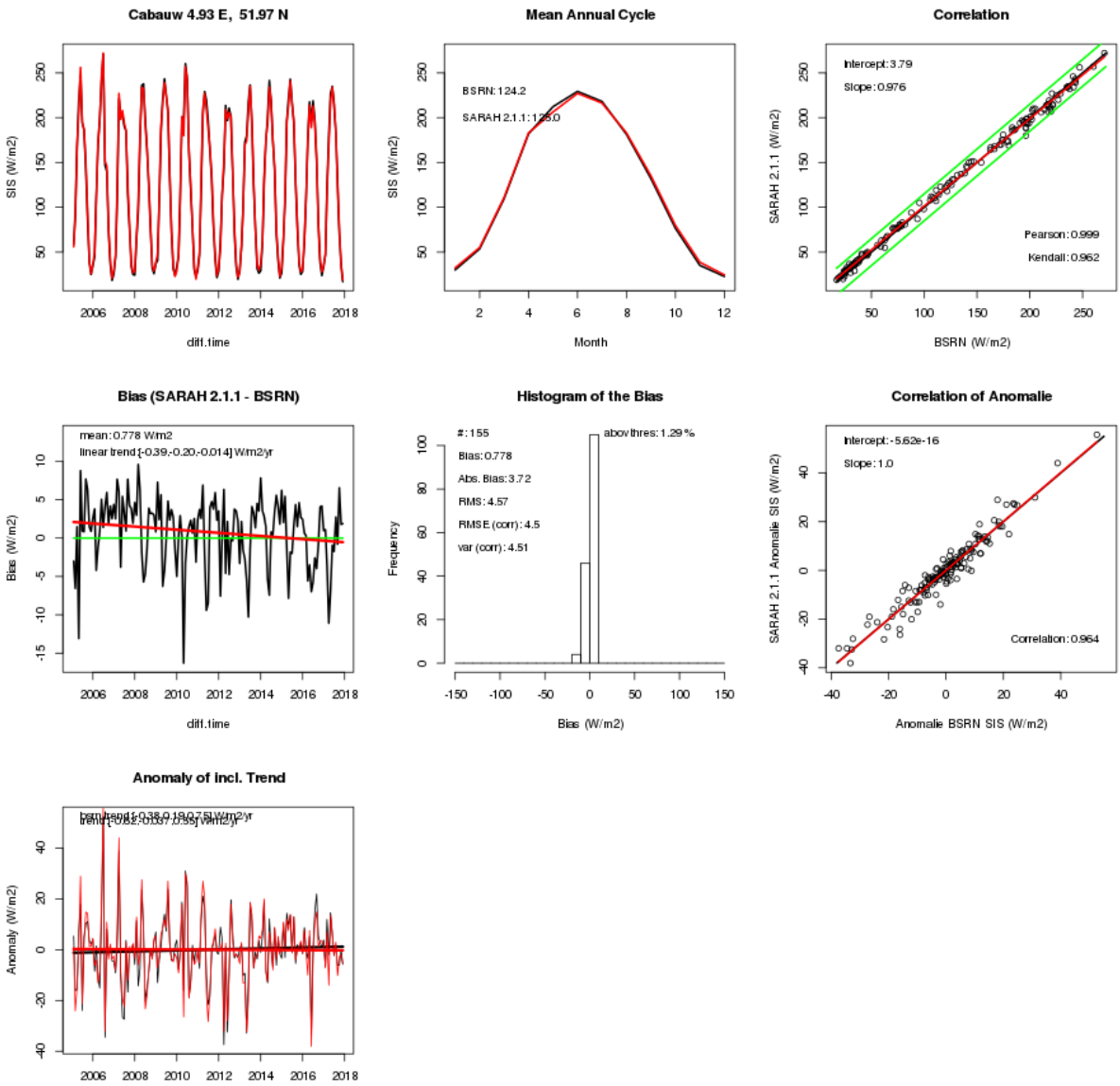
SID, Monthly means



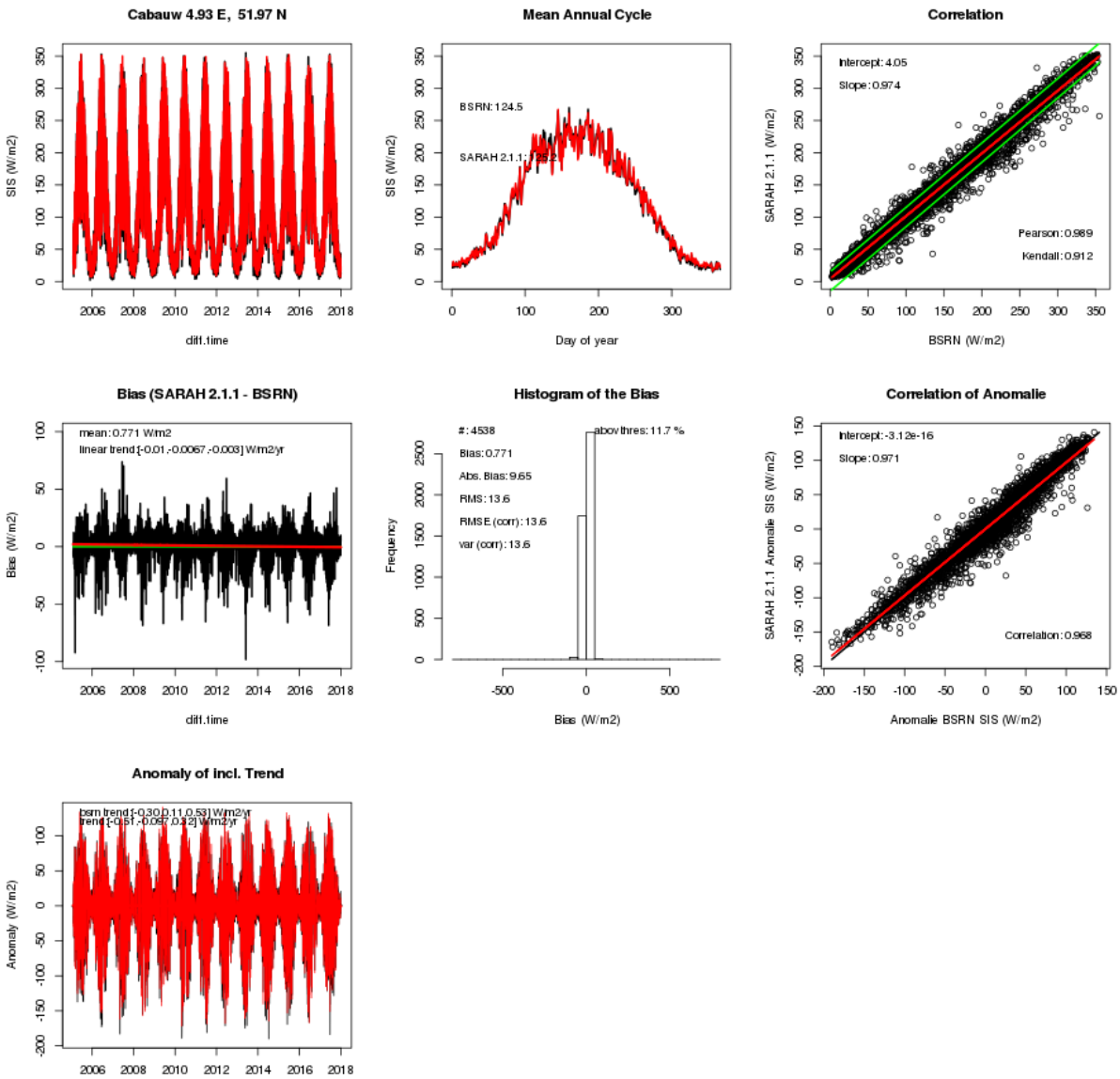
SID, Daily means



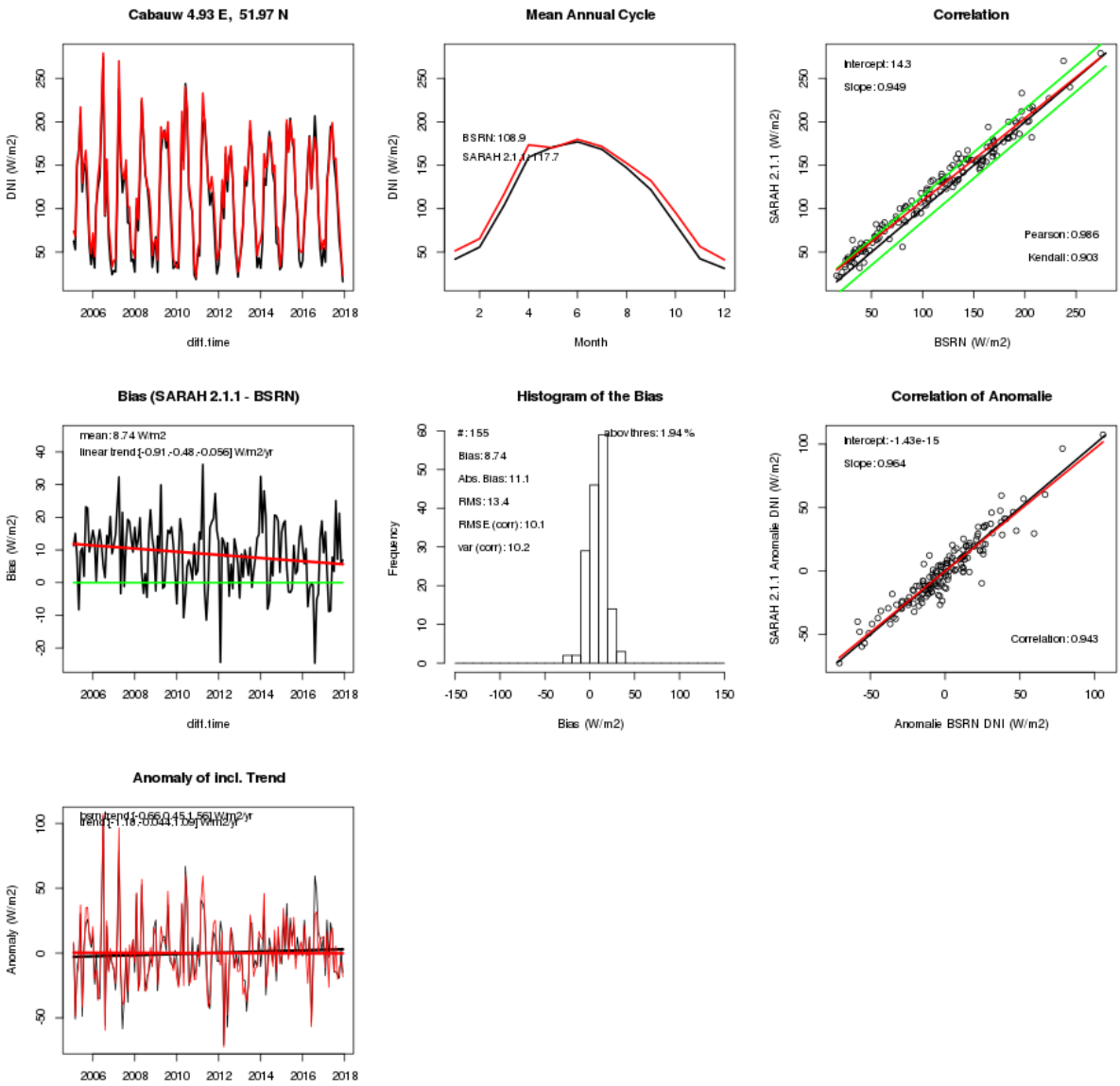
Cabauw, SIS, monthly mean



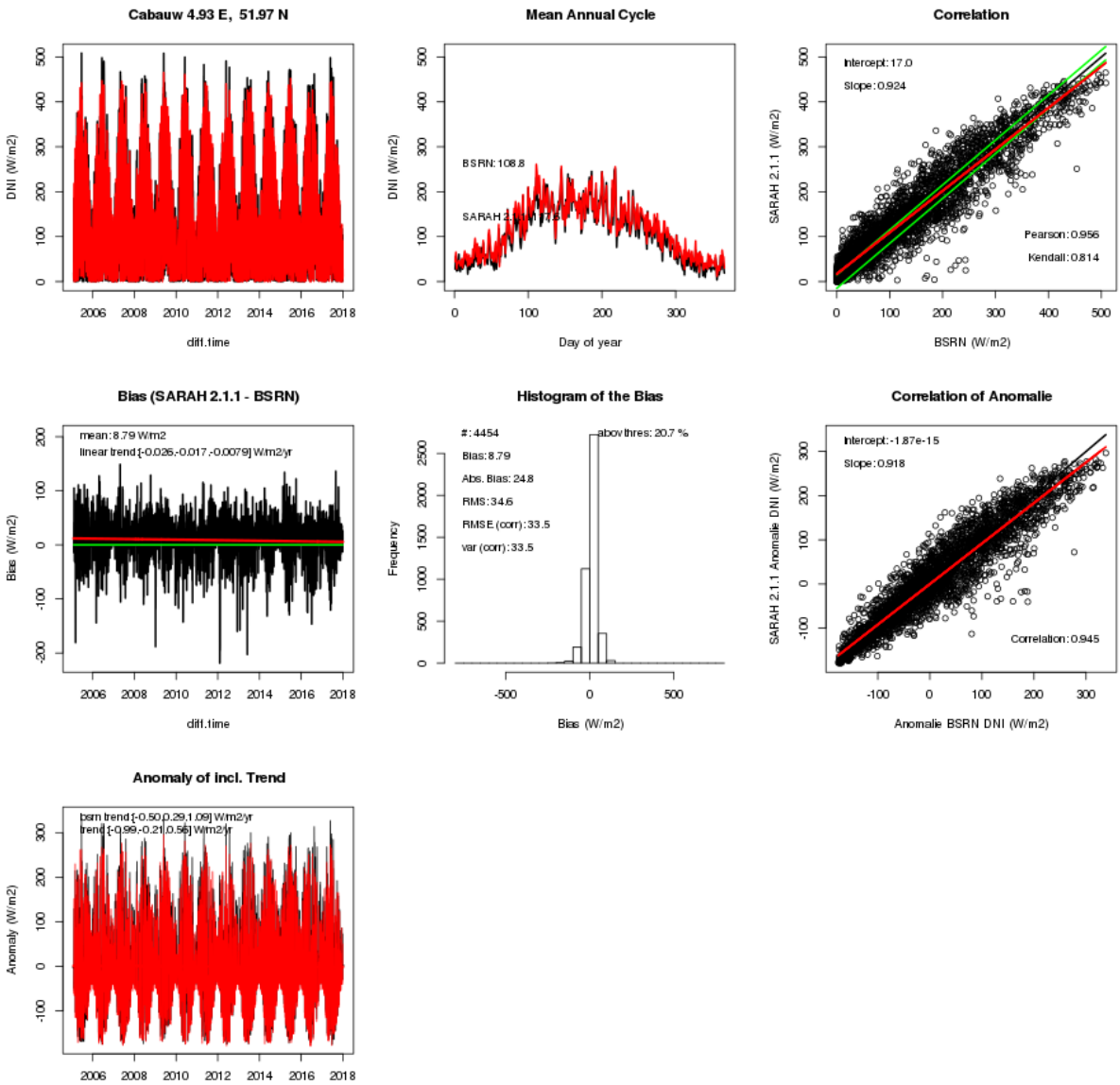
Cabauw, SIS, daily mean



Cabauw, DNI, monthly mean



Cabauw, DNI, daily mean



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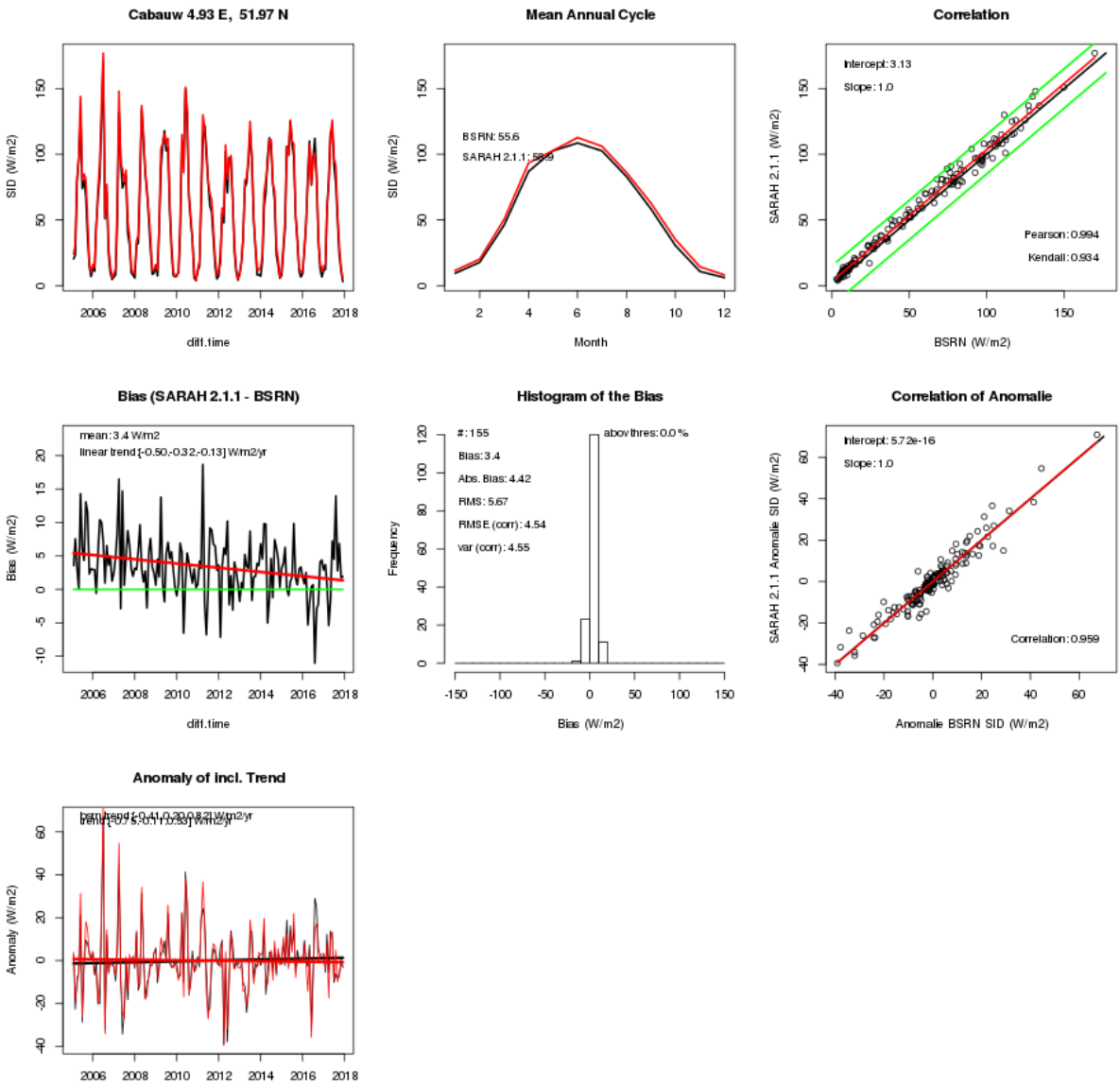

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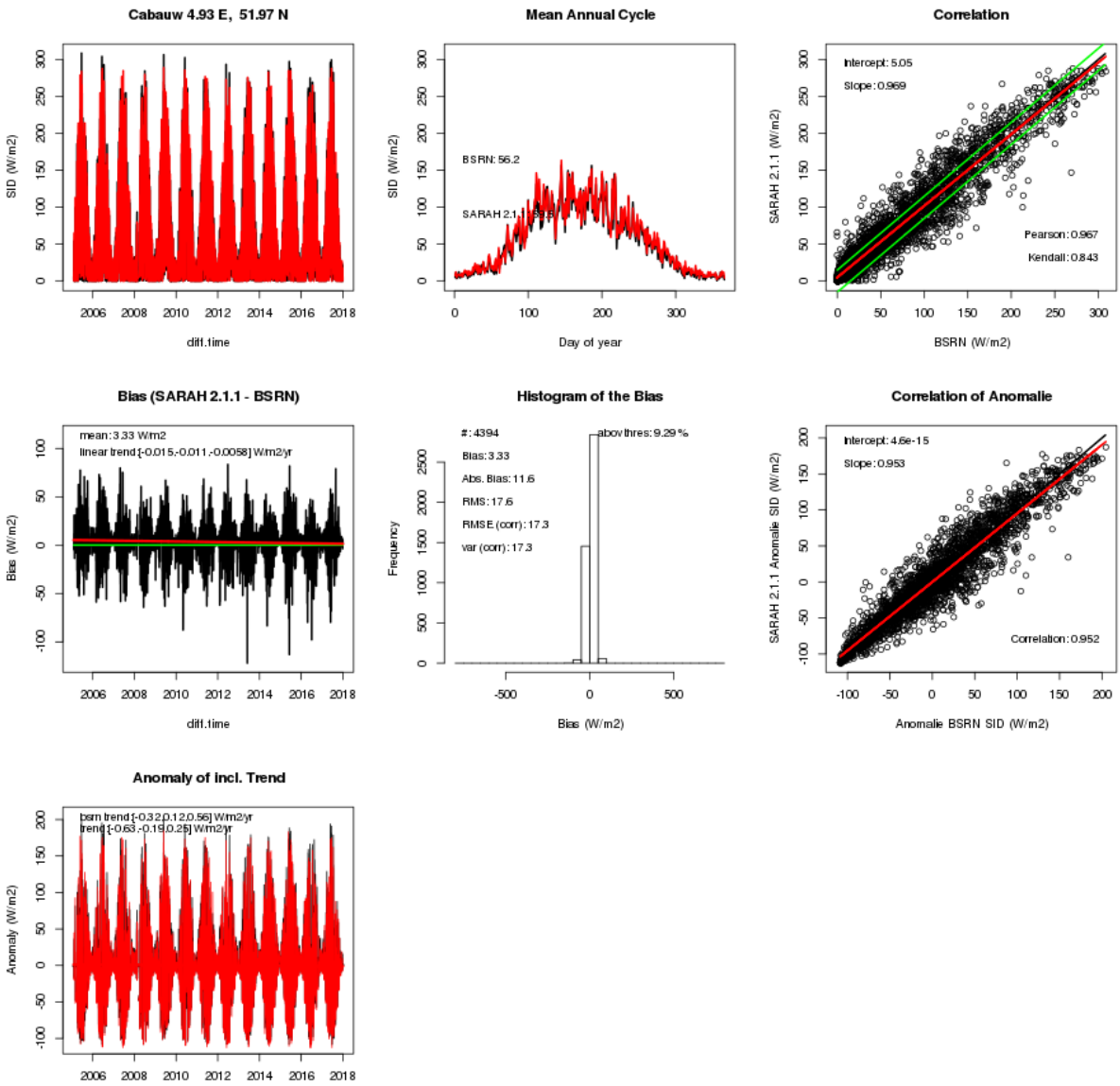
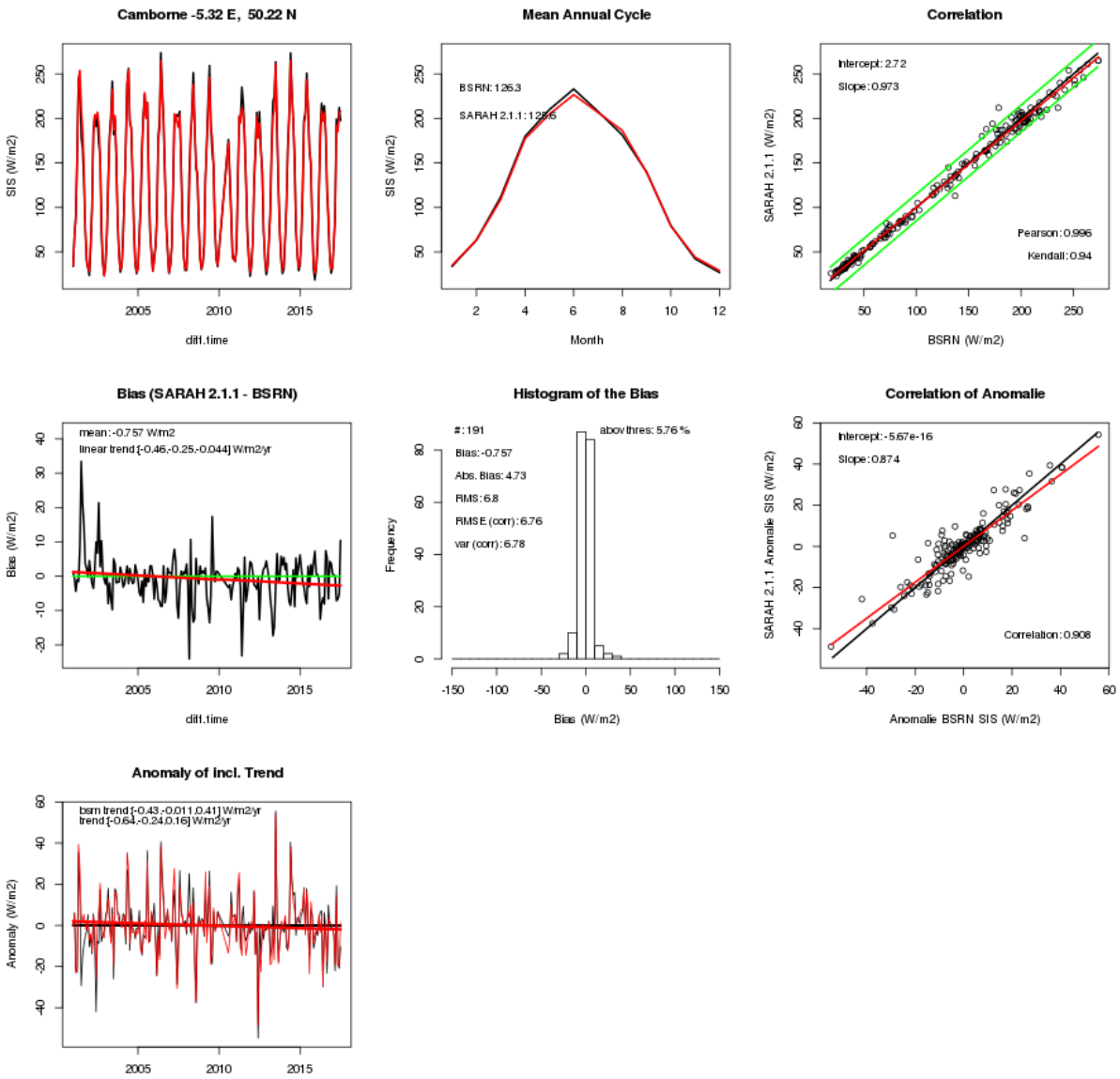
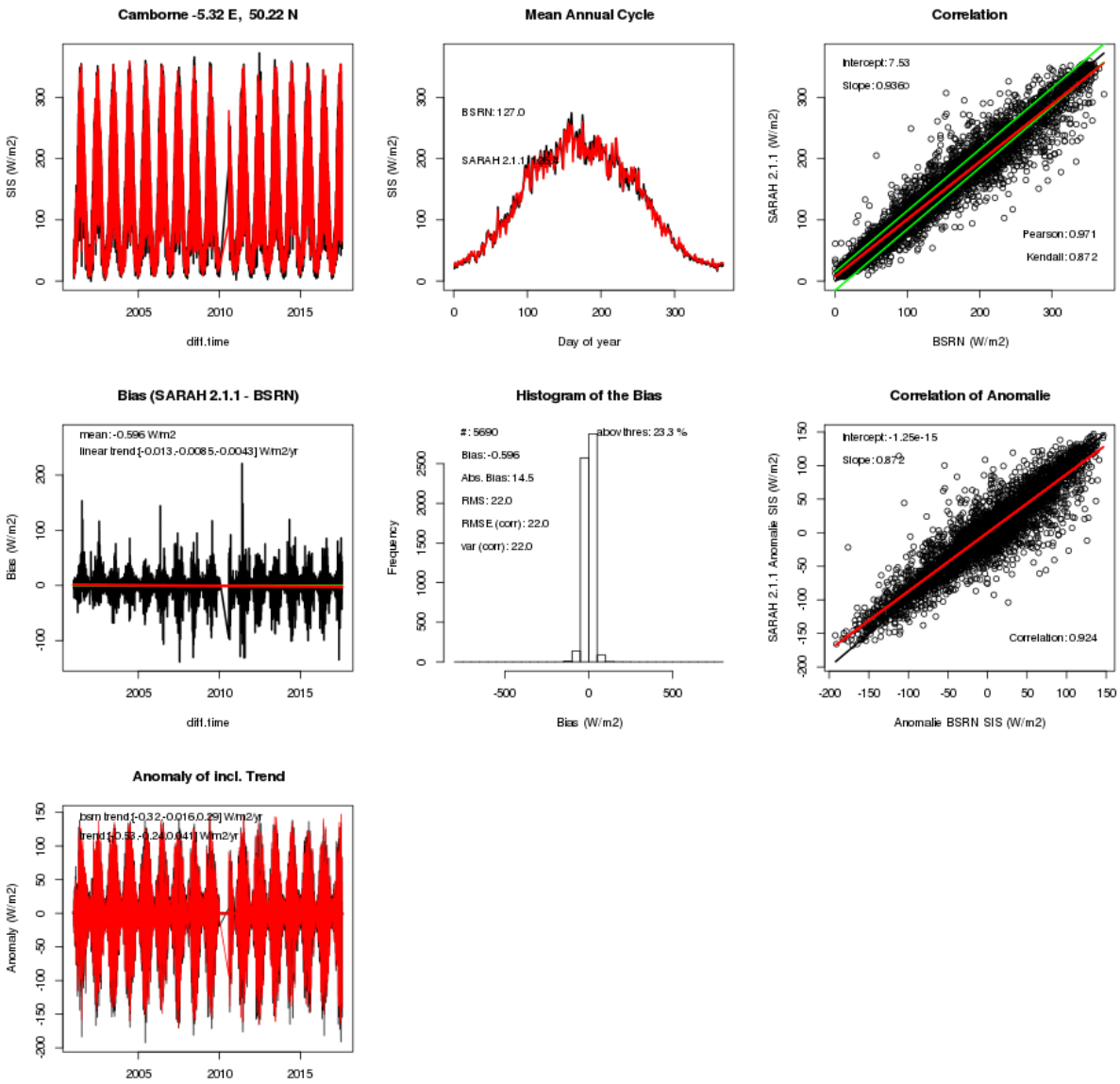


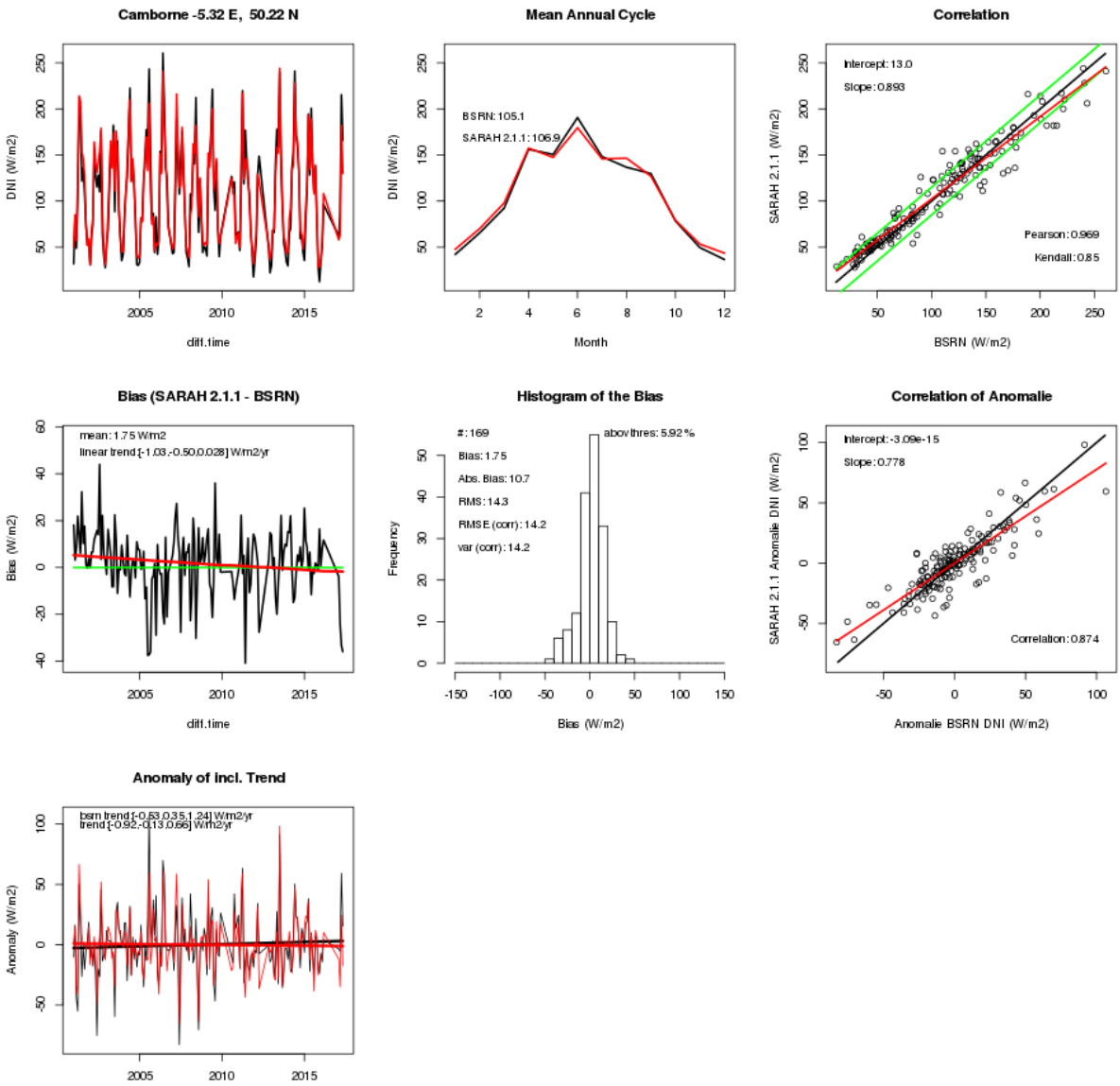
Camborne, SIS, monthly mean



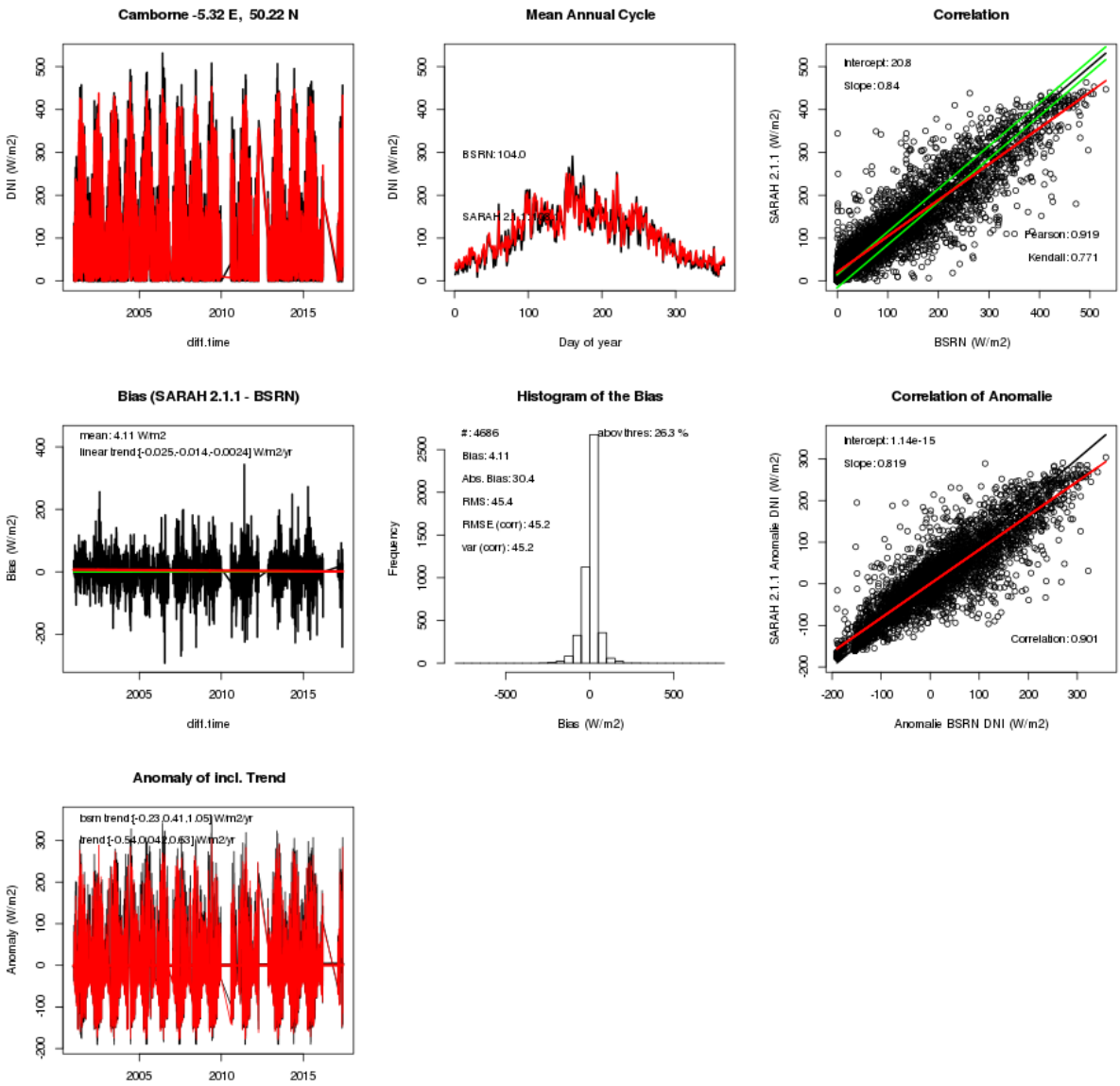
Camborne, SIS, daily mean



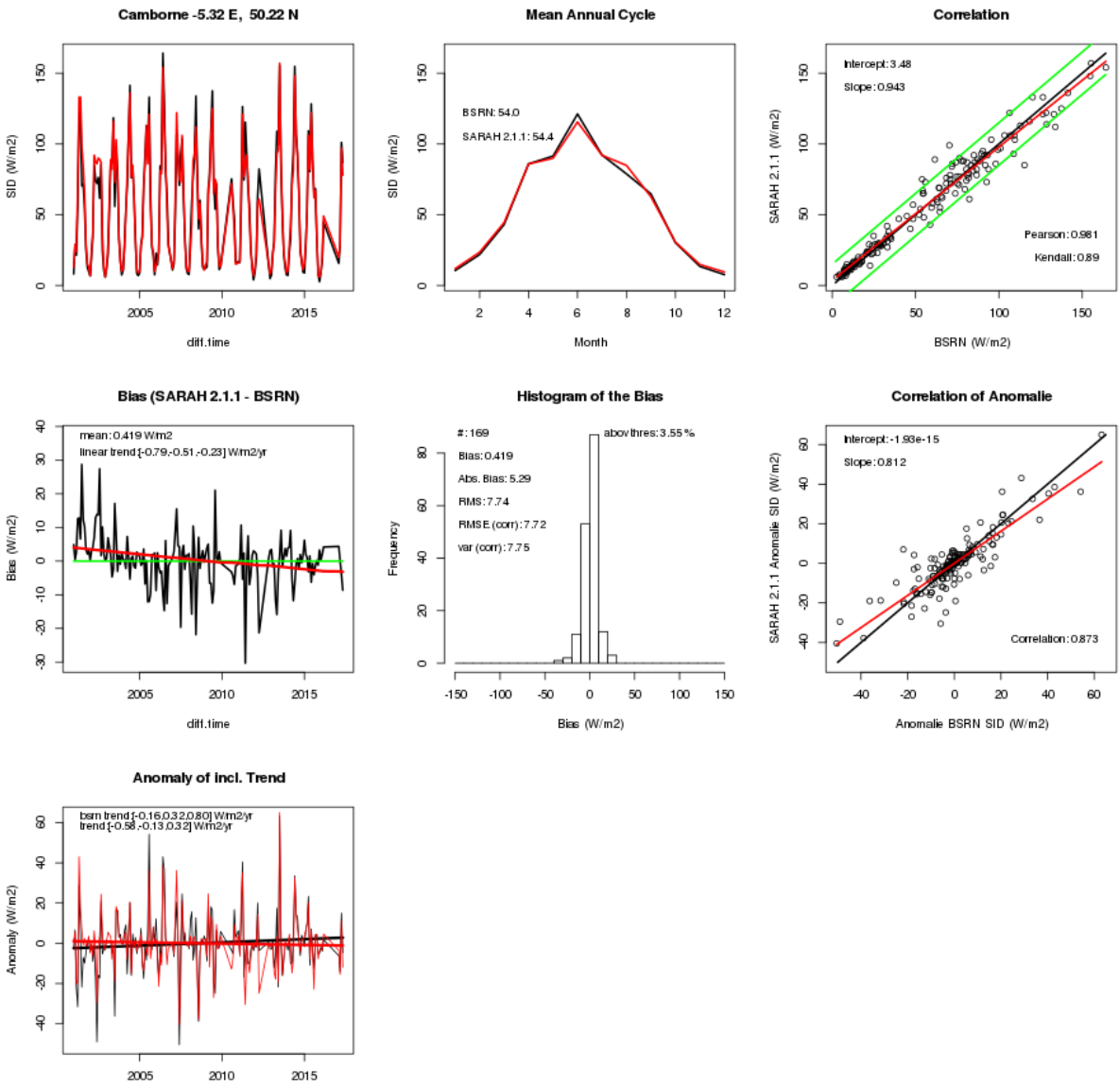
Camborne, DNI, monthly mean



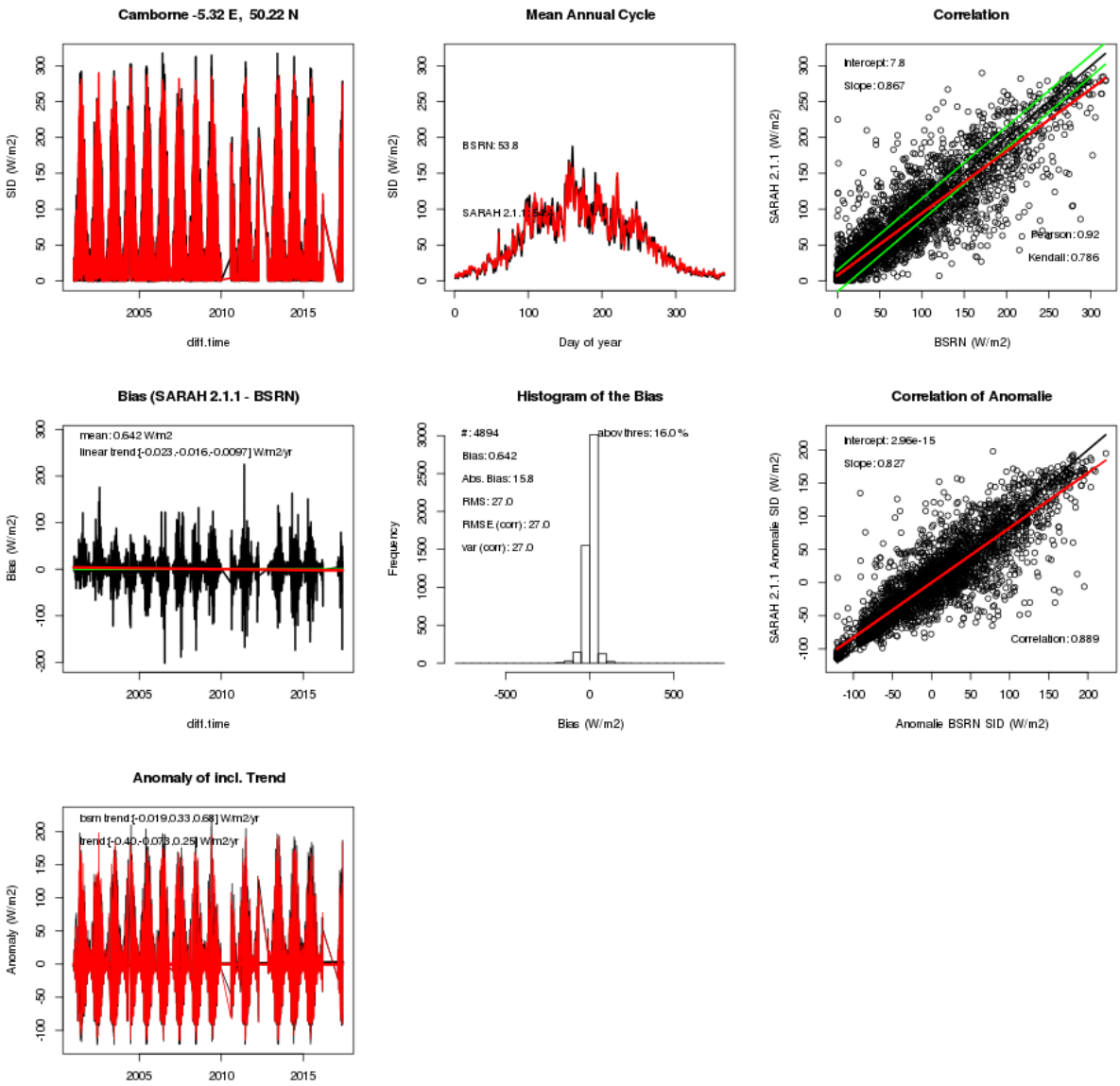
Camborne DNI, daily mean



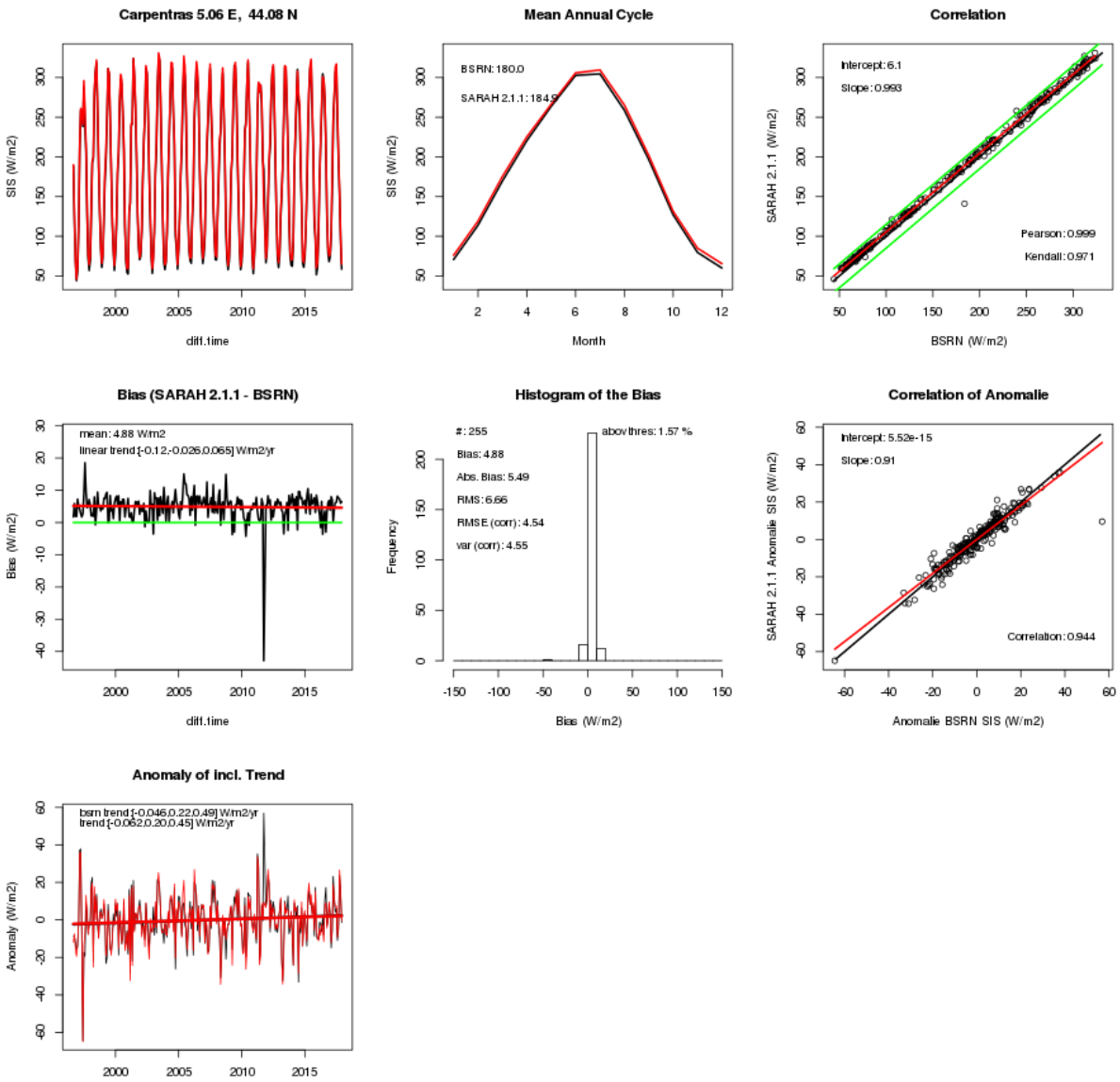
Camborne SID, montly mean



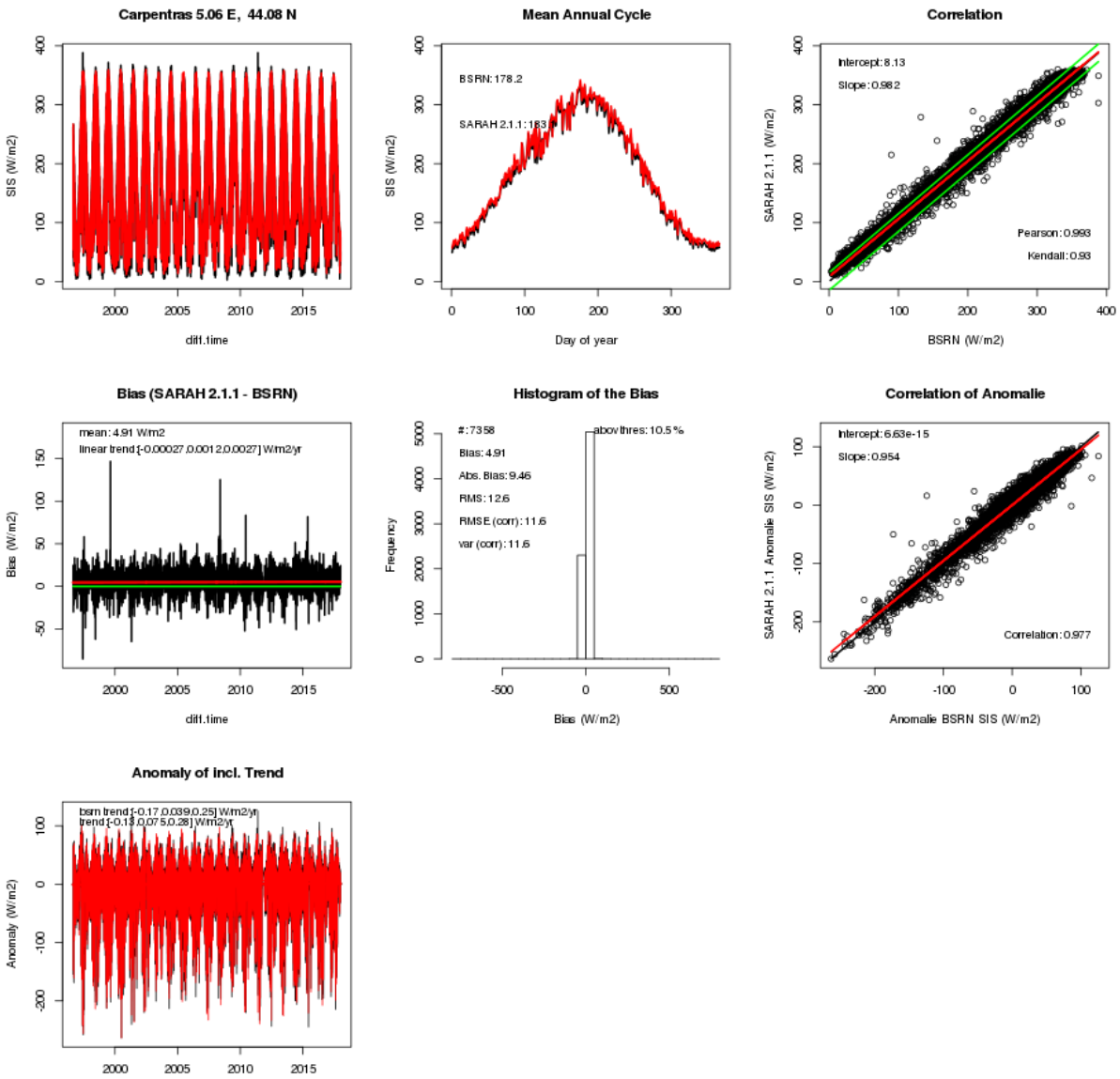
Camborne SID, daily mean



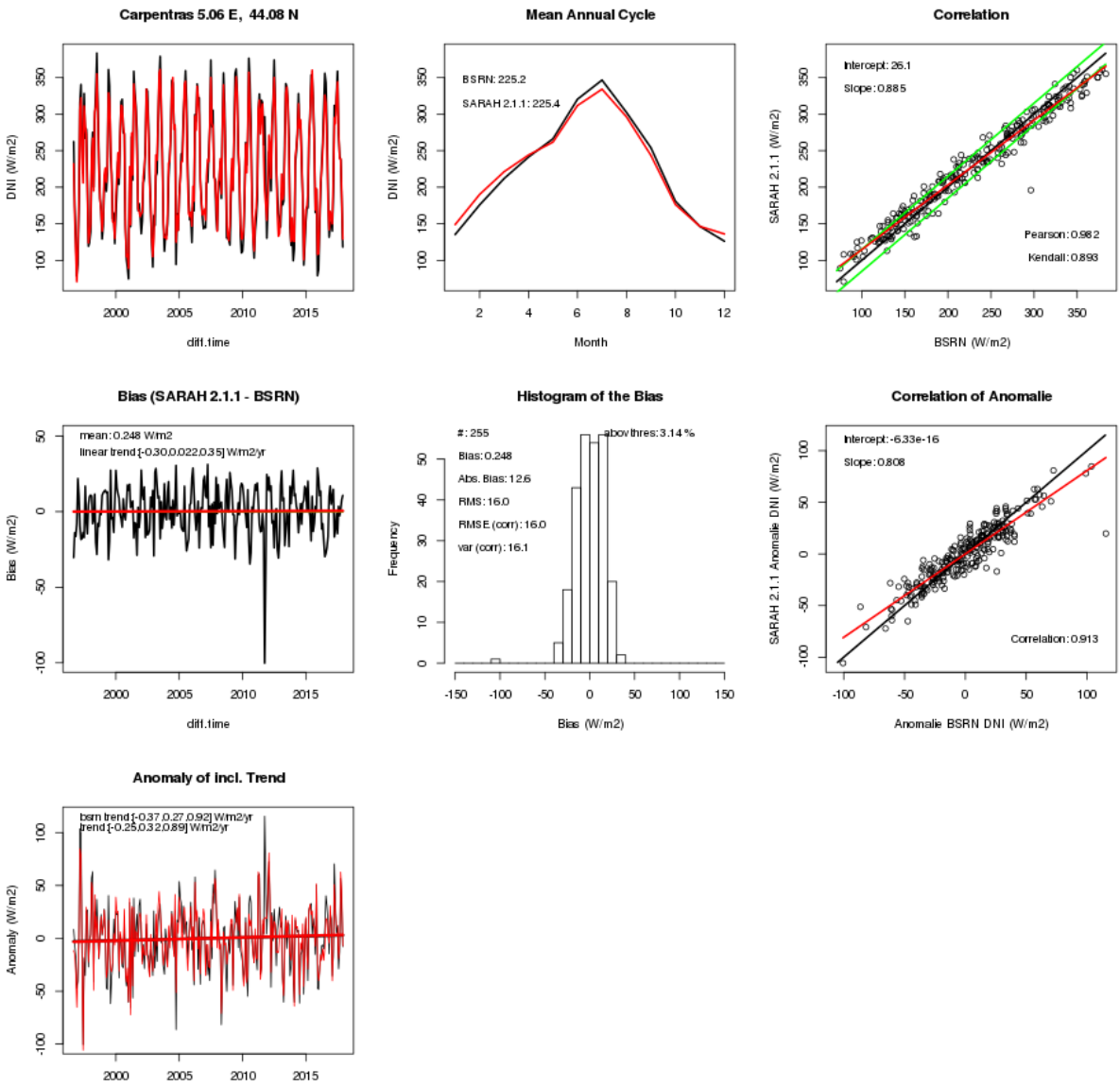
Carpentras, SIS, monthly mean



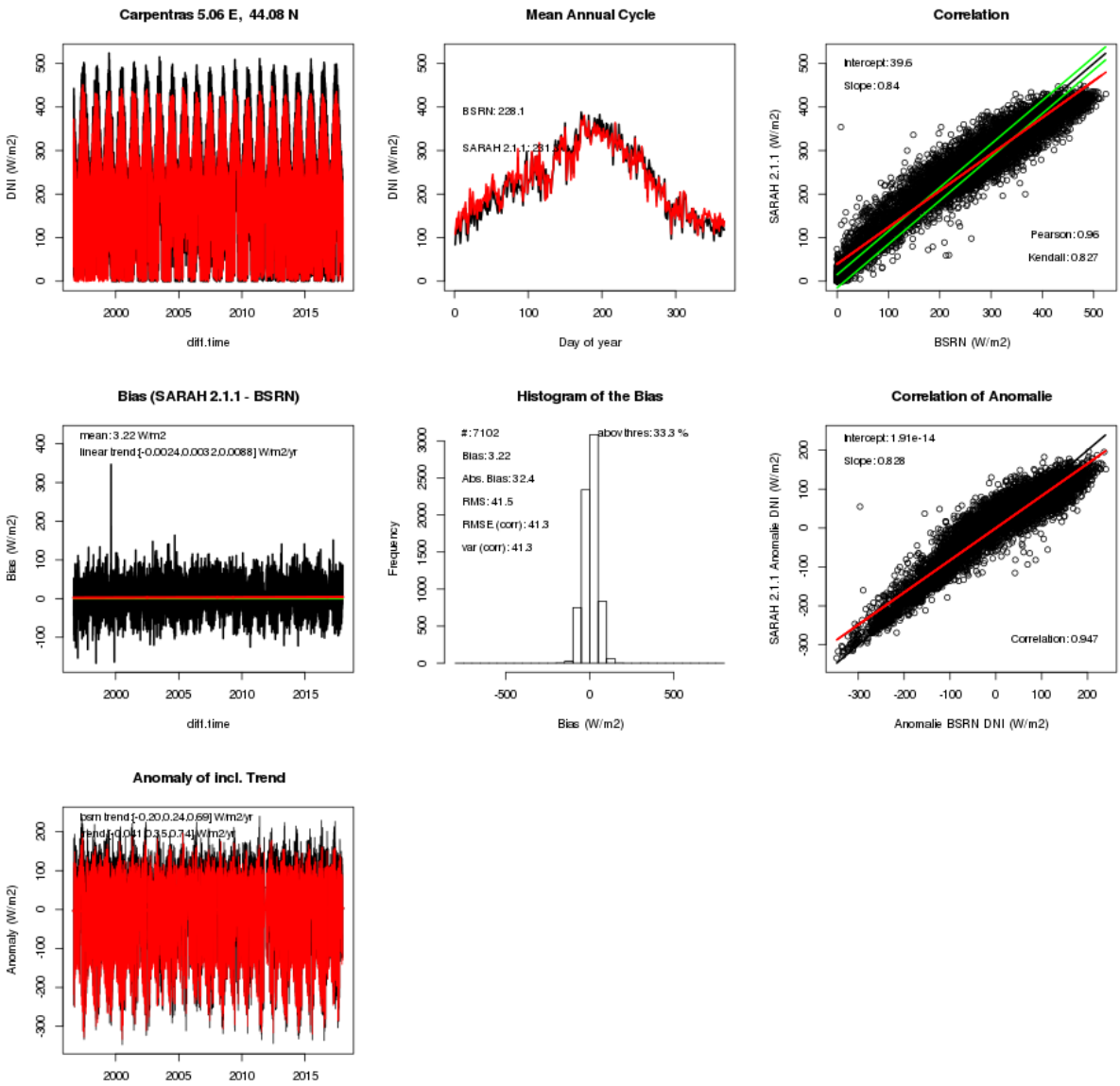
Carpentras, SIS, daily mean



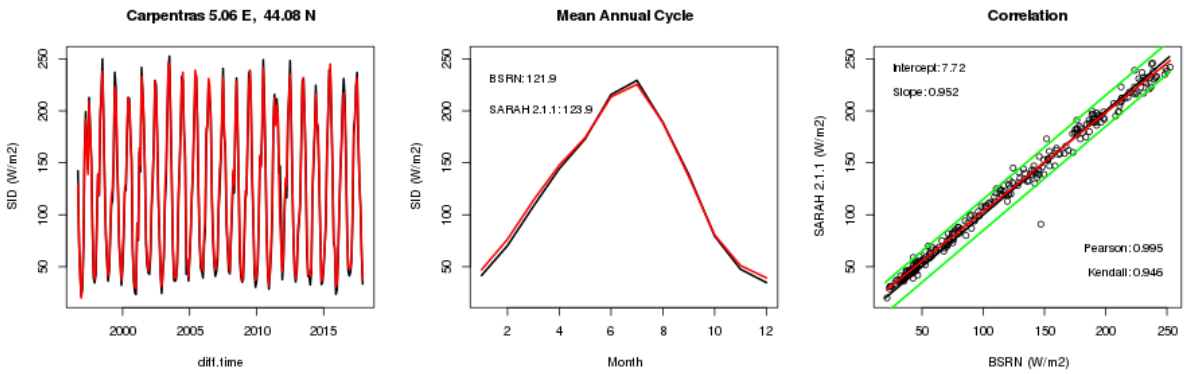
Carpentras, DNI, monthly mean

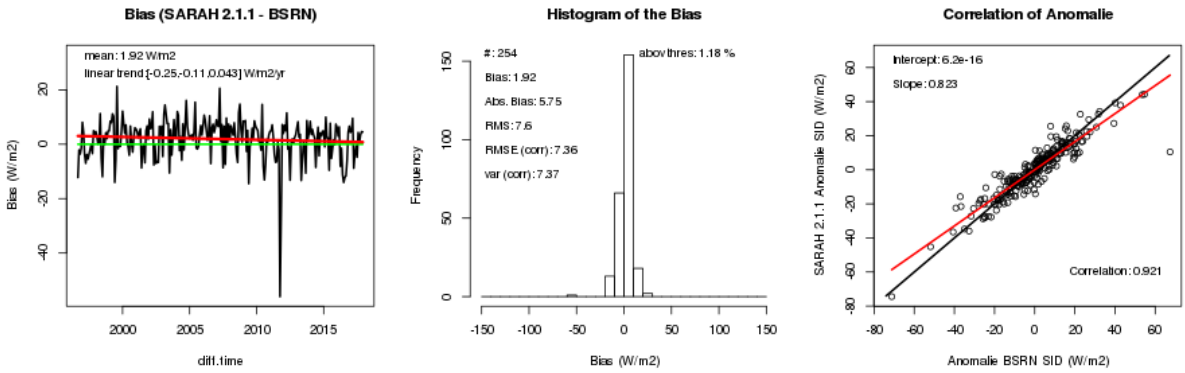


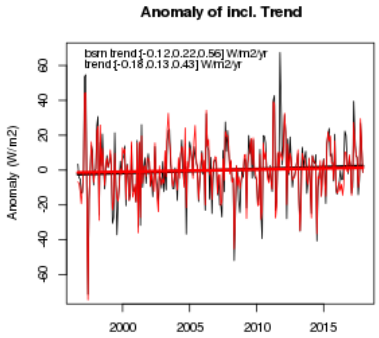
Carpentras, DNI, daily mean



Carpentras, SID, monthly mean







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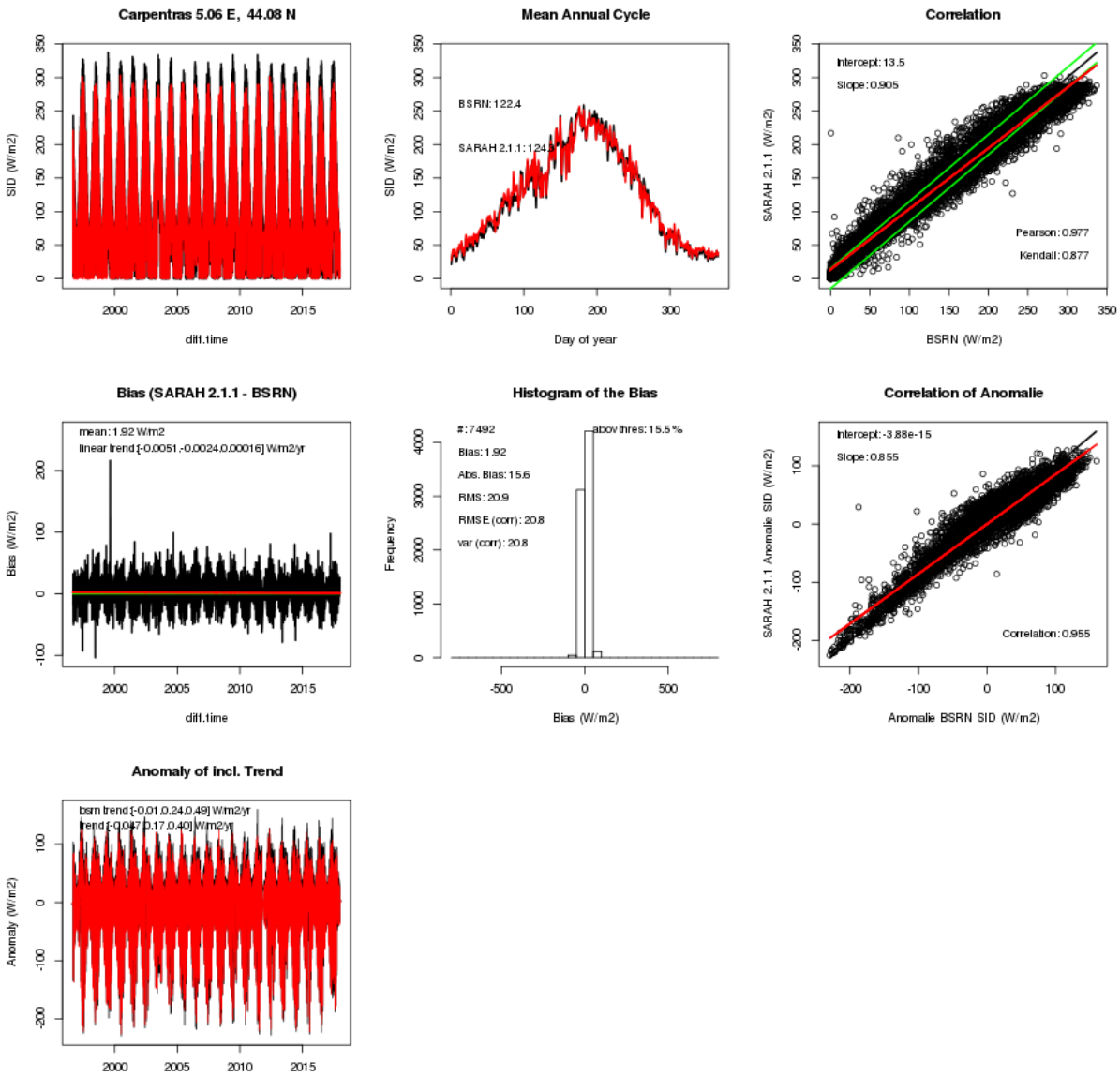
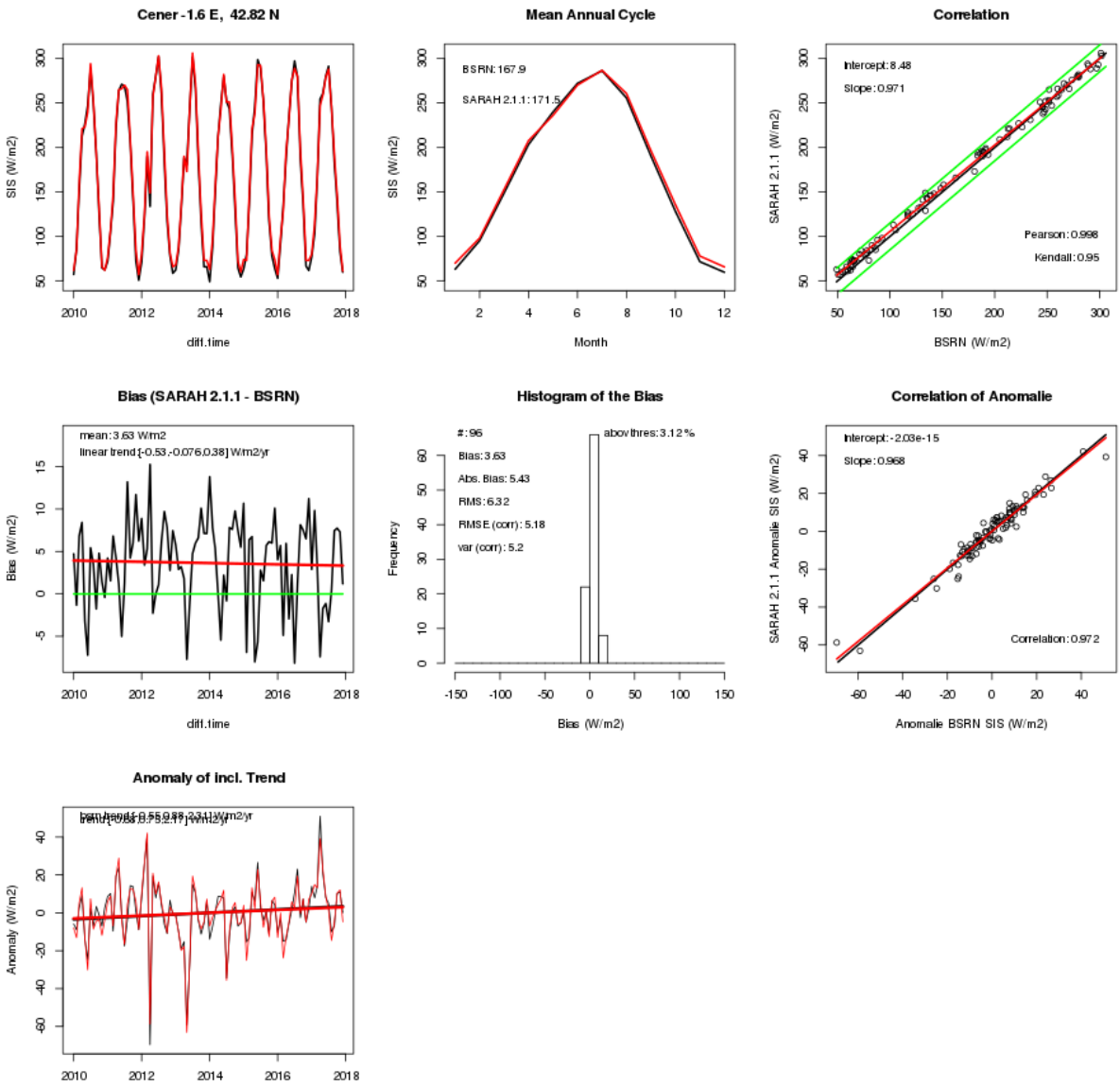


Cener, SIS, monthly mean



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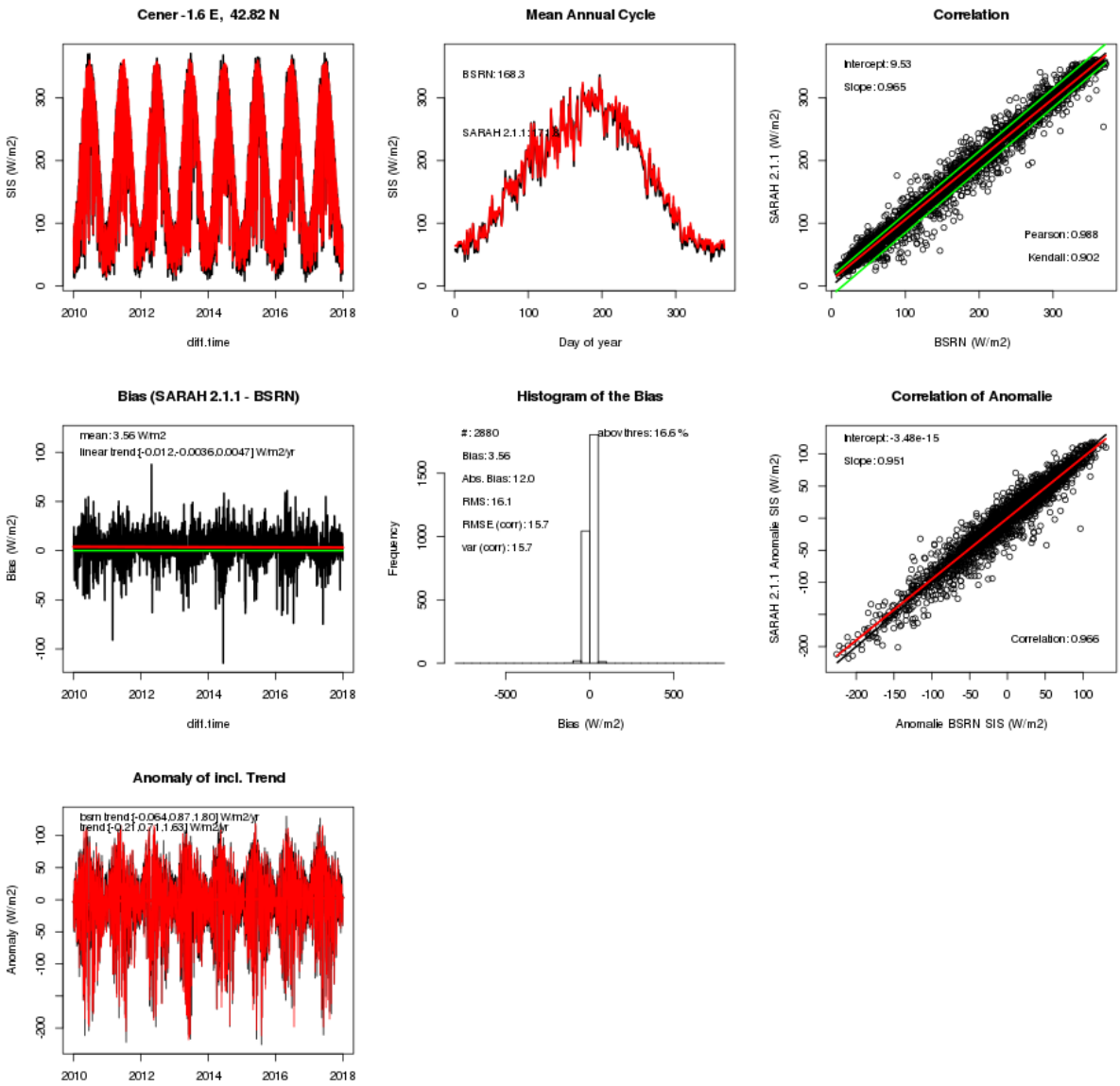
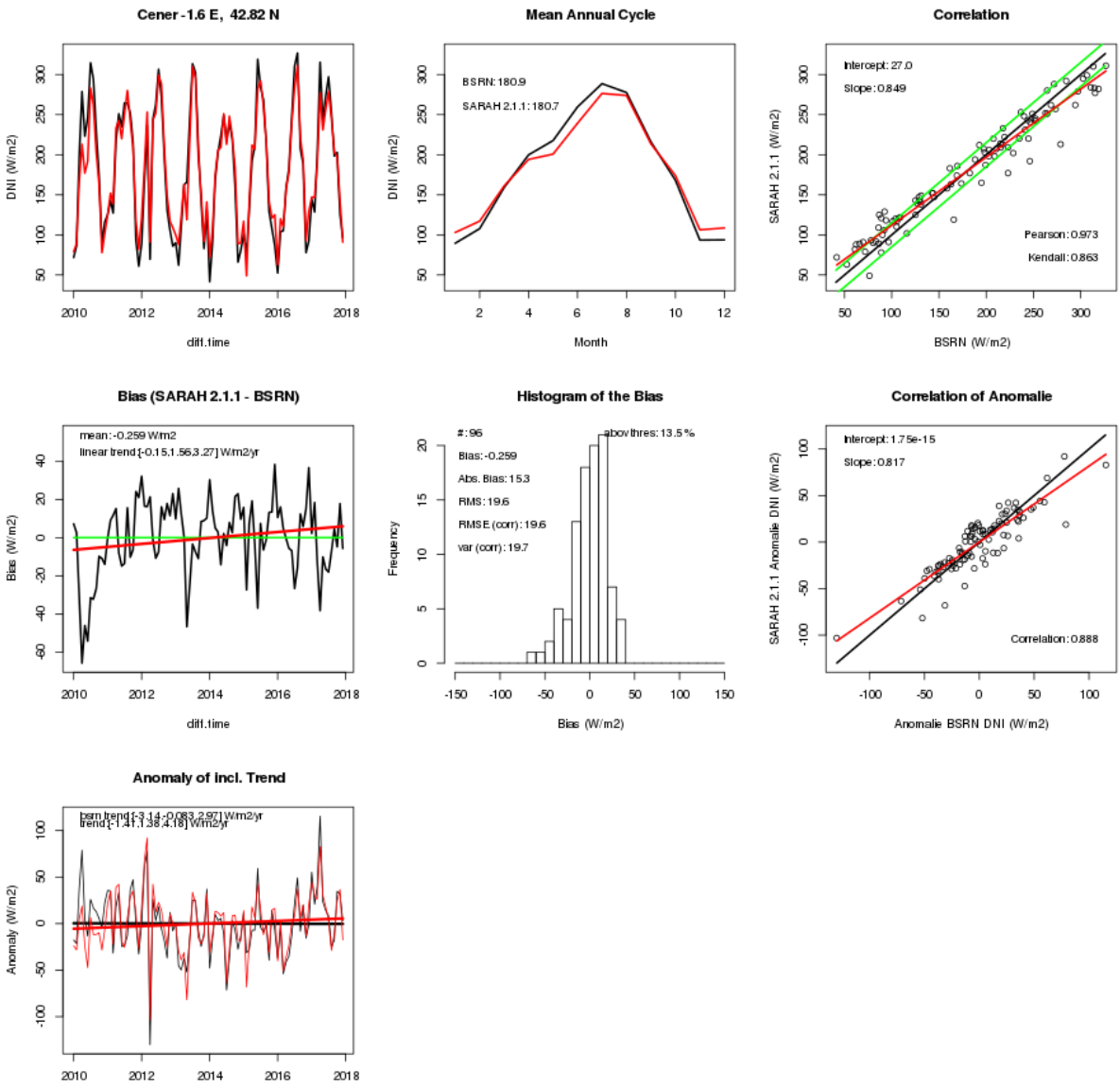


Cener, DNI, monthly mean



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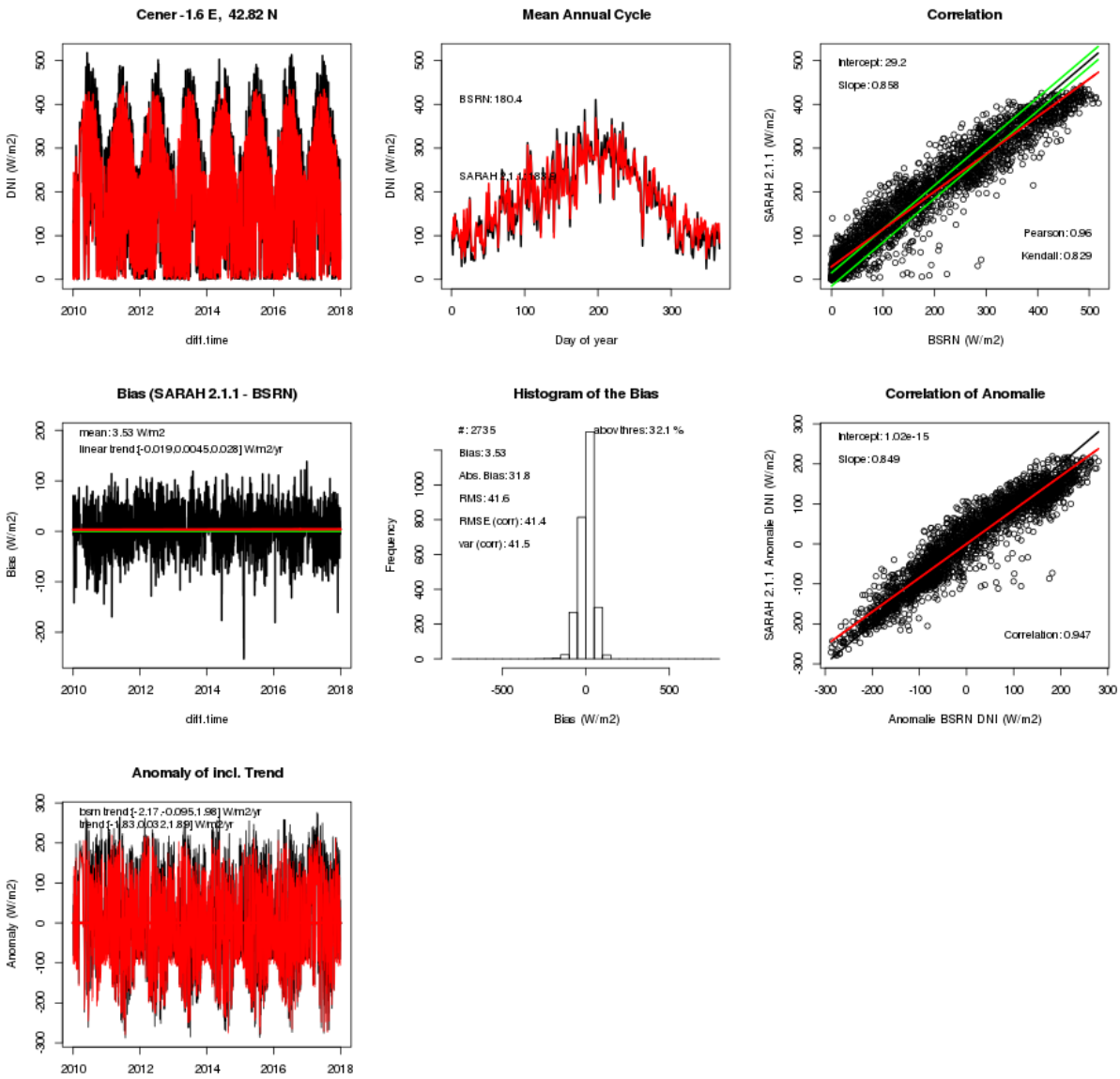

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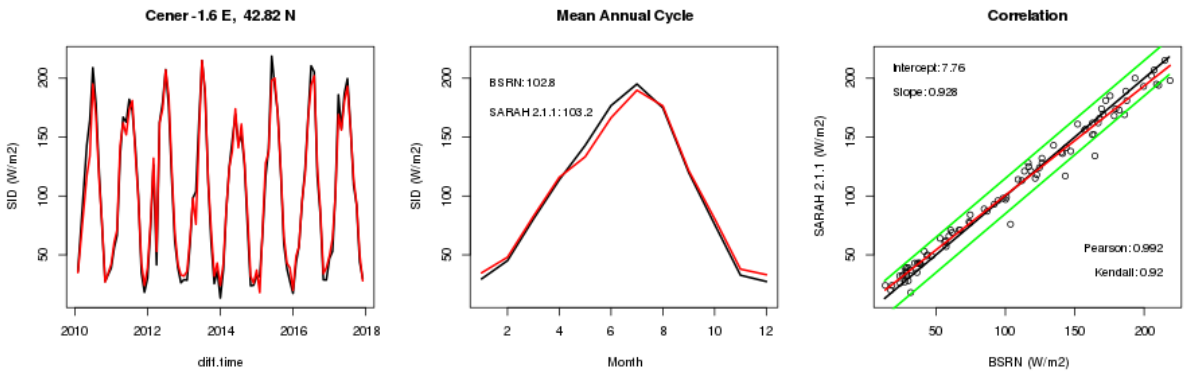

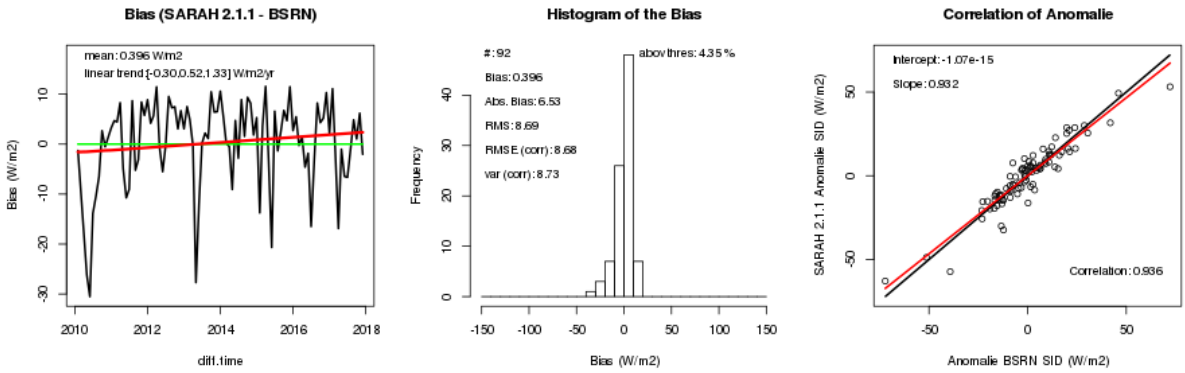

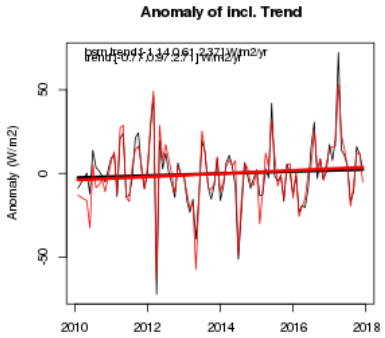

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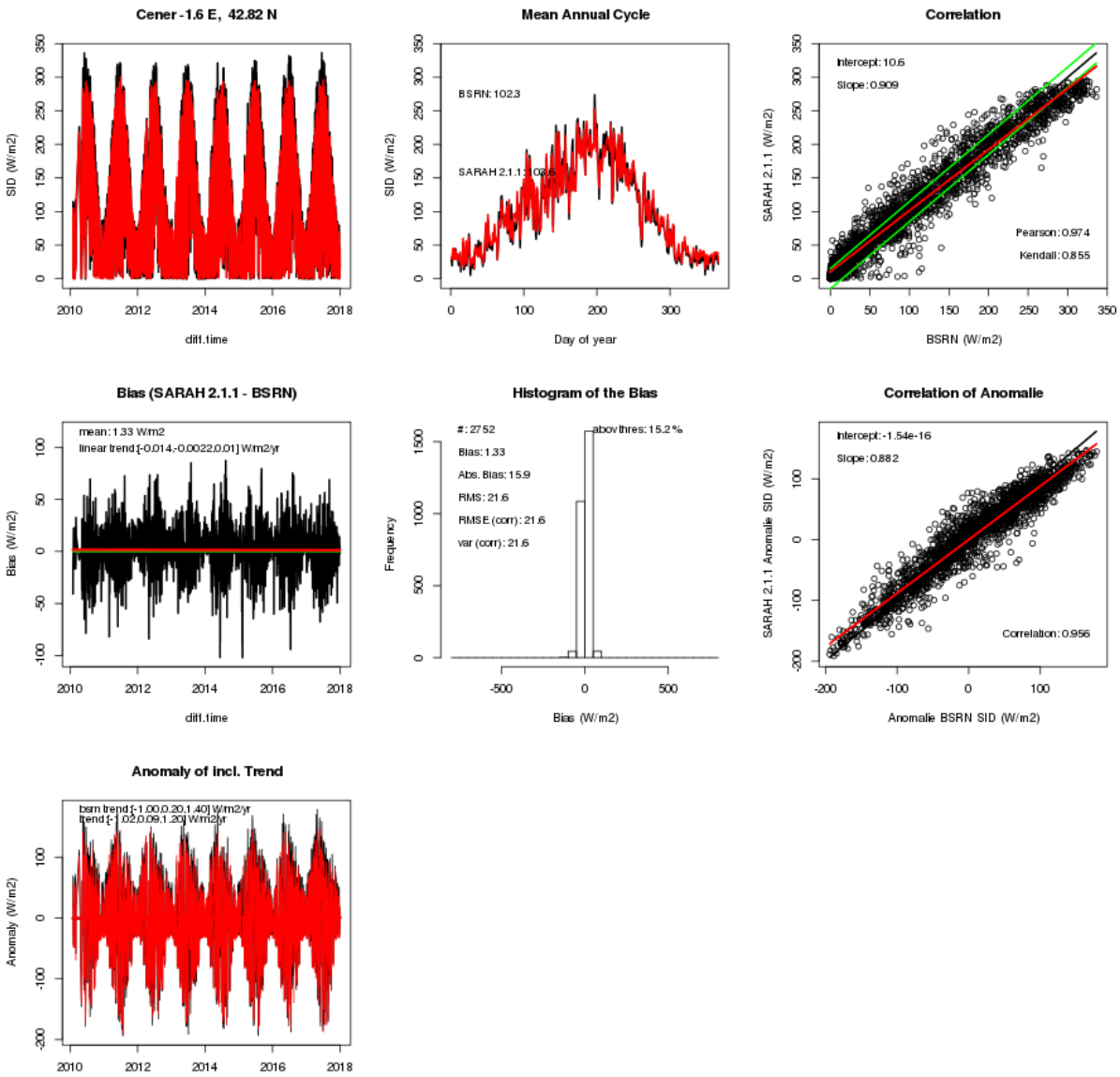
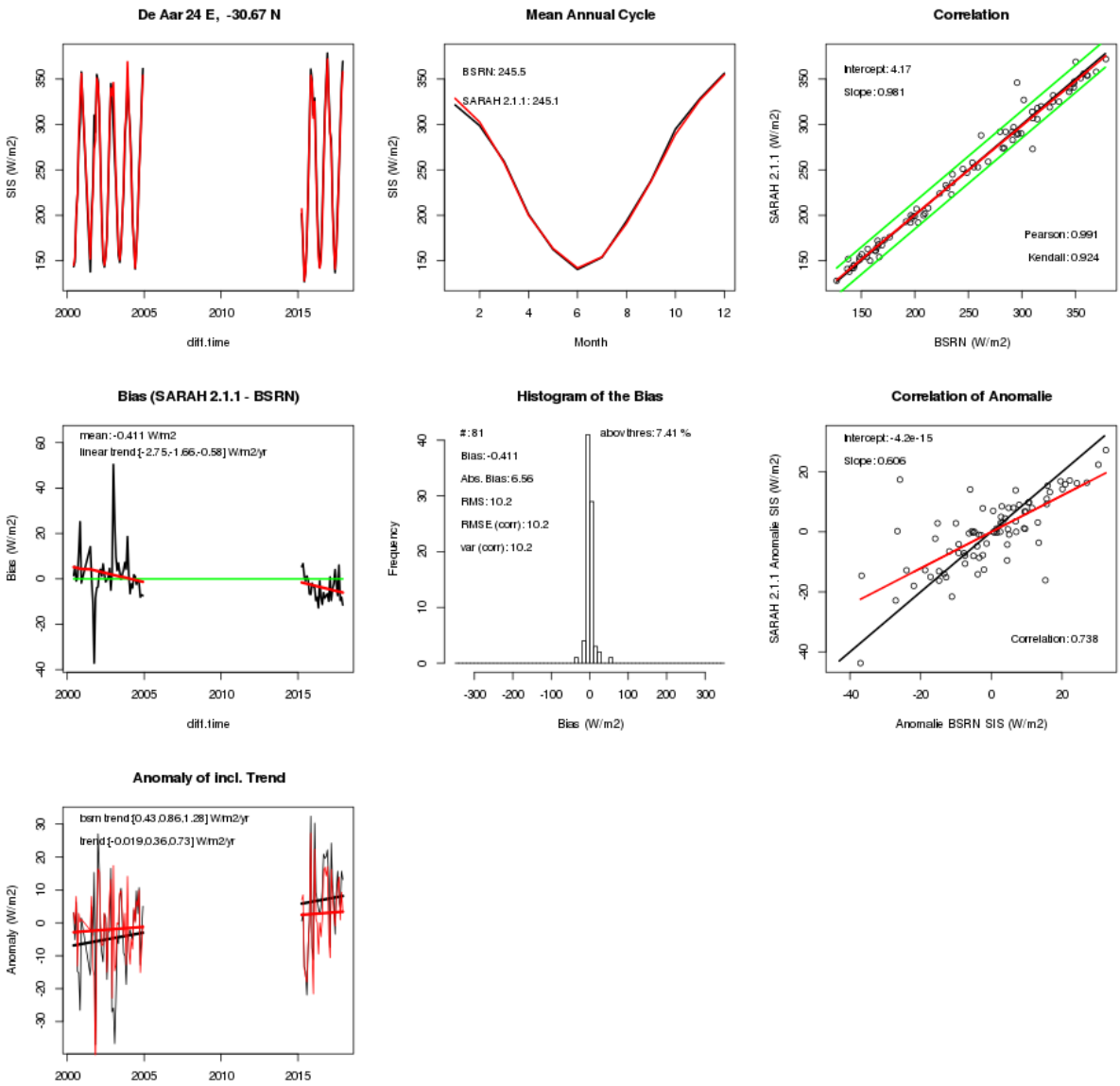
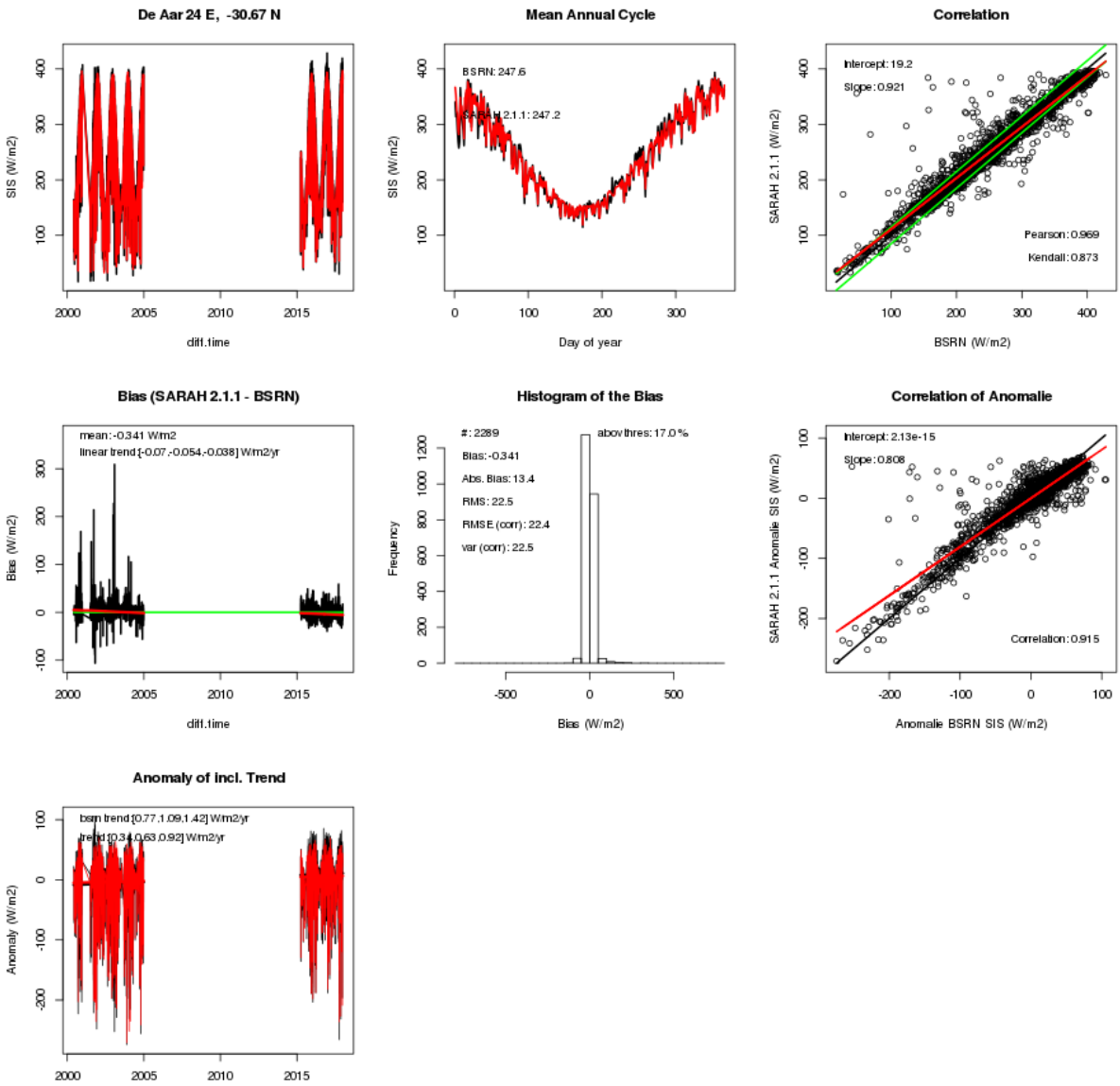


De Aar, SIS, monthly mean



De Aar, SIS, daily mean



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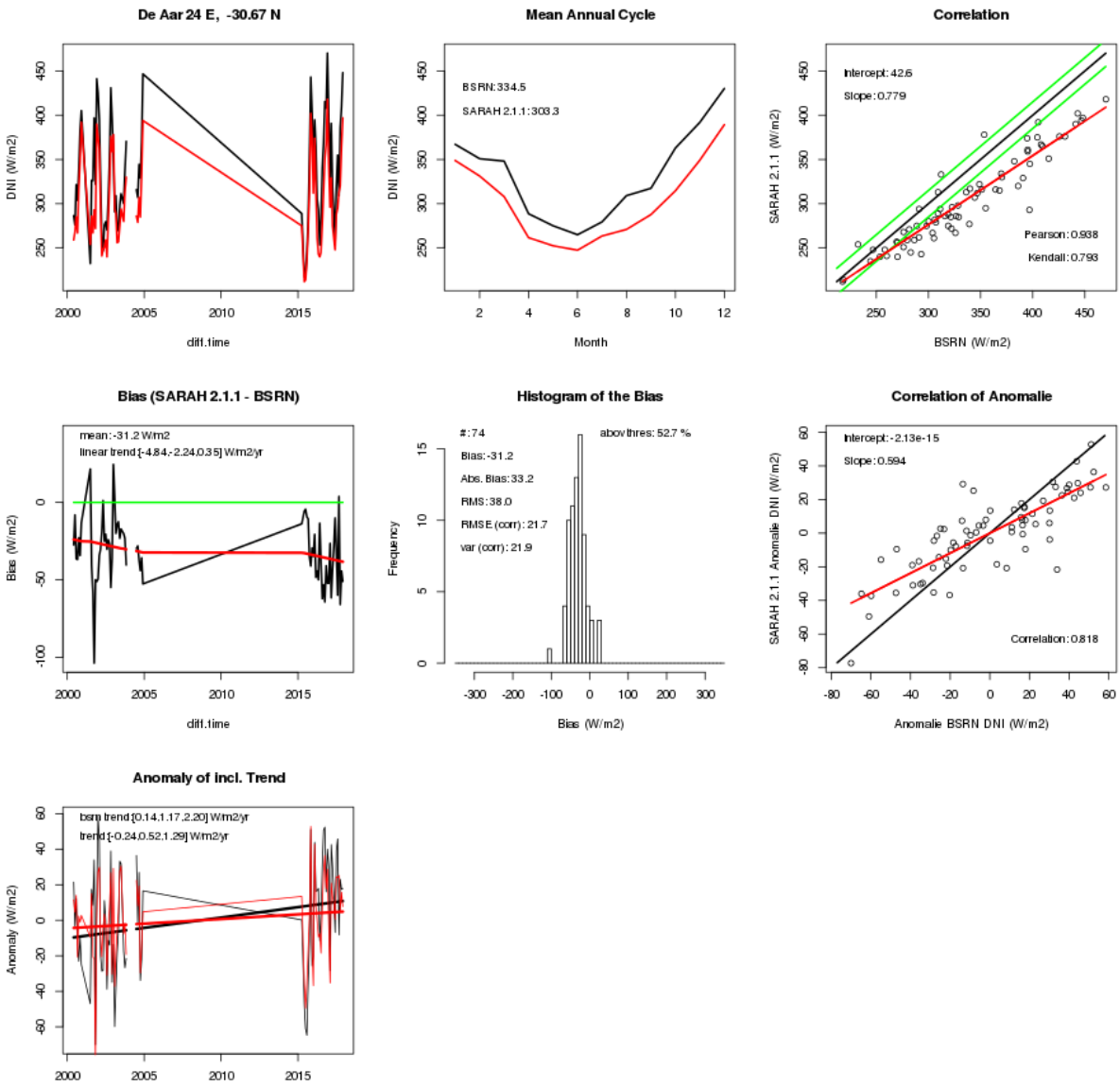

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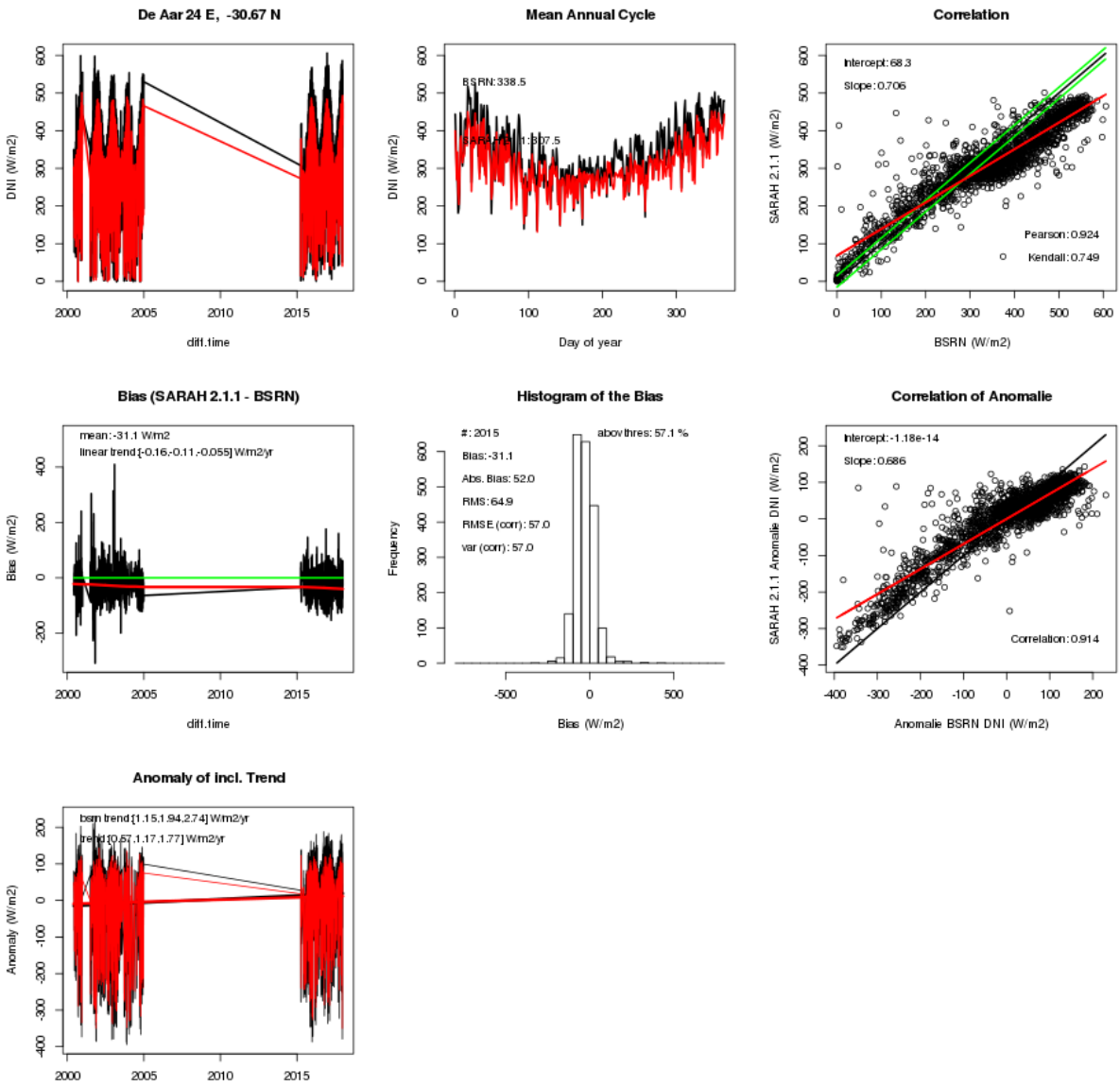

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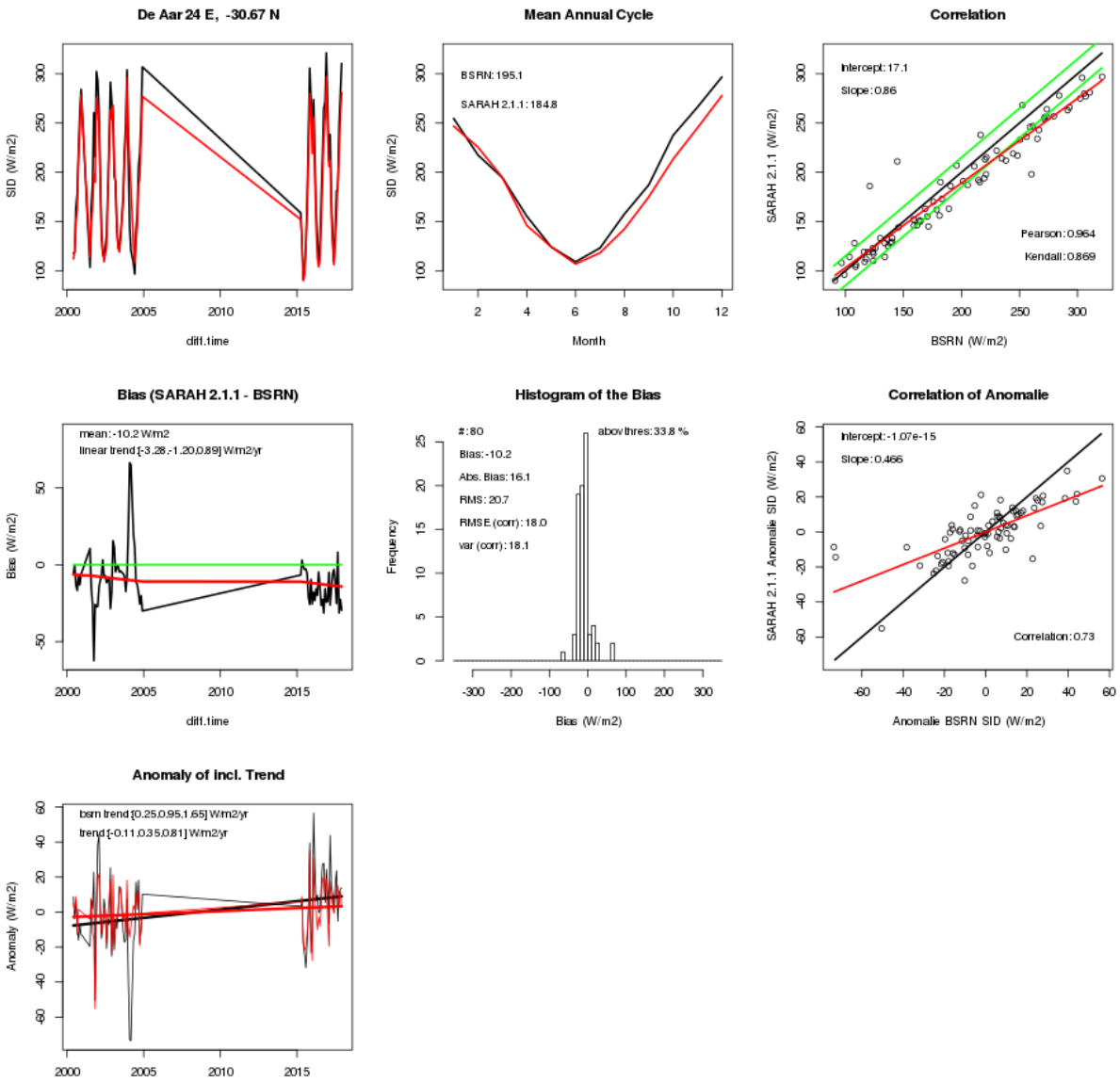

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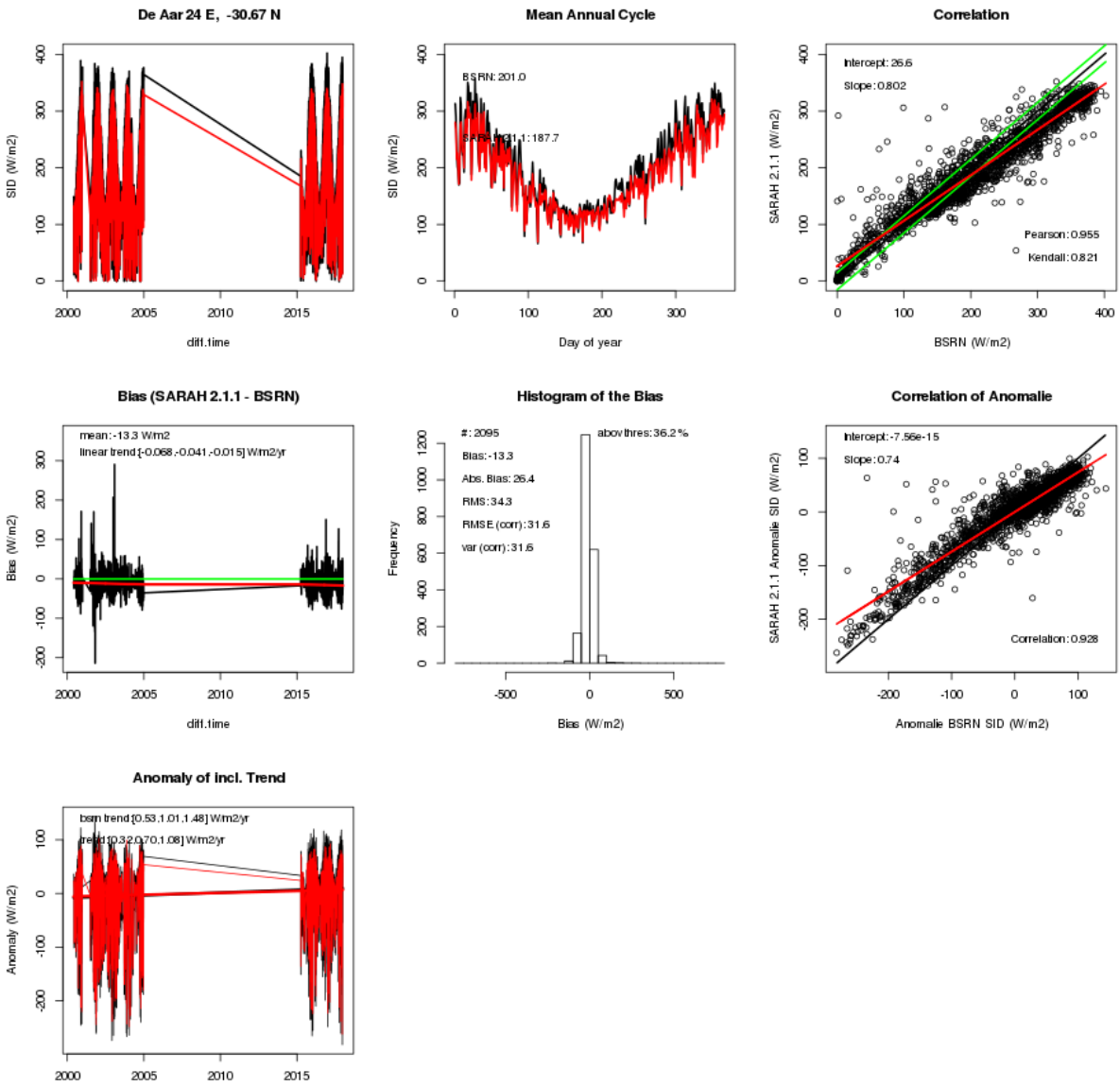
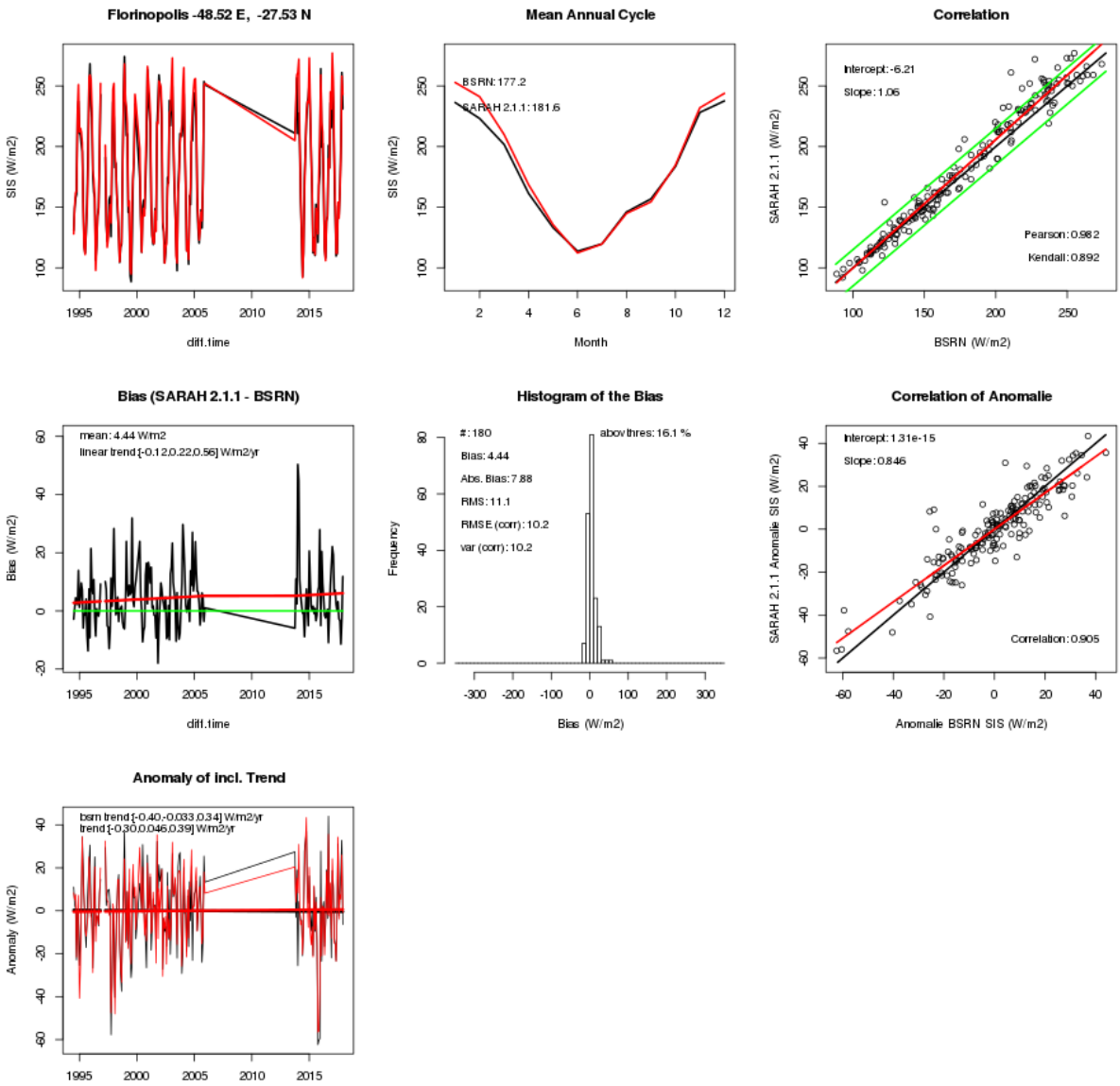
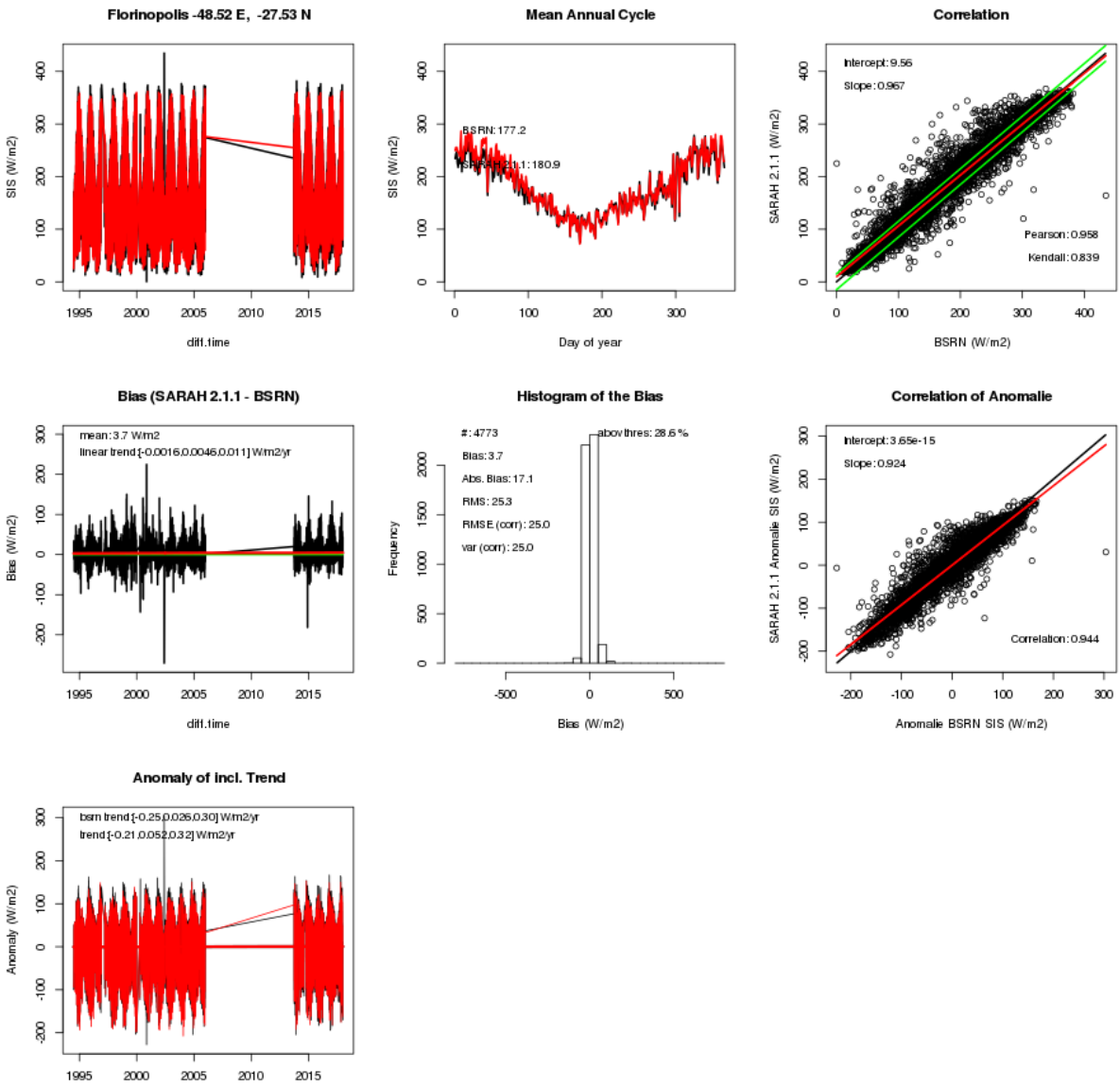


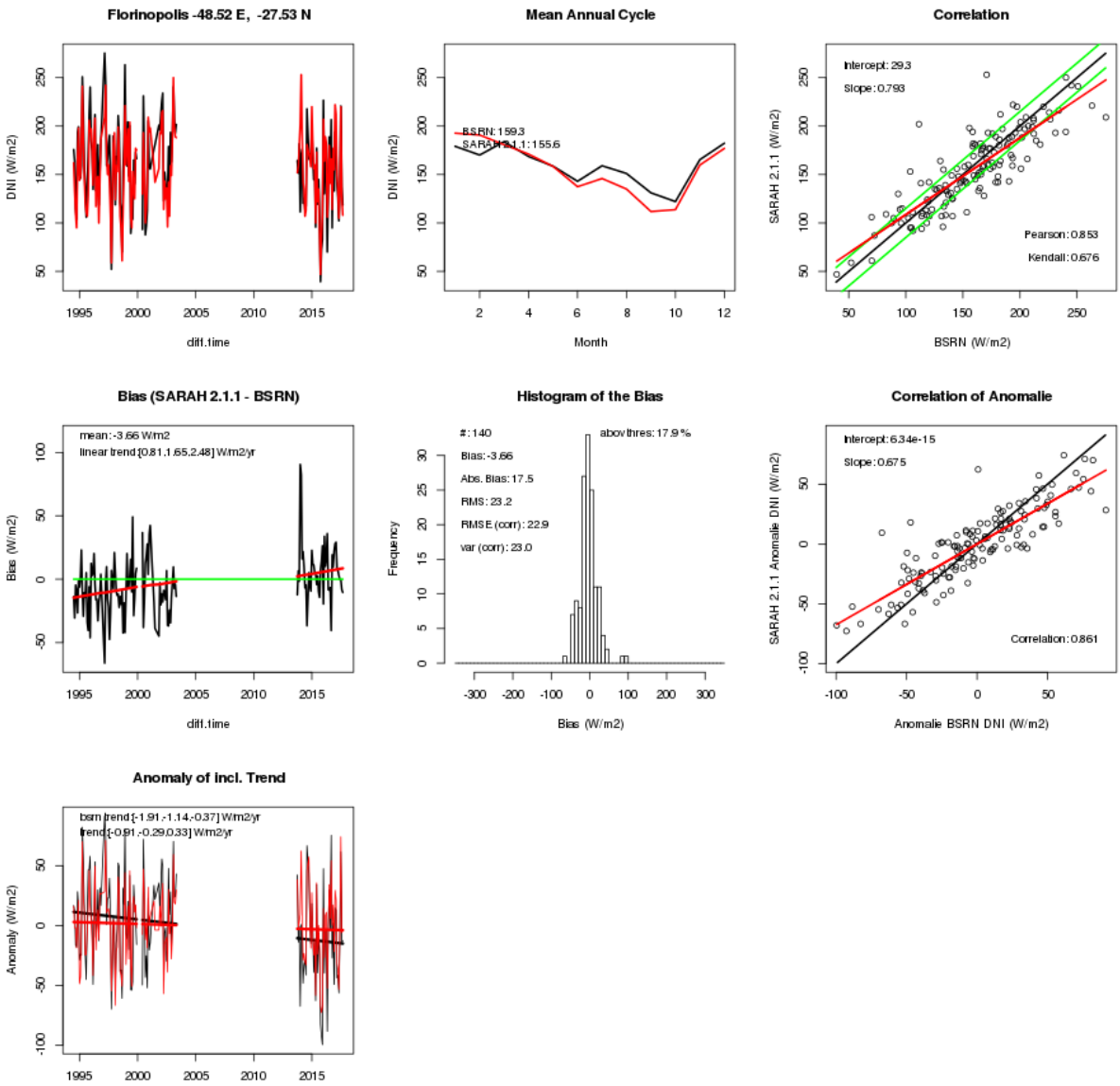
Florinopolis, SIS, monthly mean



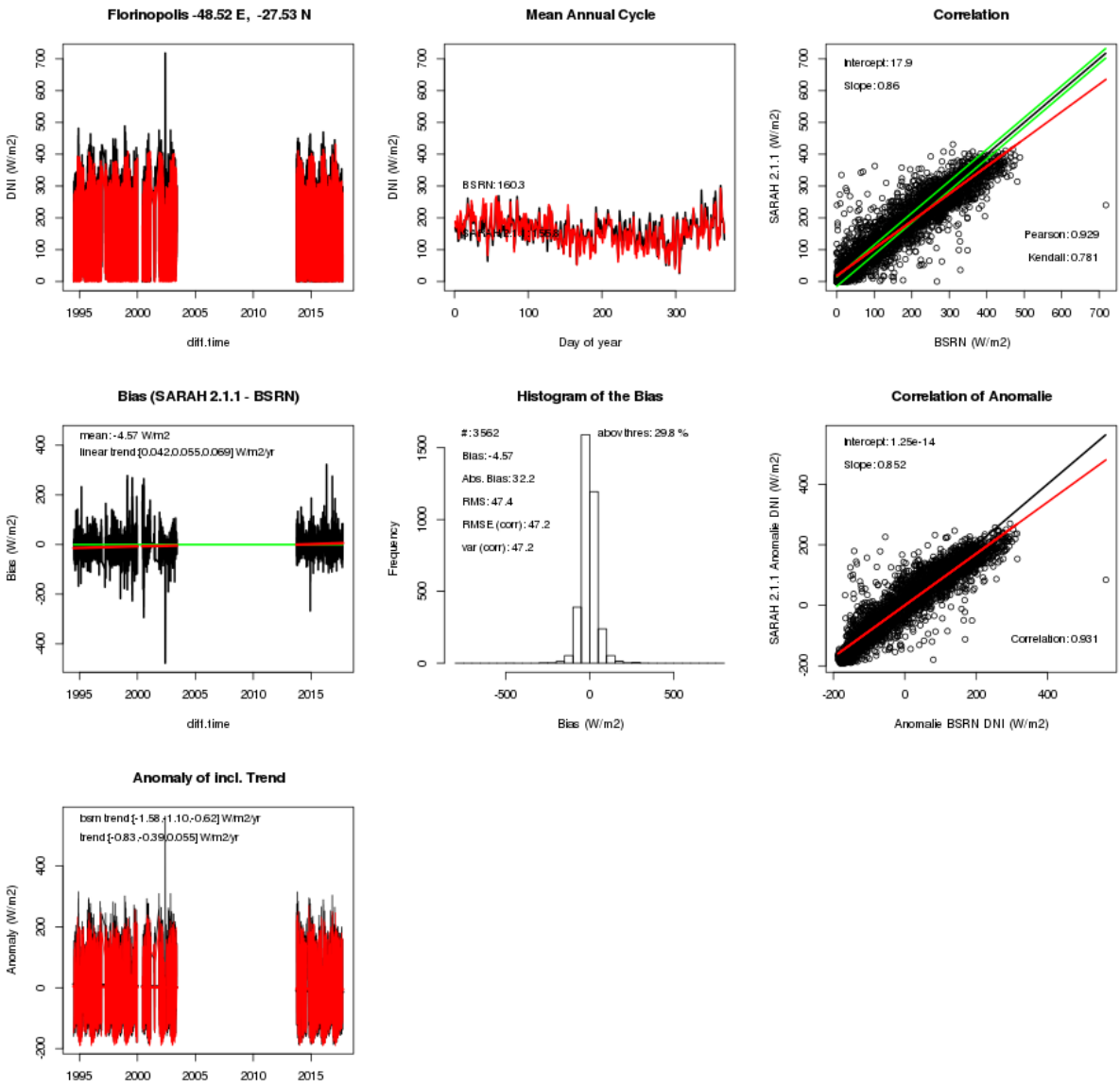
Florinopolis, SIS, daily mean



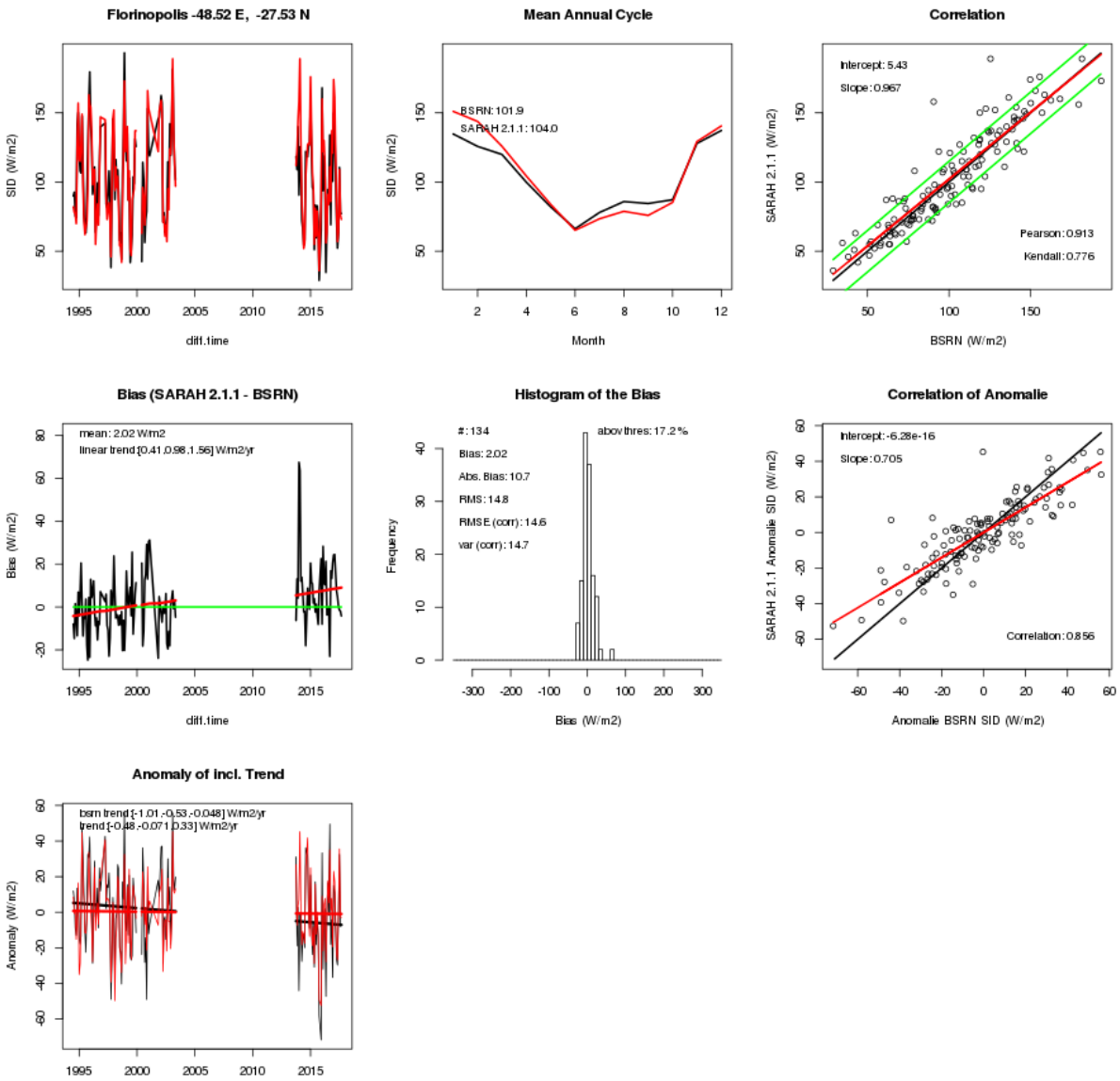
Florinopolis, DNI, monthly mean



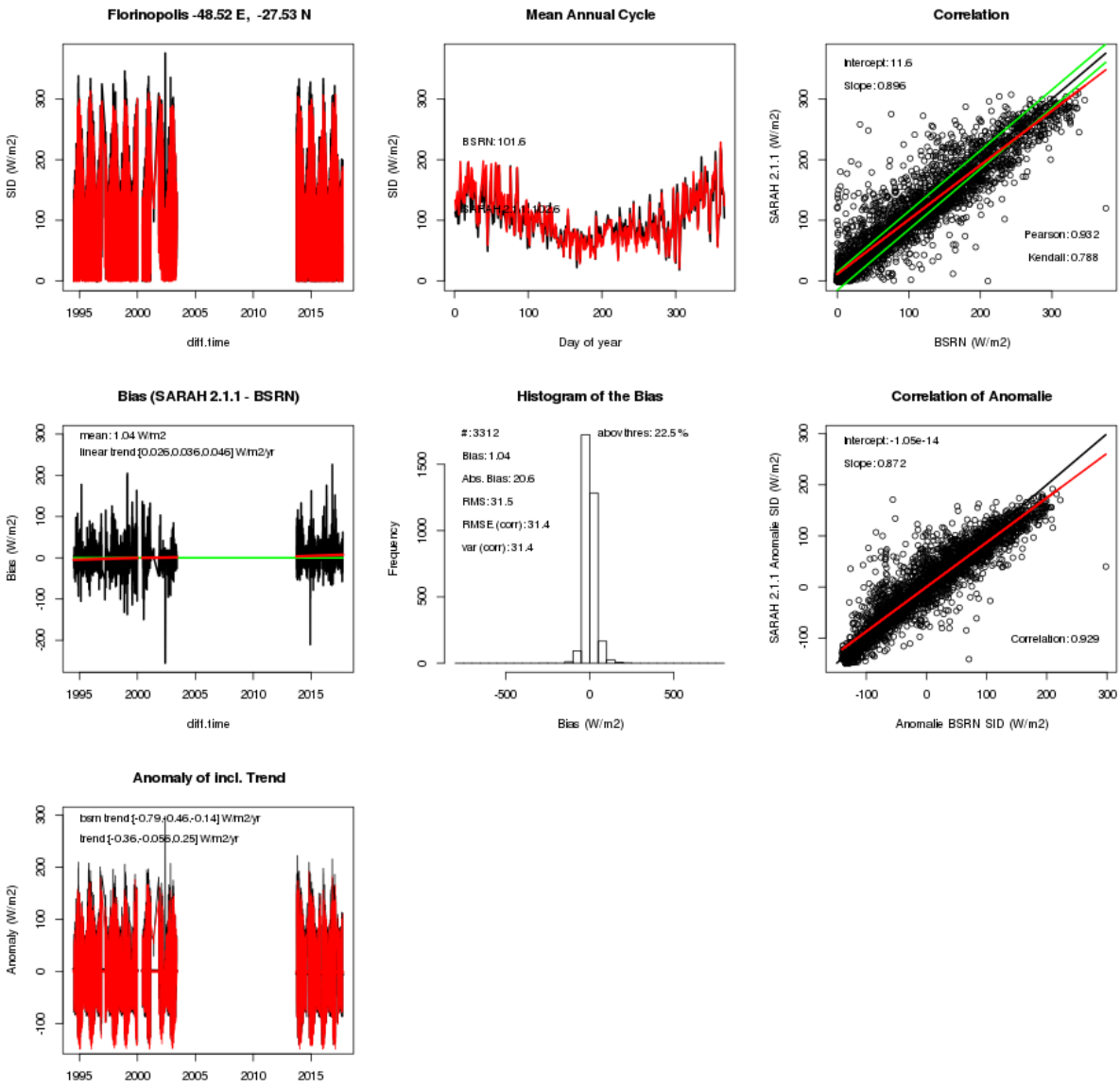
Florinopolis, DNI, daily mean



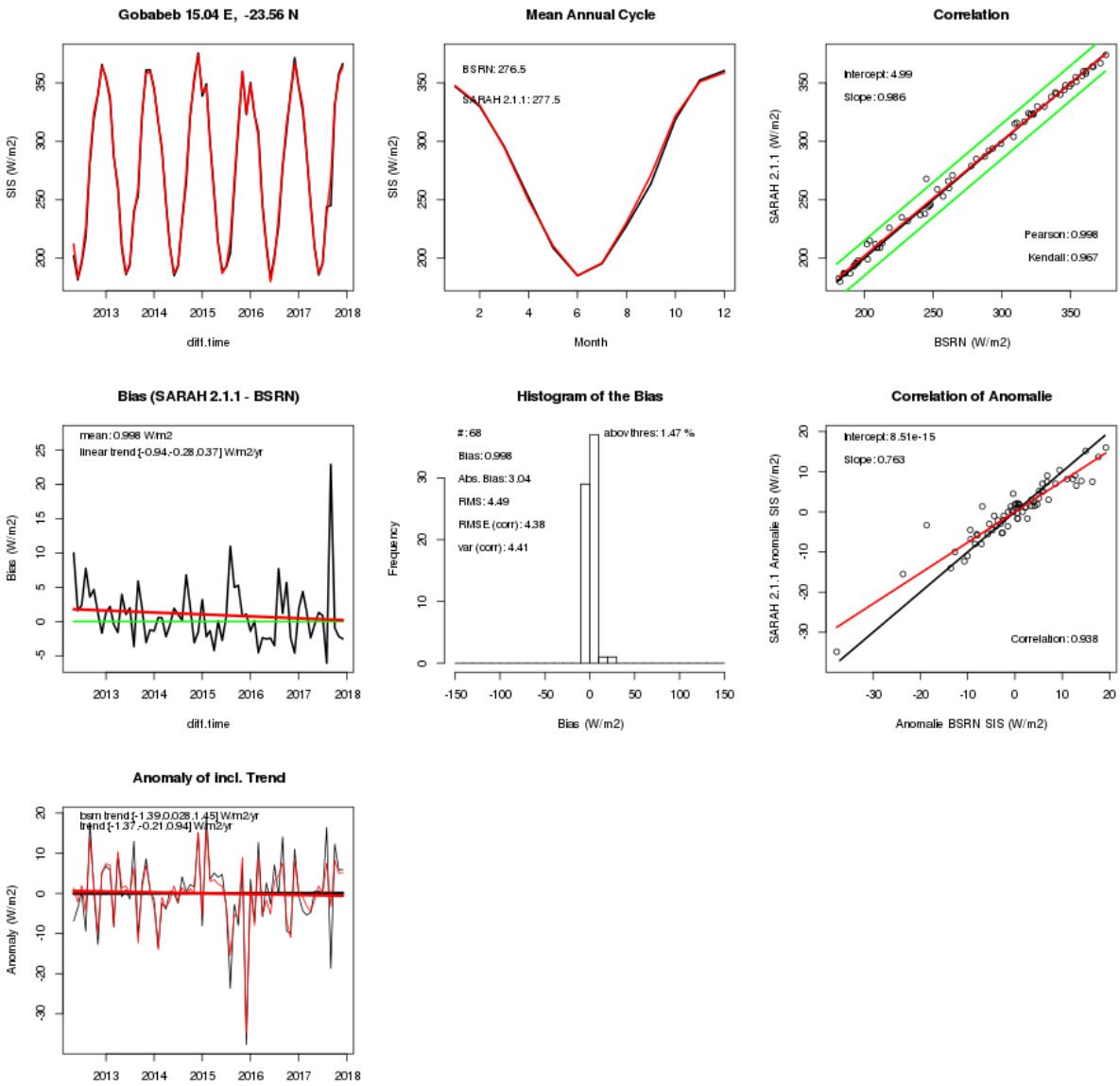
Florinopolis, SID, monthly mean



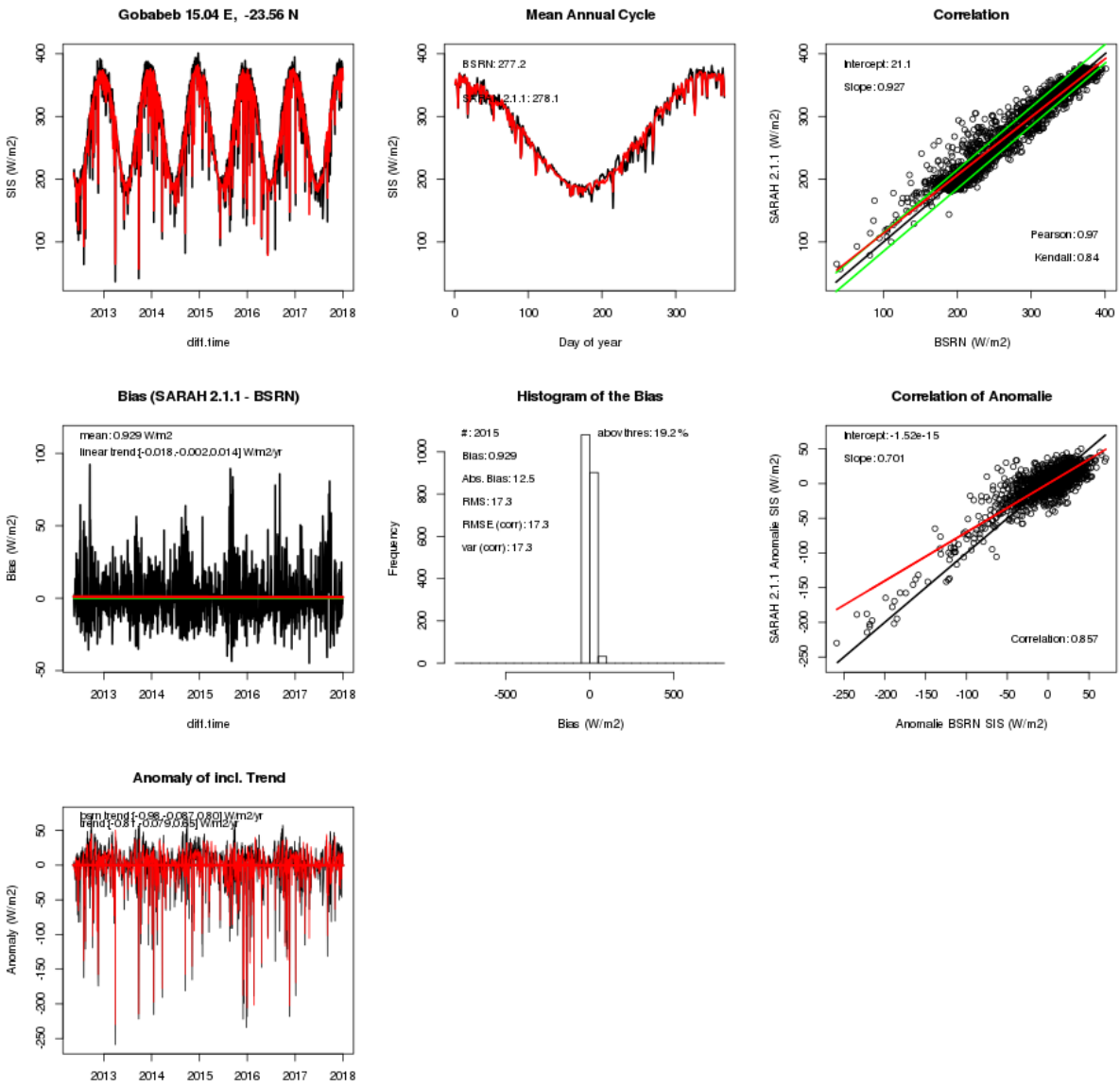
Florinopolis, SID, daily mean



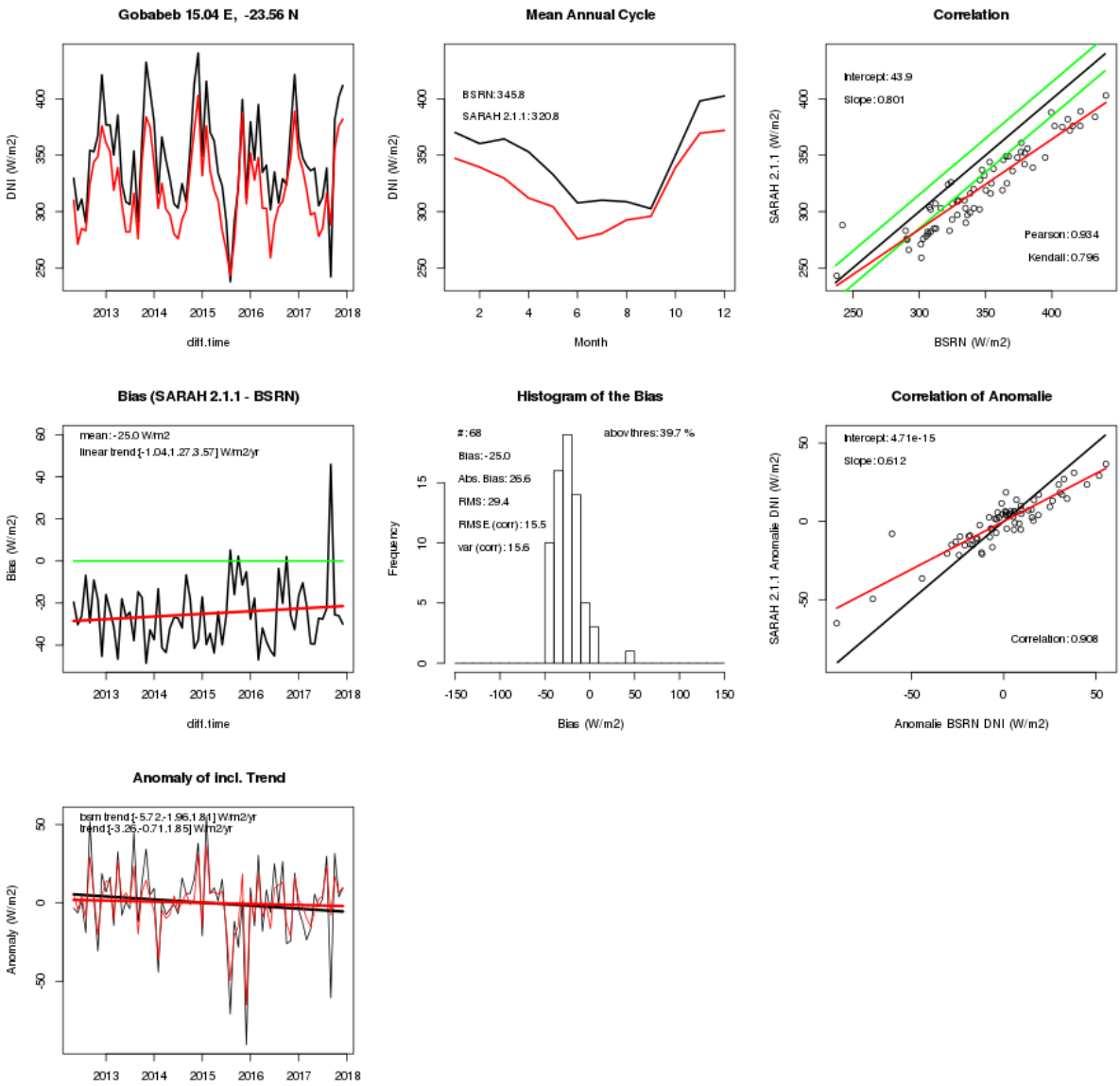
Gobabeb, SIS; monthly mean



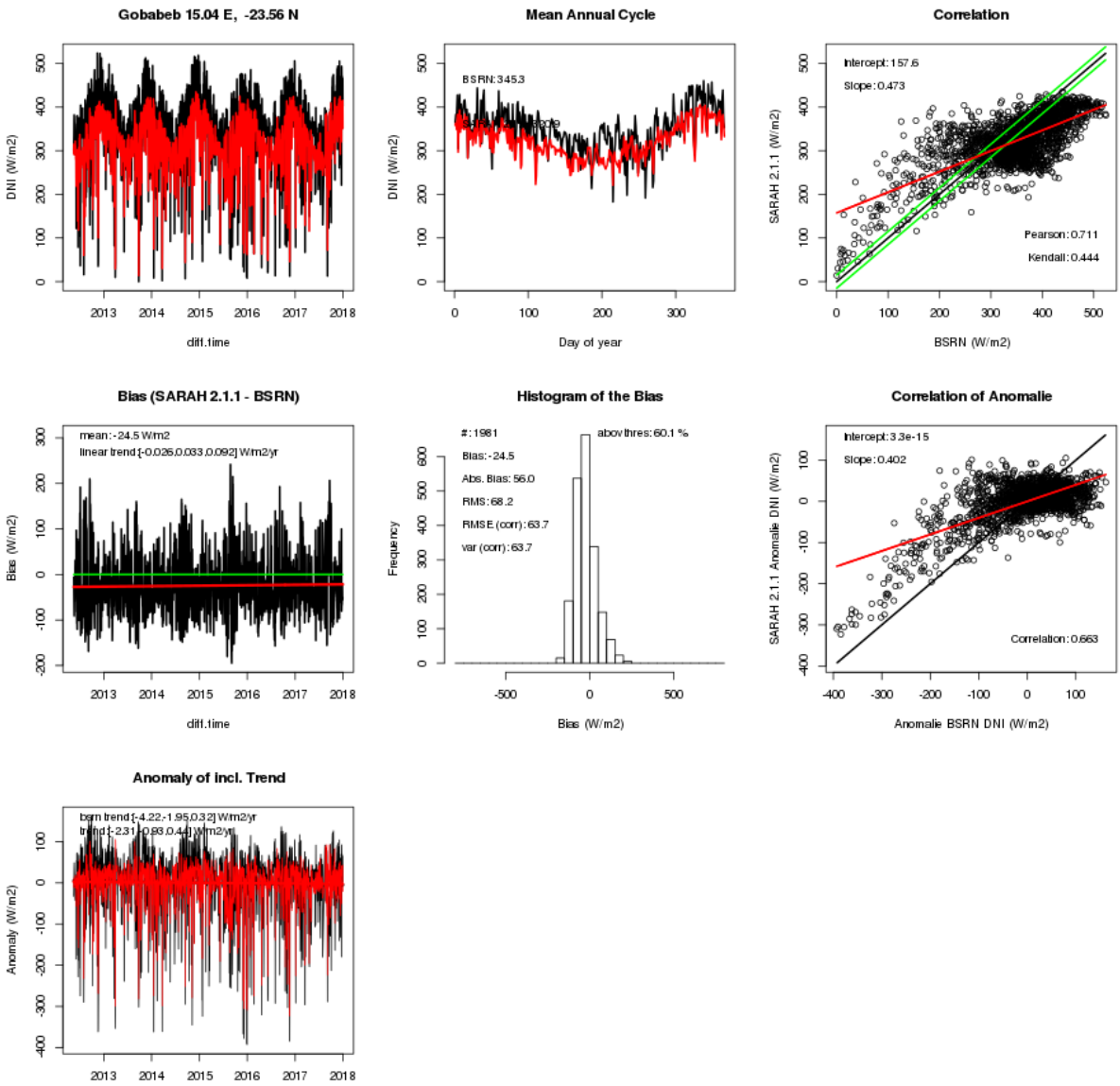
Gobabeb, SIS; daily mean



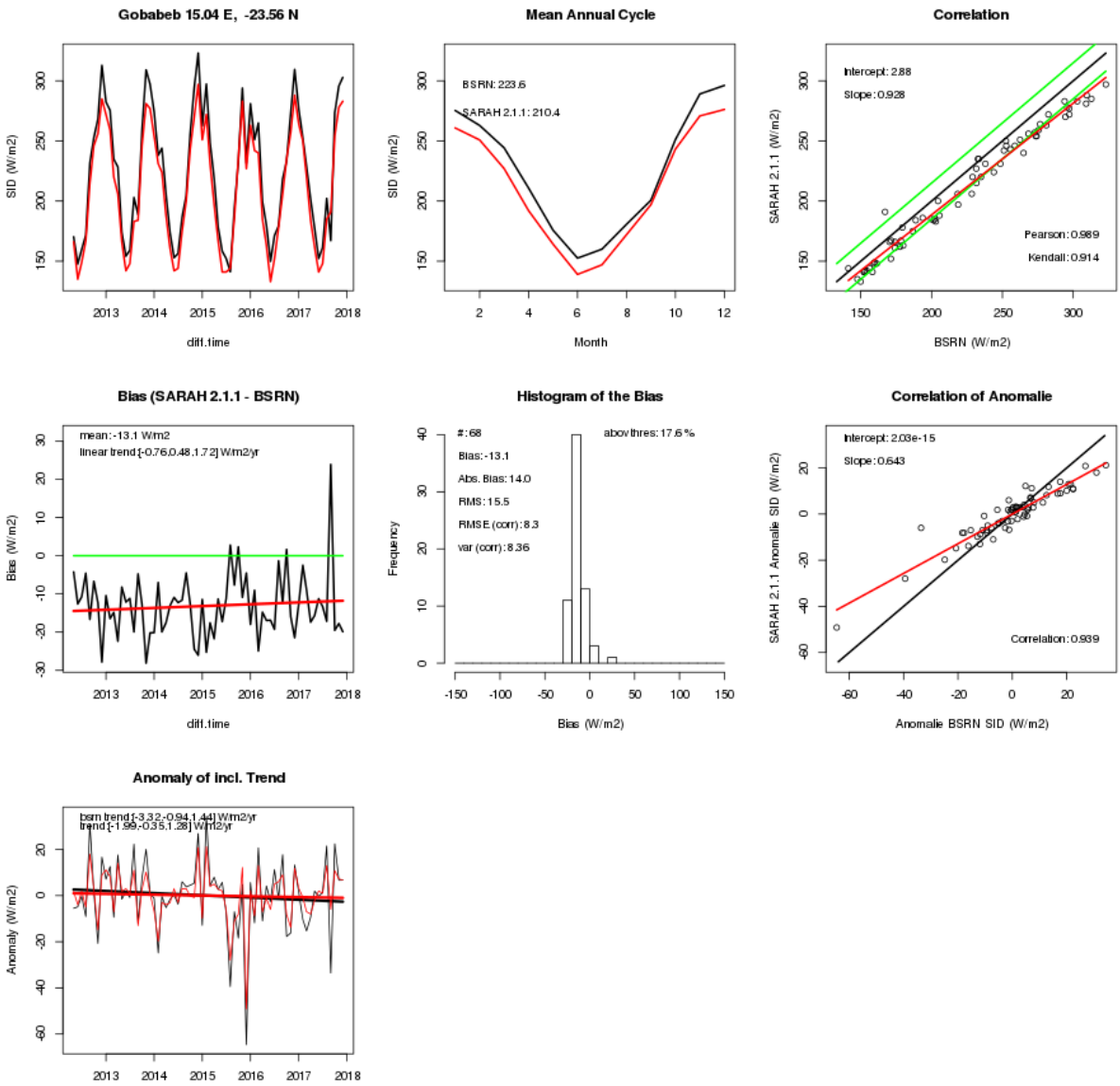
Gobabeb, DNI, monthly mean



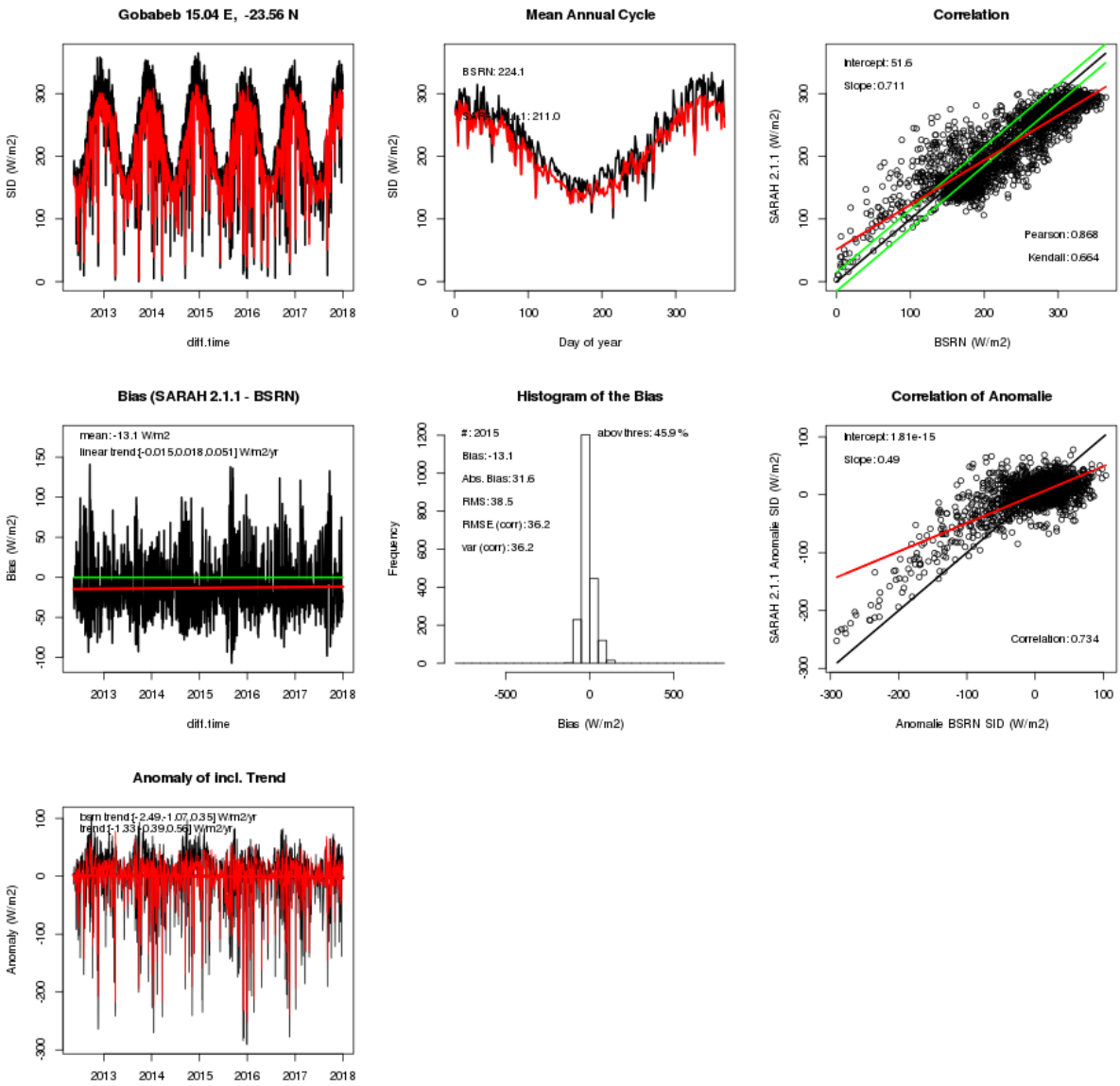
Gobabeb, DNI, daily mean



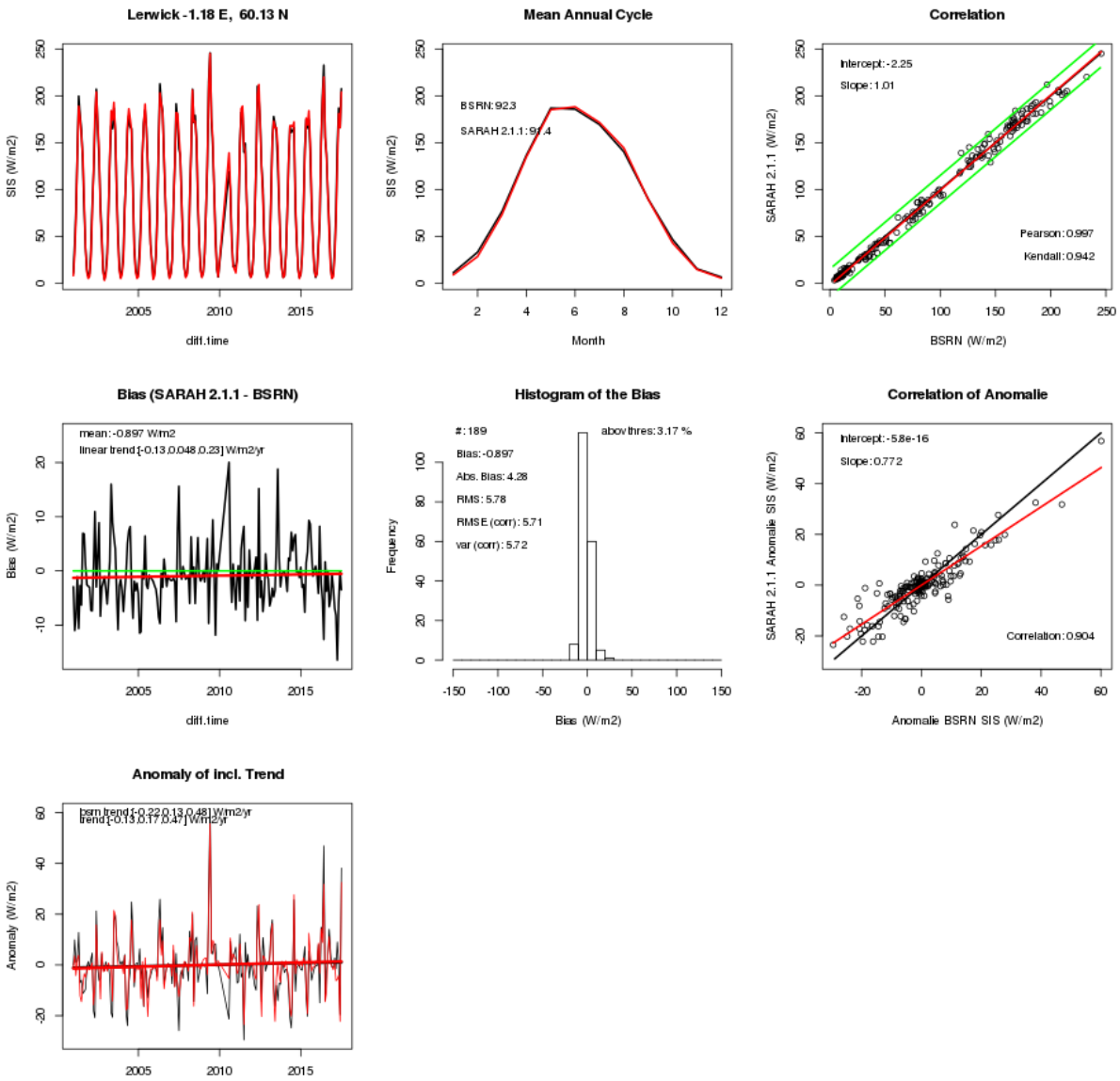
Gobabeb, SID, monthly mean



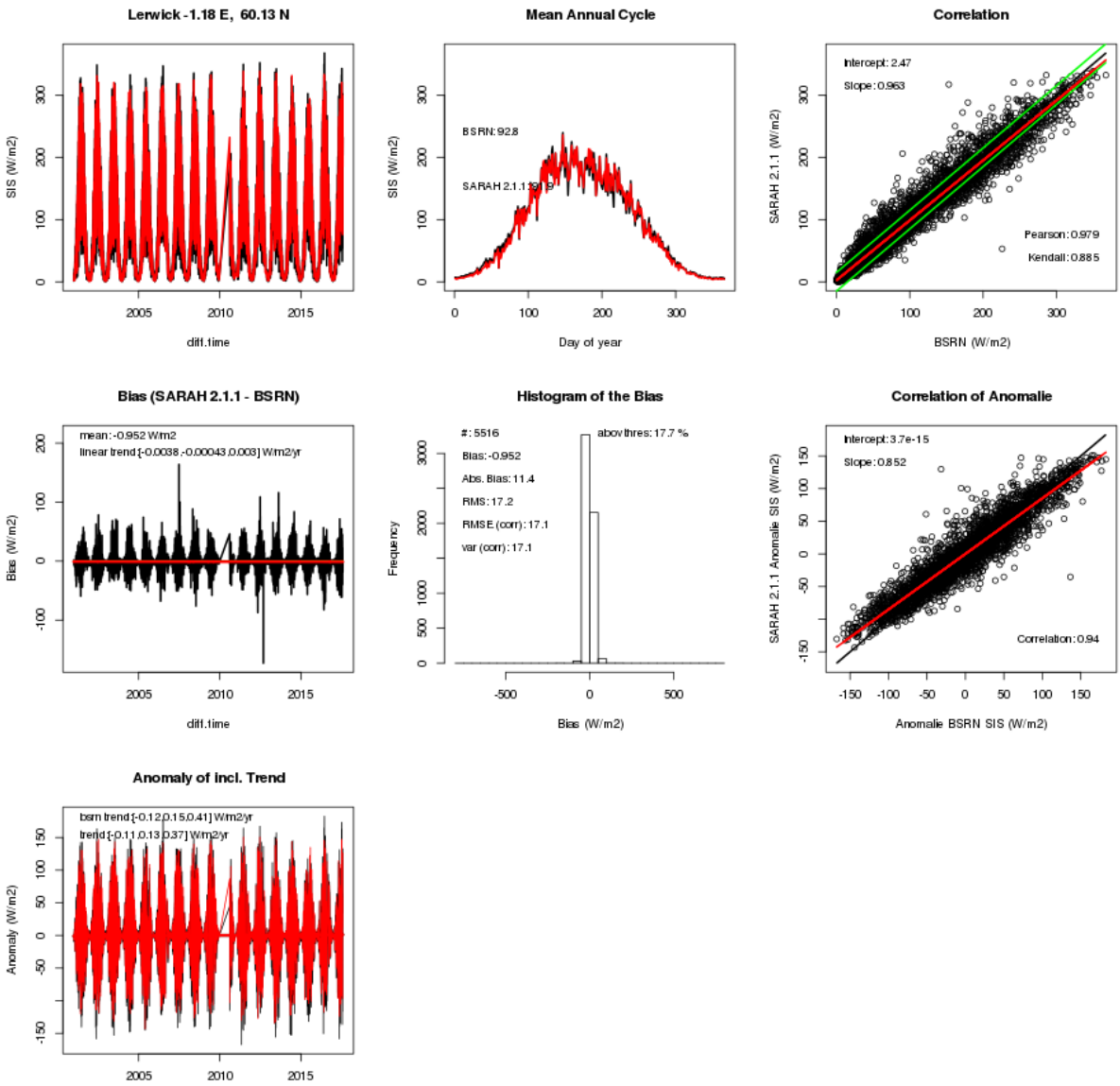
Gobabeb, SID, daily mean



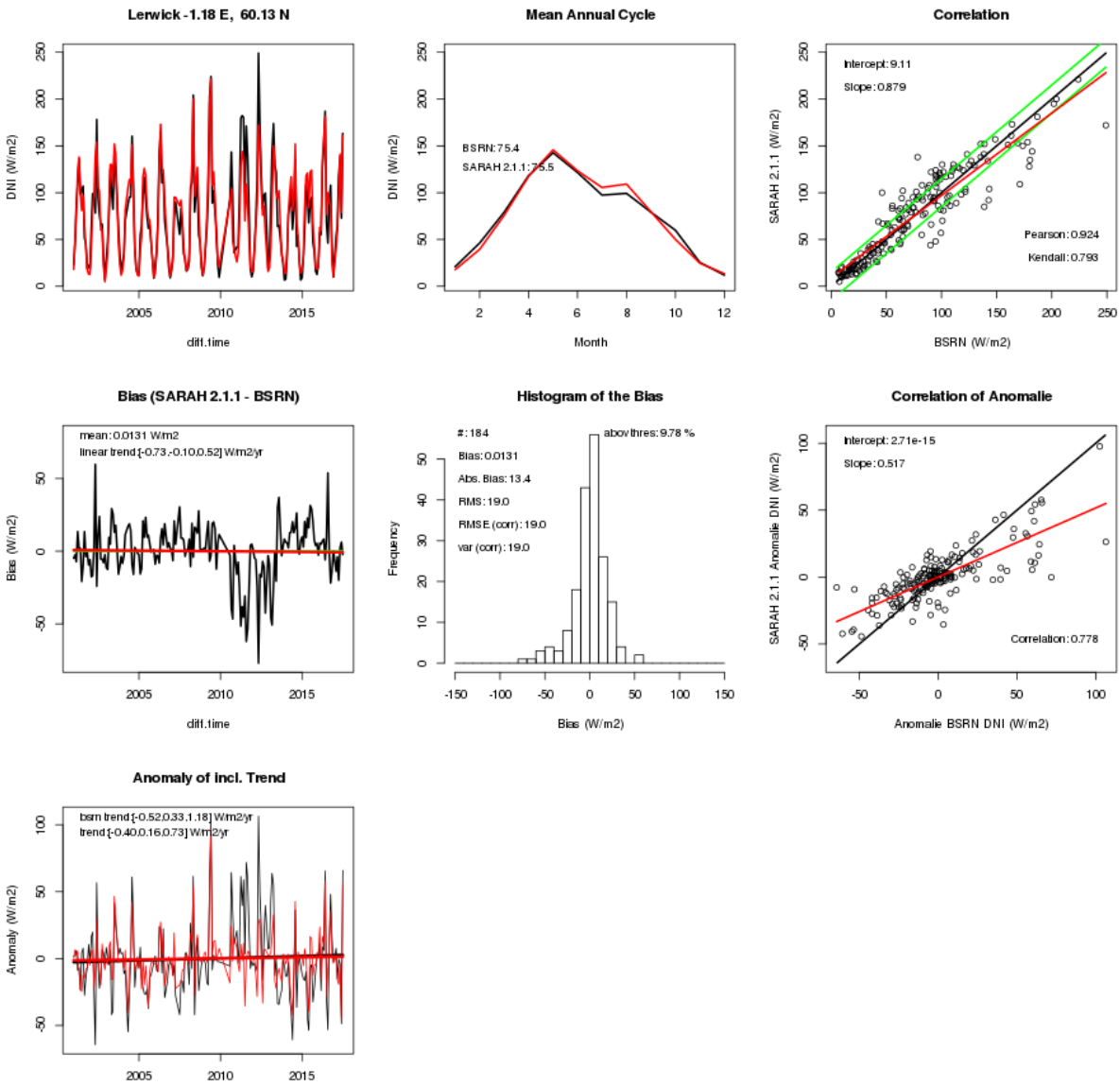
Lerwick, SIS; monthly mean



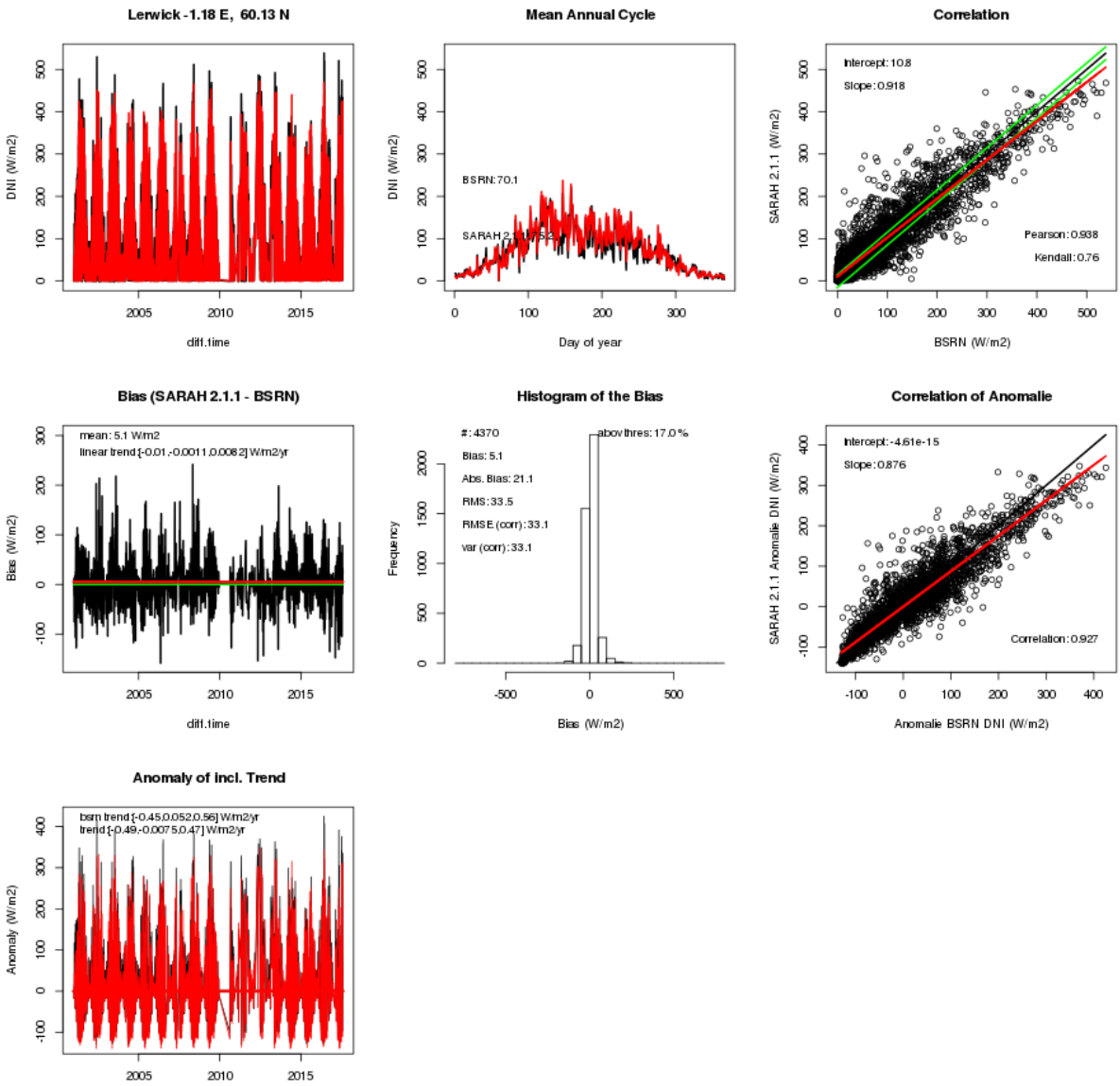
Lerwick, SIS; daily mean



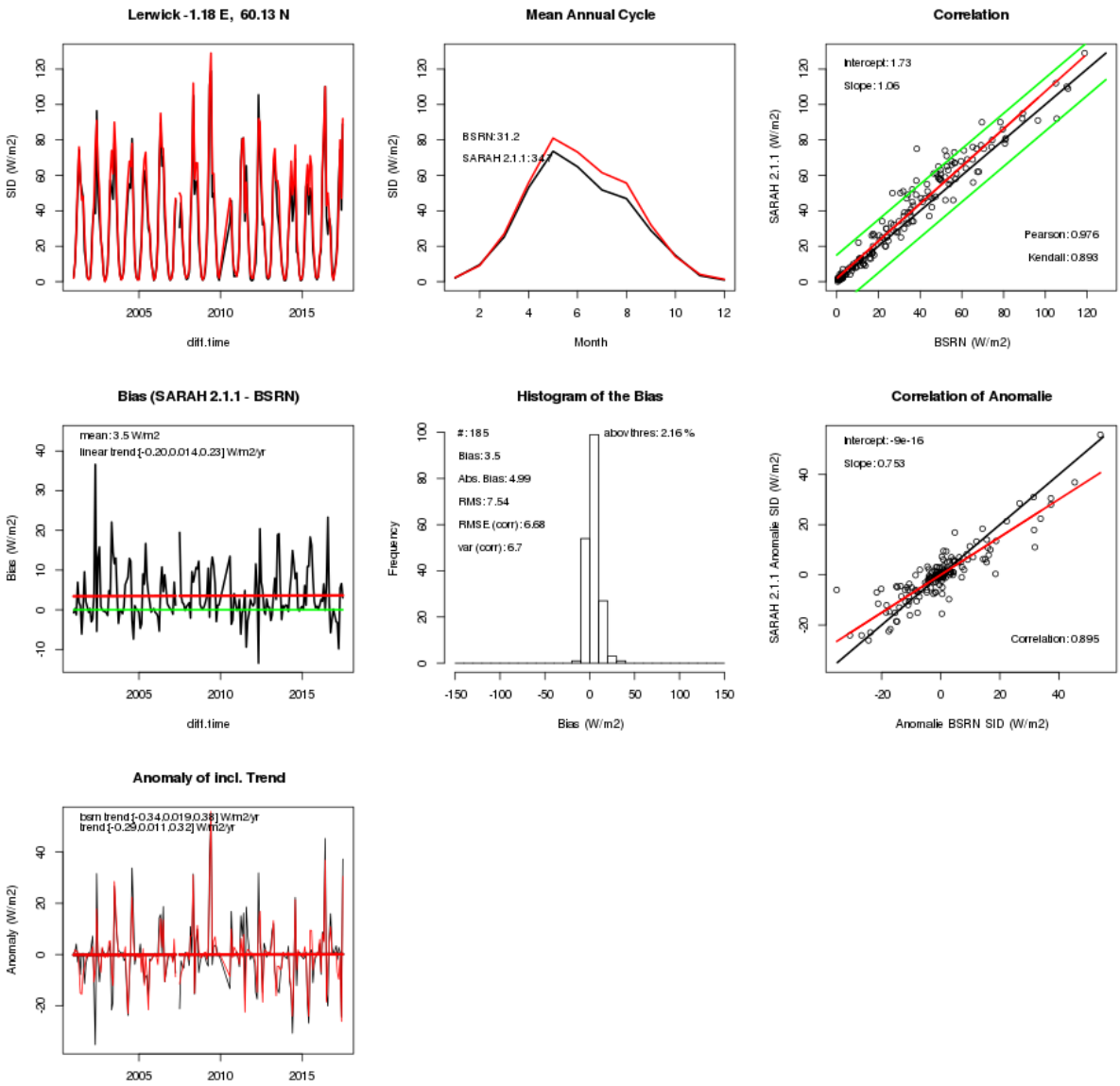
Lerwick, DNI, monthly mean



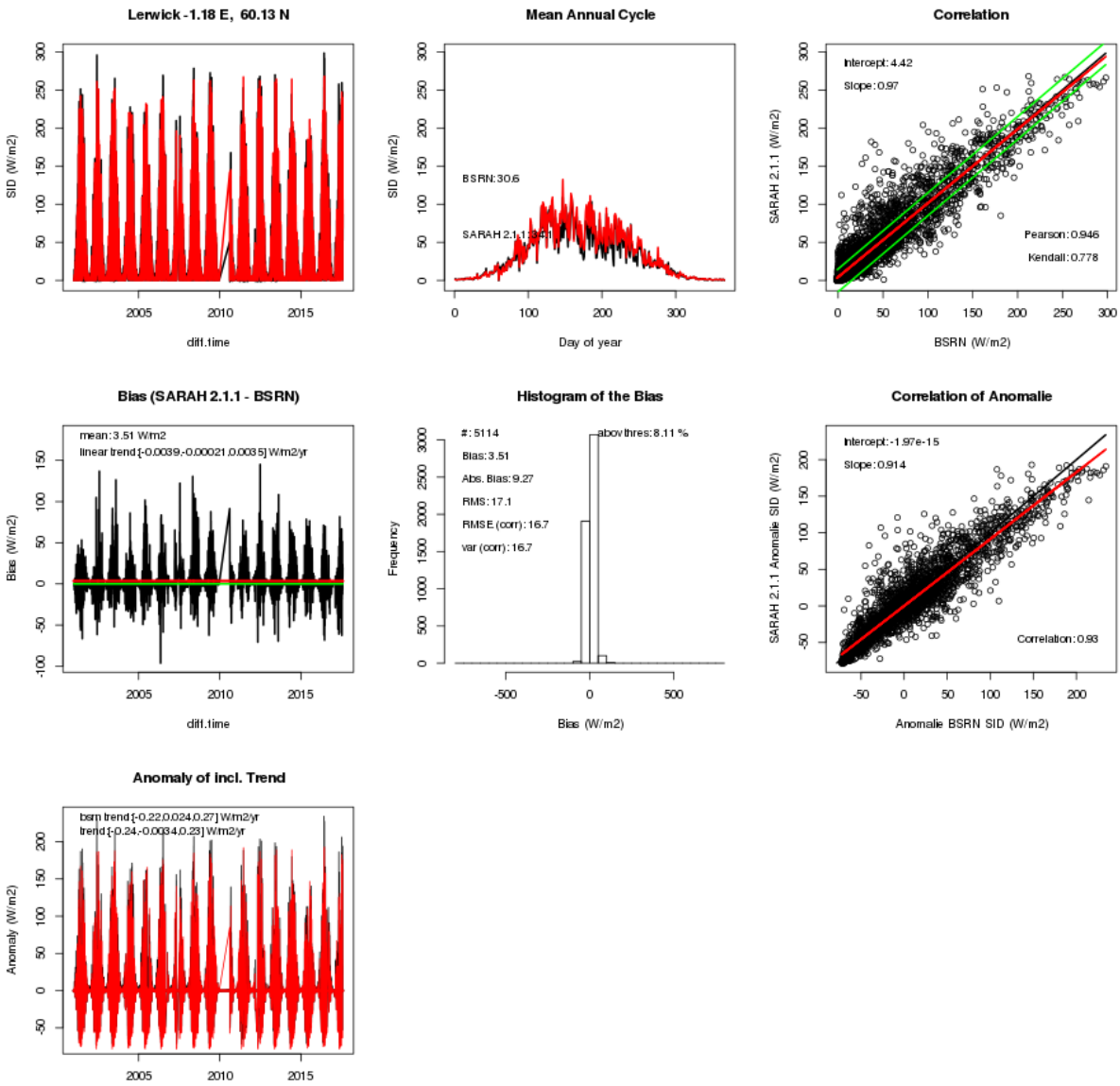
Lerwick, DNI, daily mean



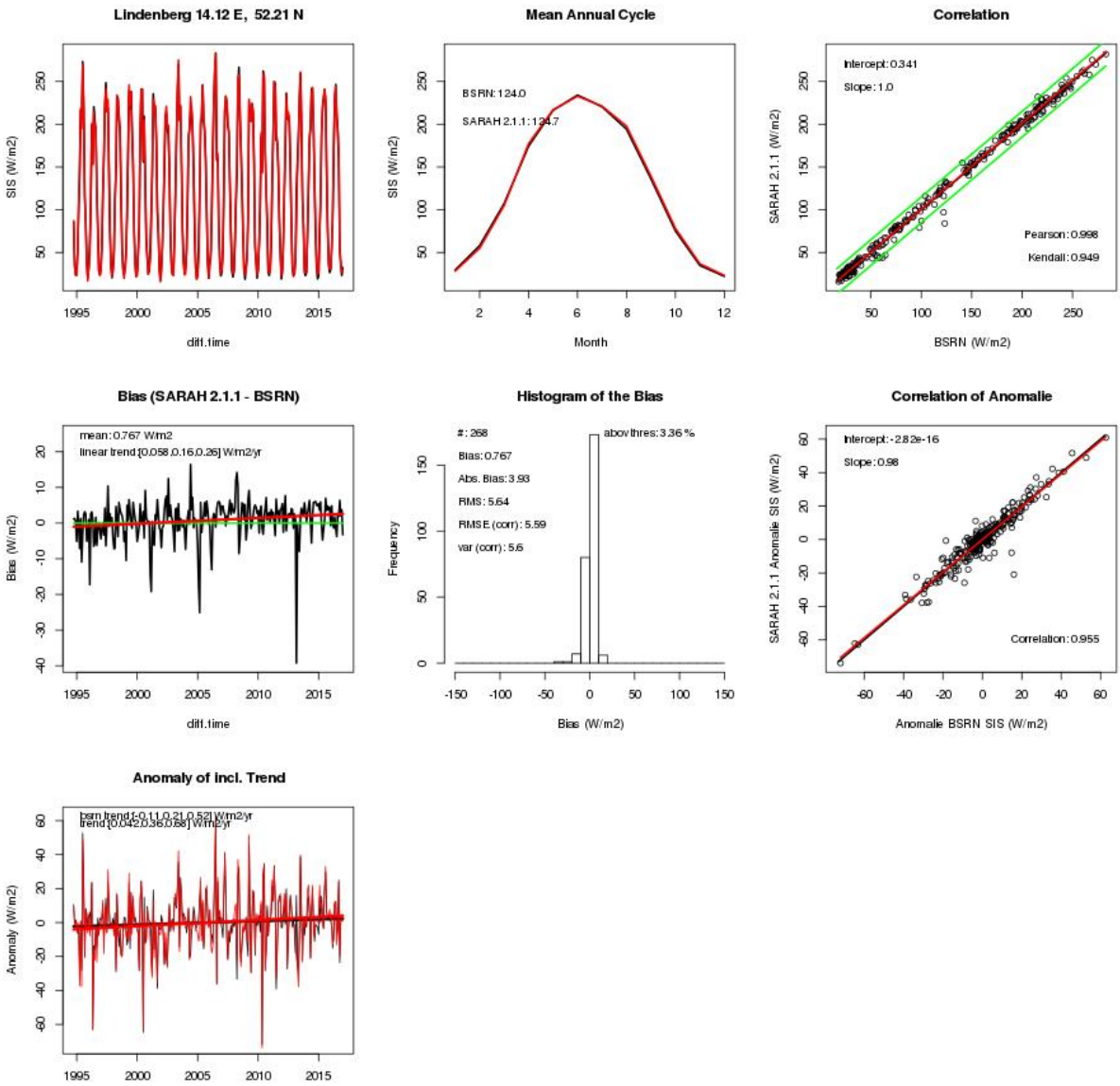
Lerwick, SID, monthly mean



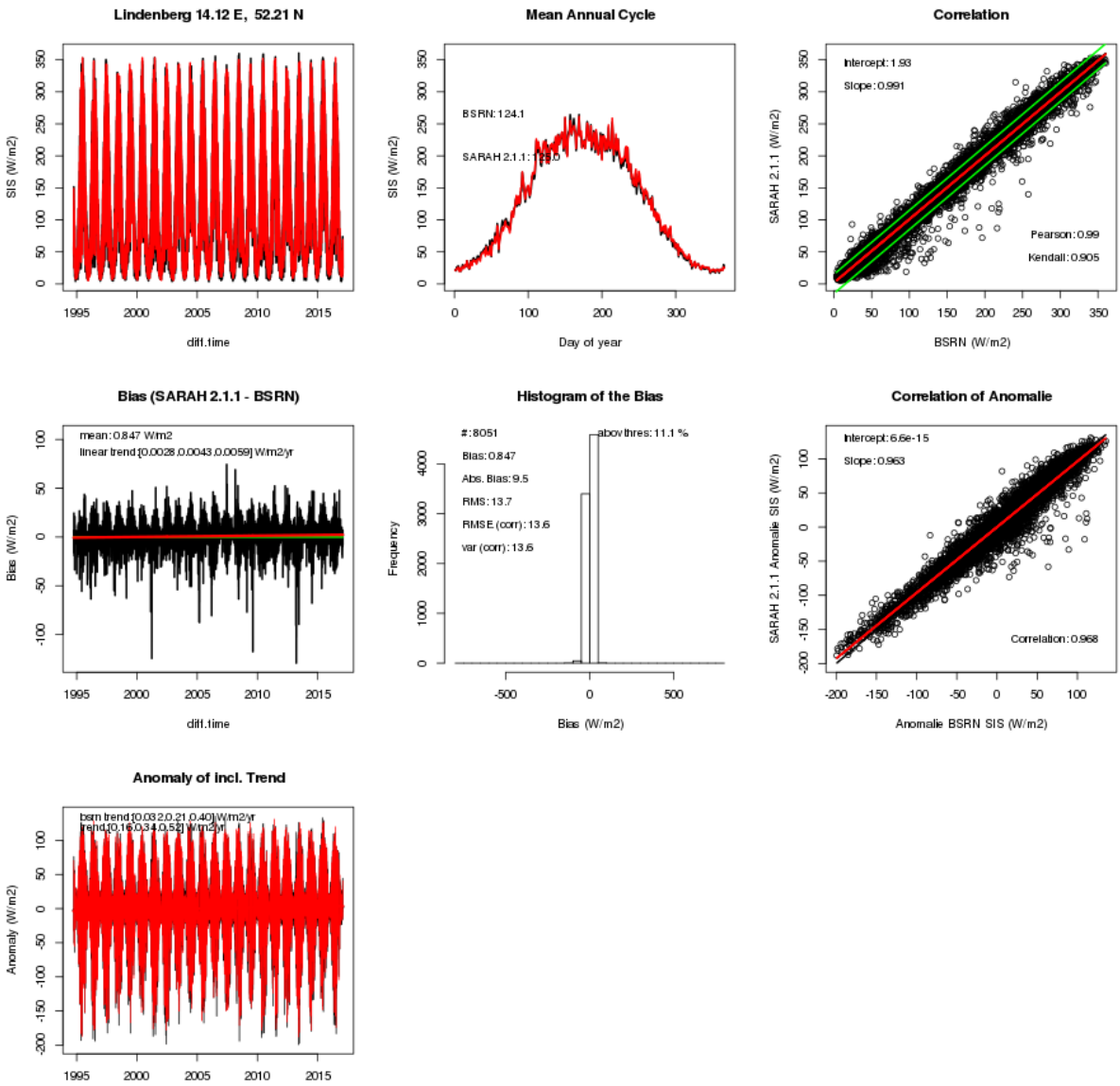
Lerwick, SID, daily mean



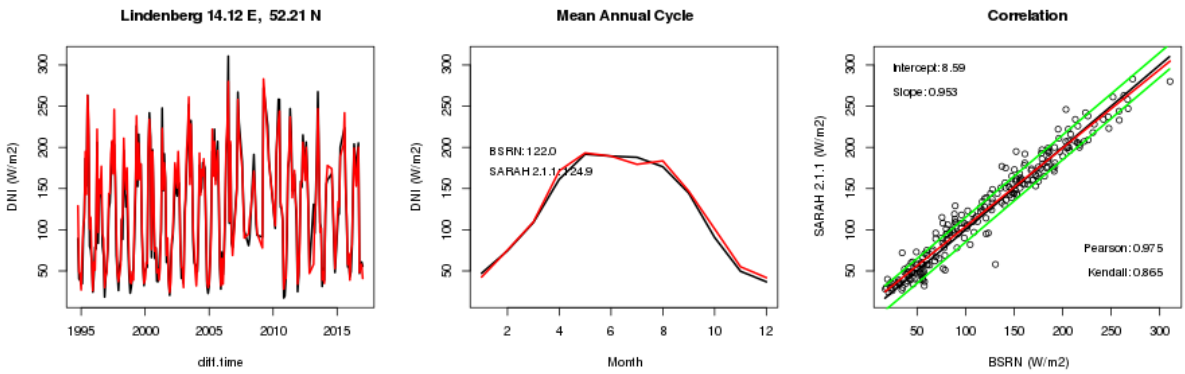
Lindenberg, SIS; monthly mean

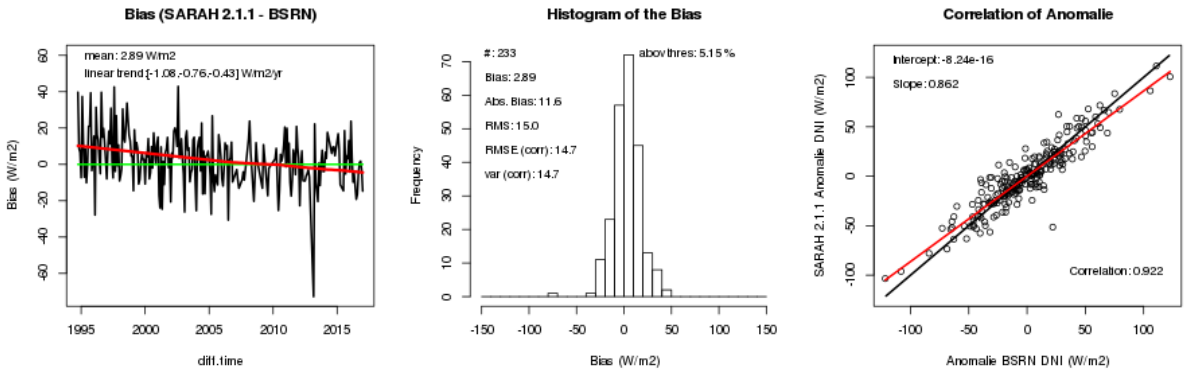


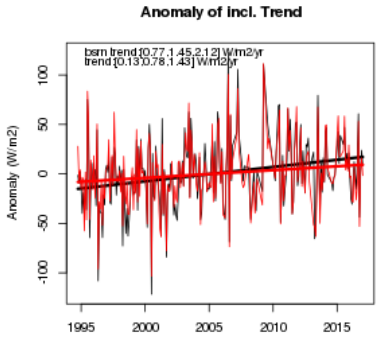
Lindenberg, SIS, daily mean



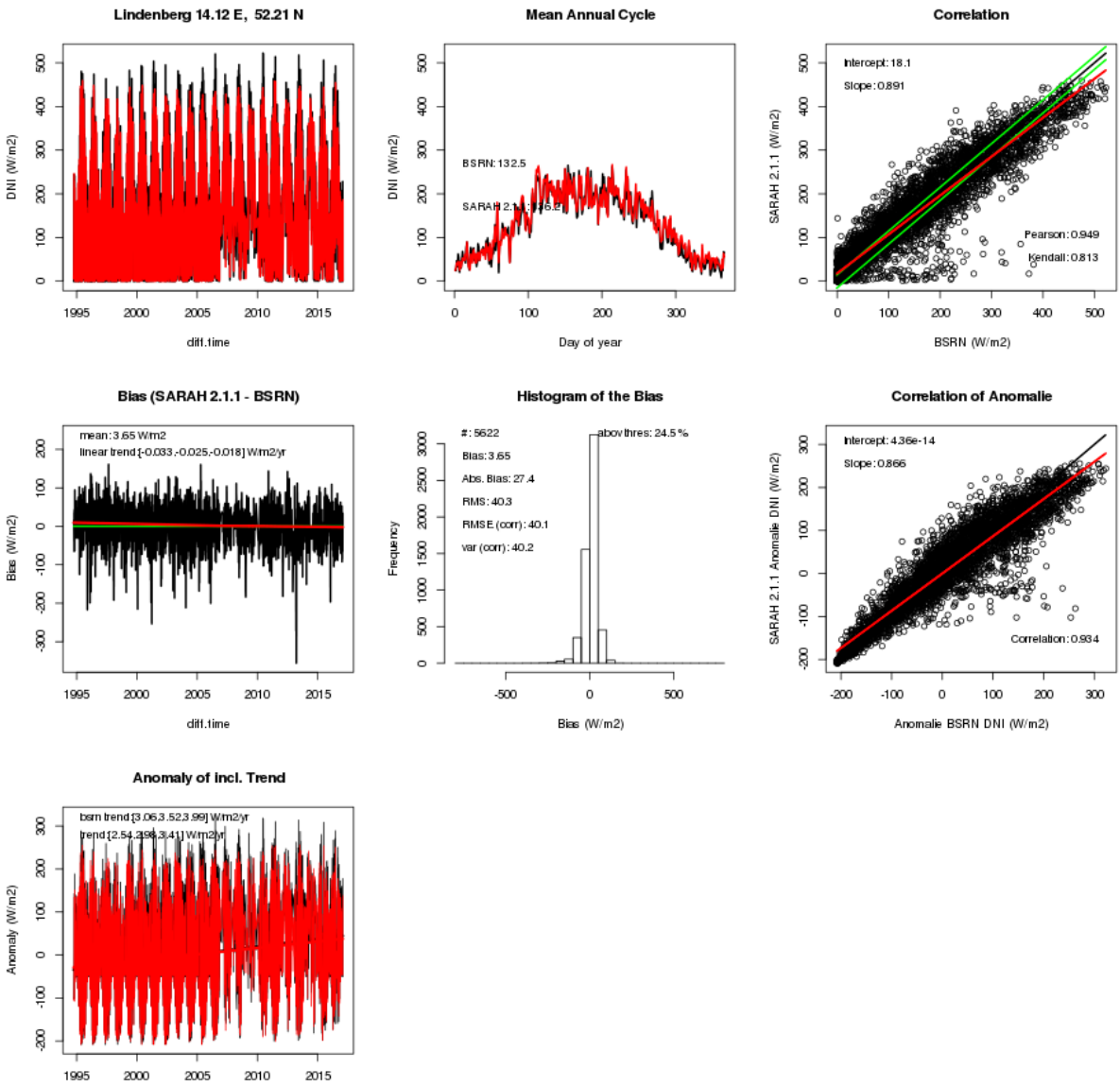
Lindenberg, DNI, monthly mean



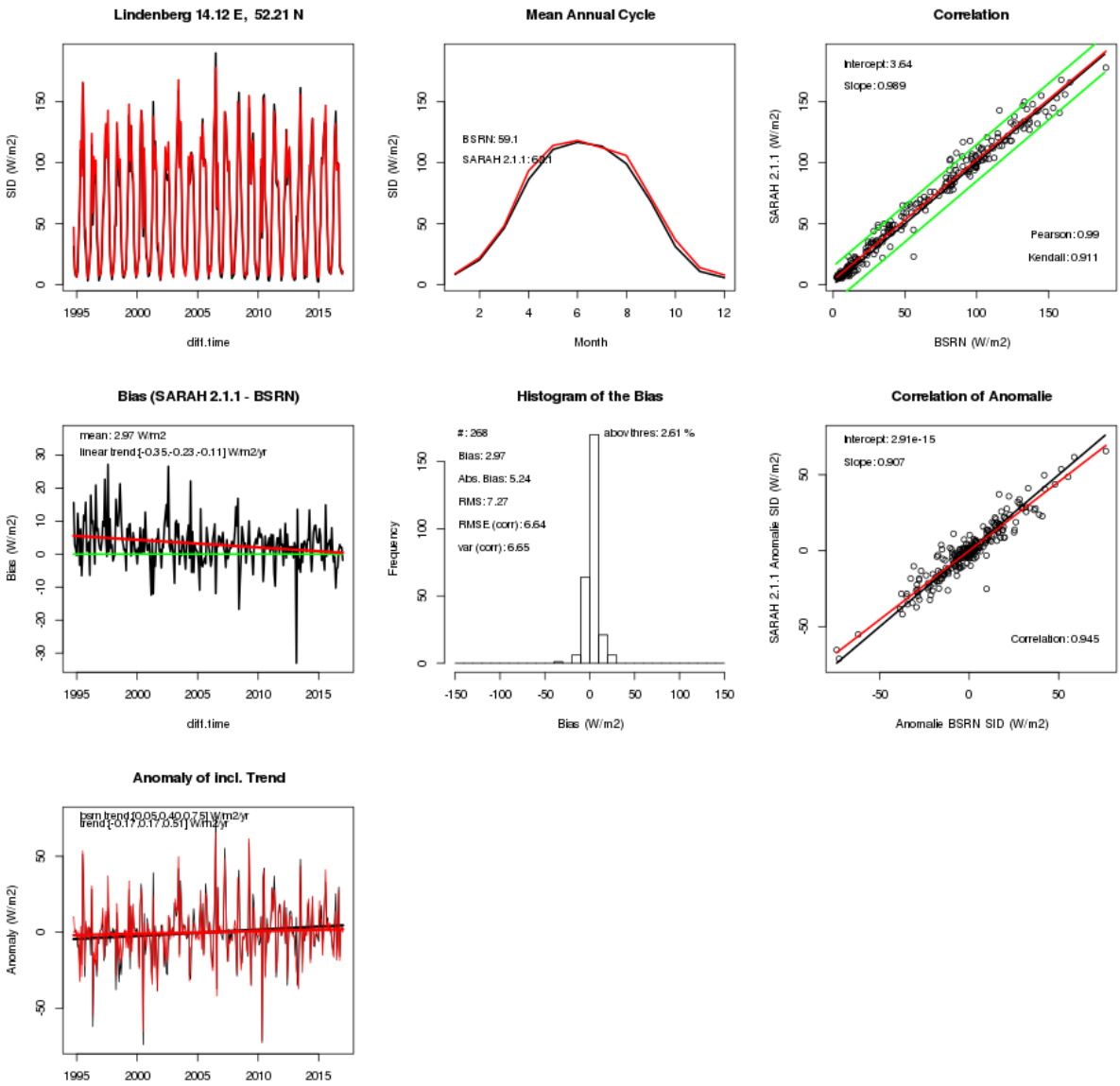




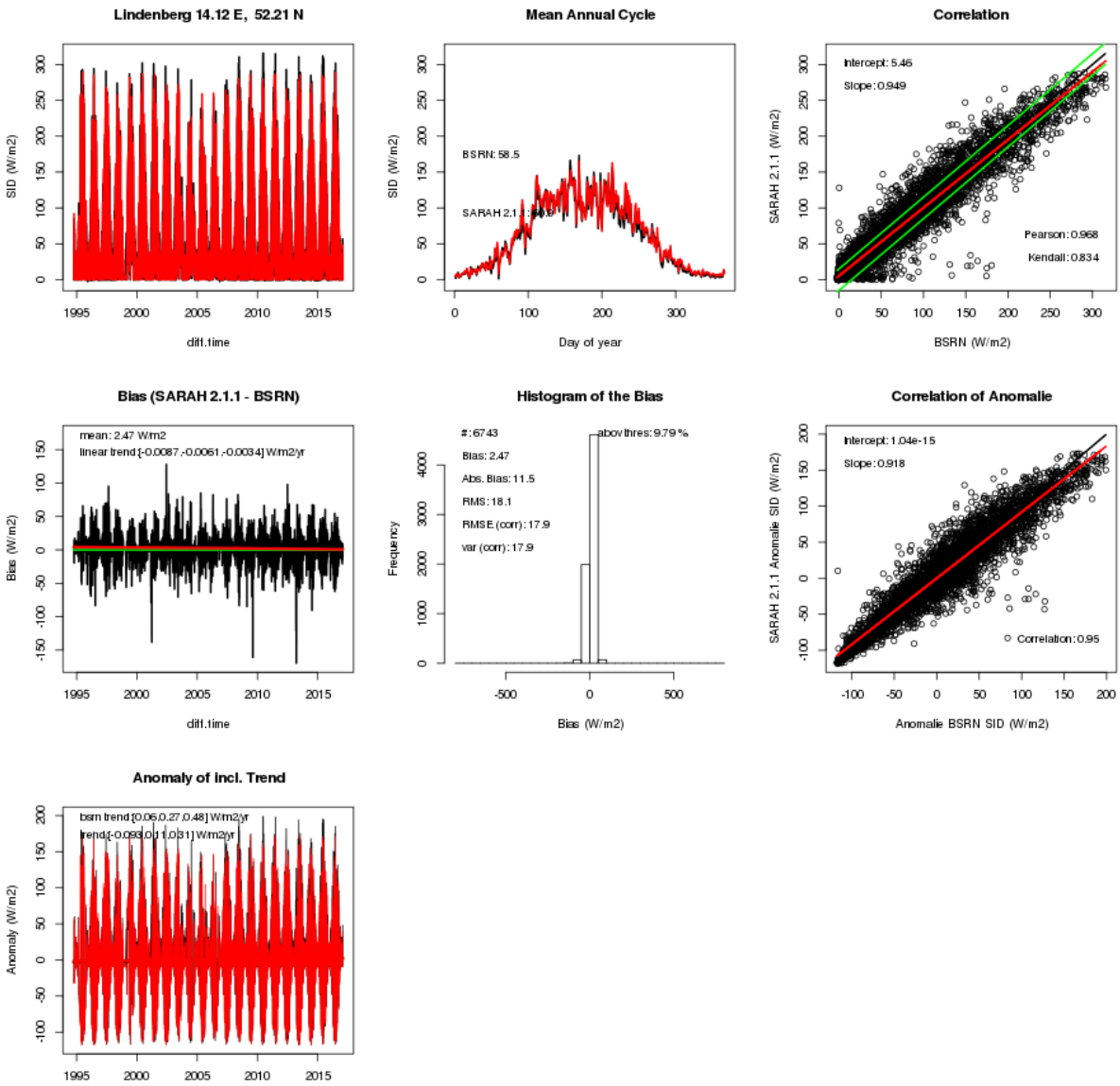
Lindenberg, DNI, daily mean



Lindenberg, SID, monthly mean



Lindenberg, SID, daily mean



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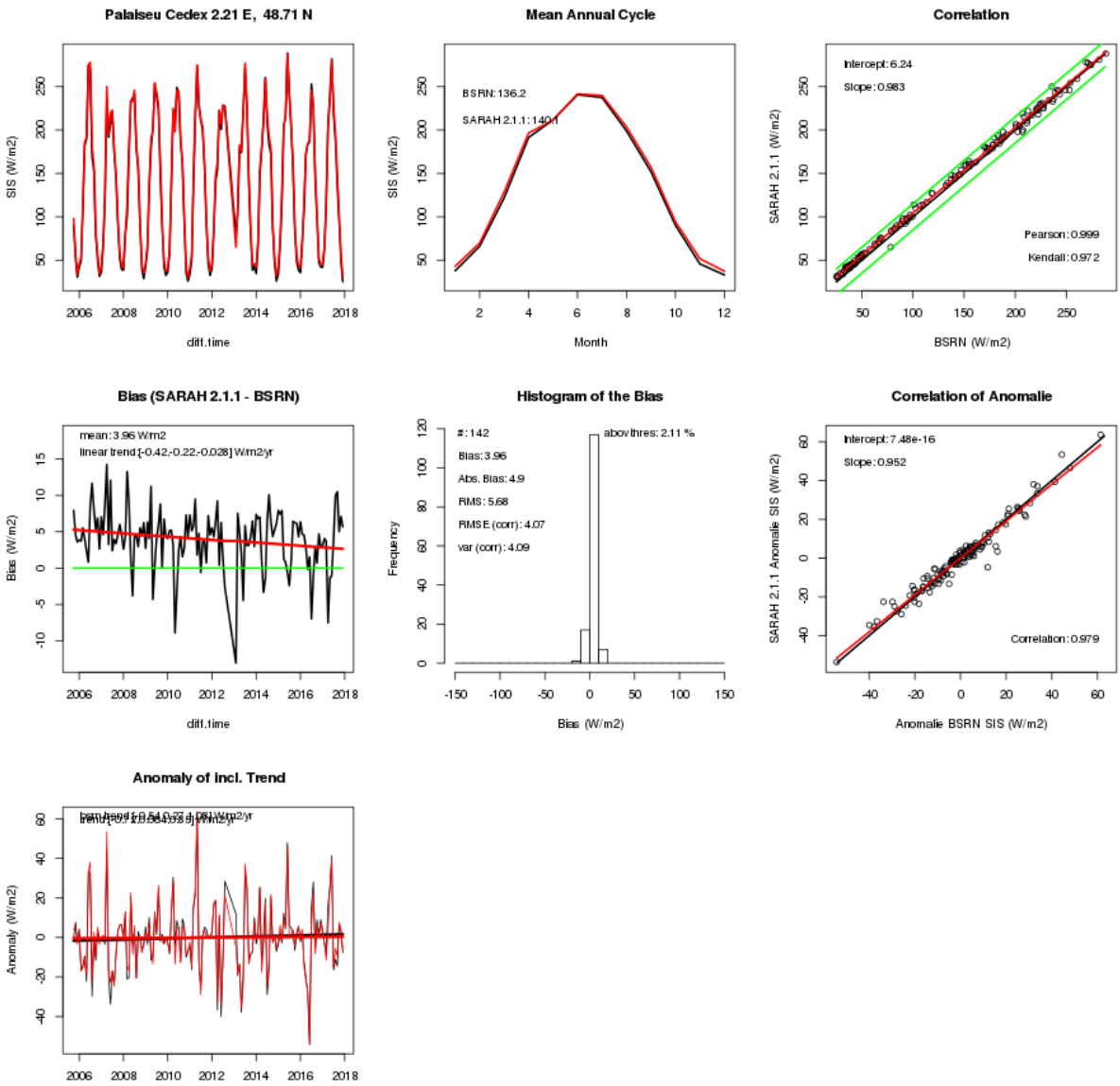

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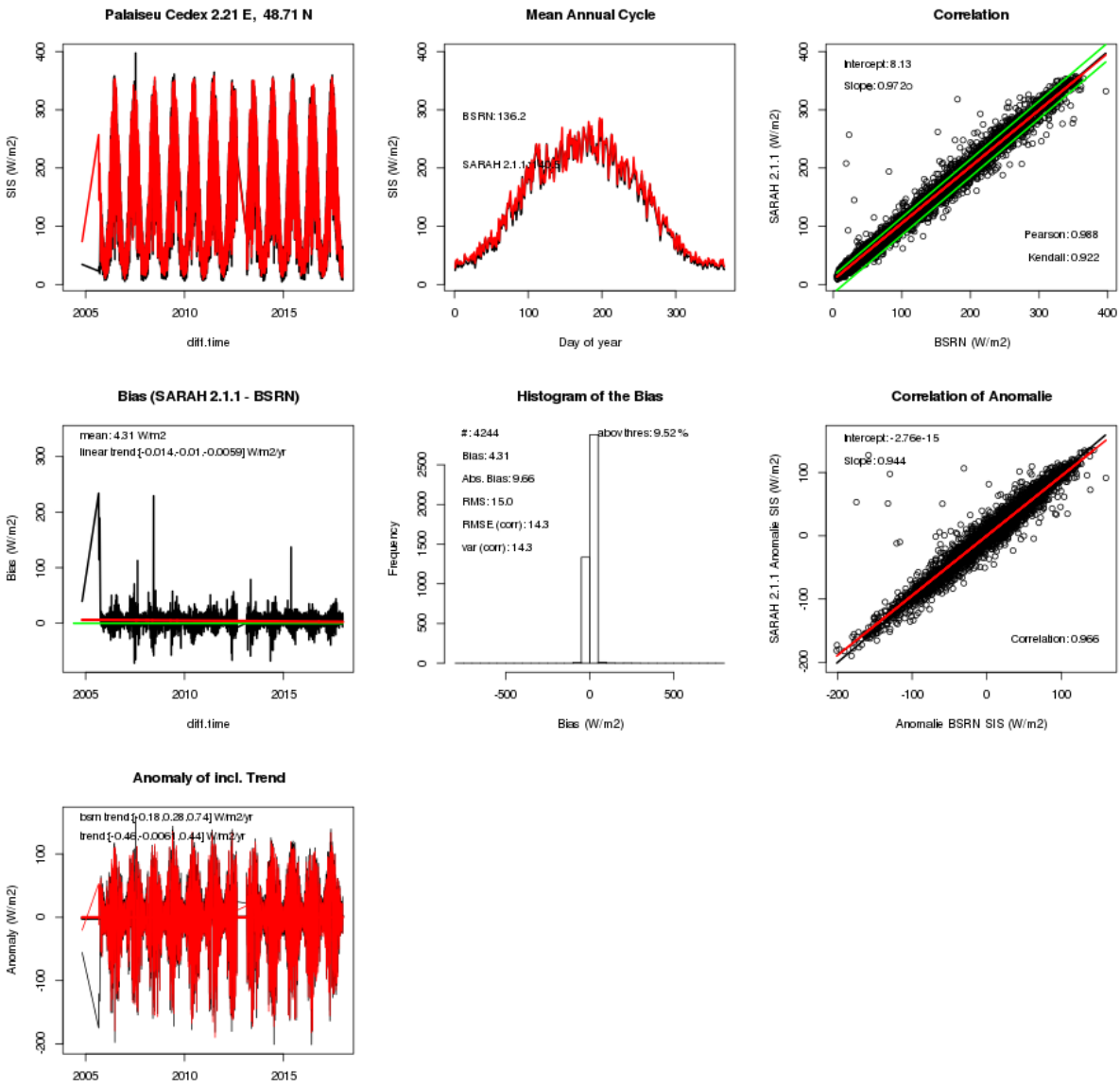

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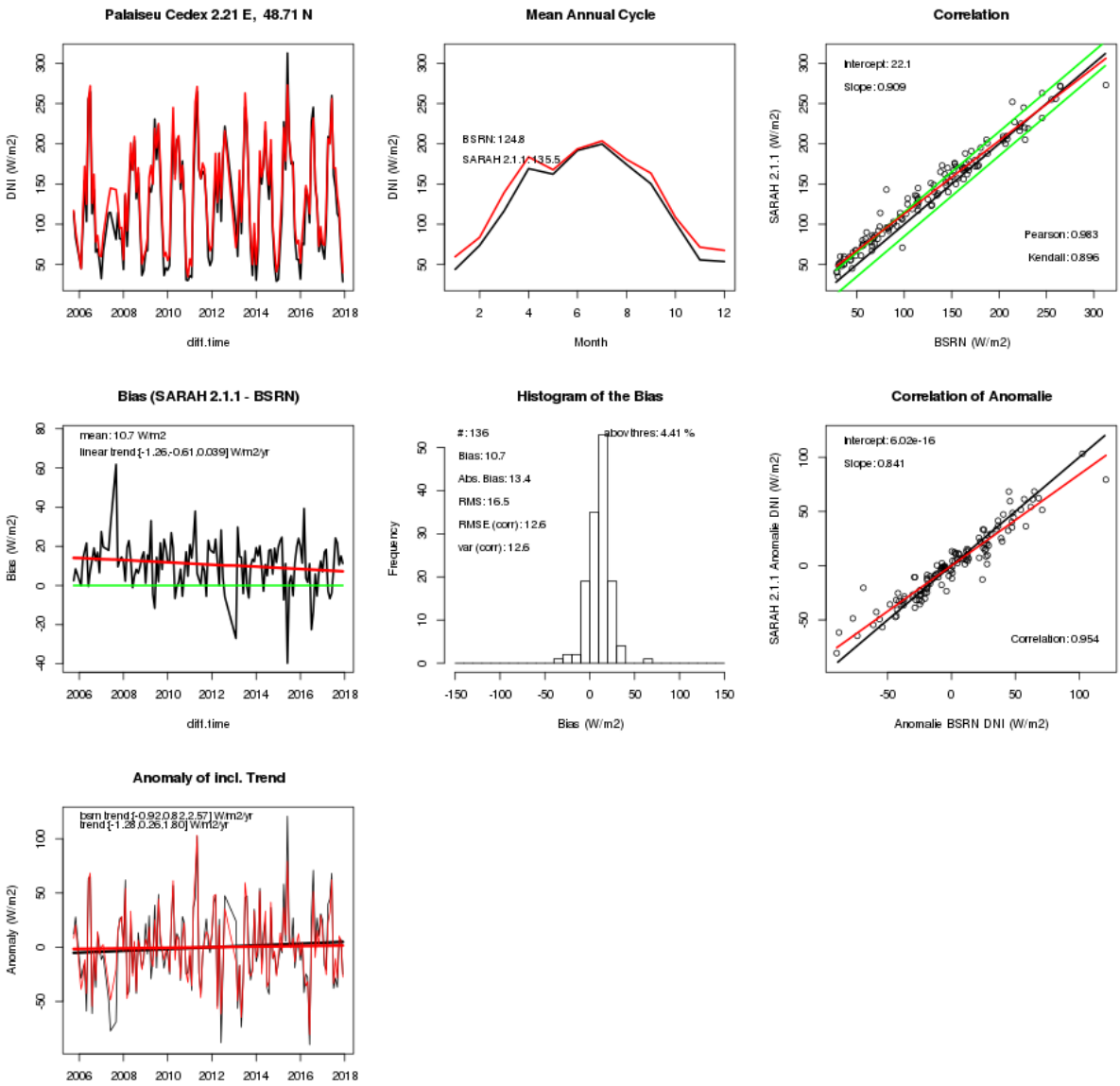

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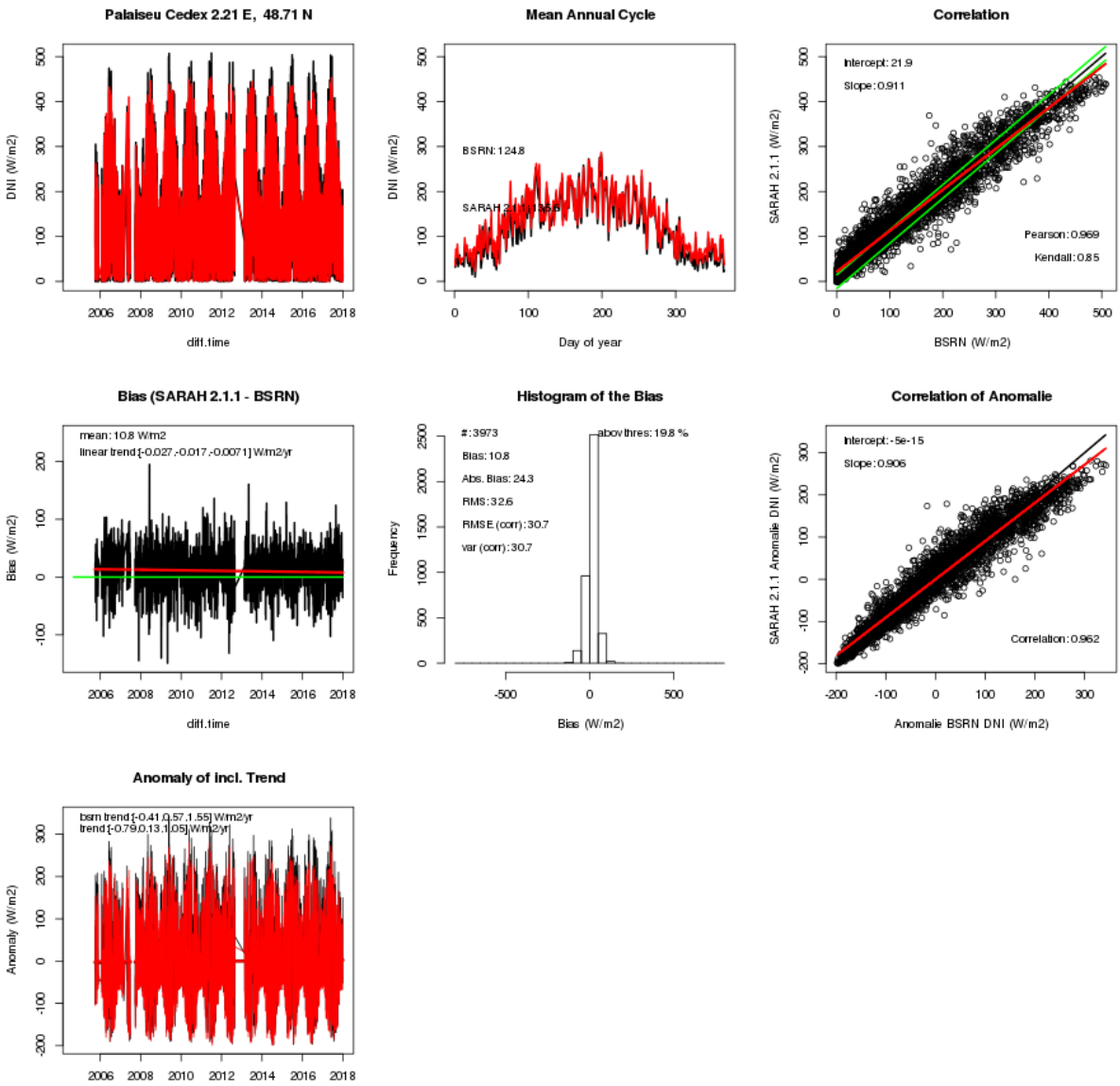

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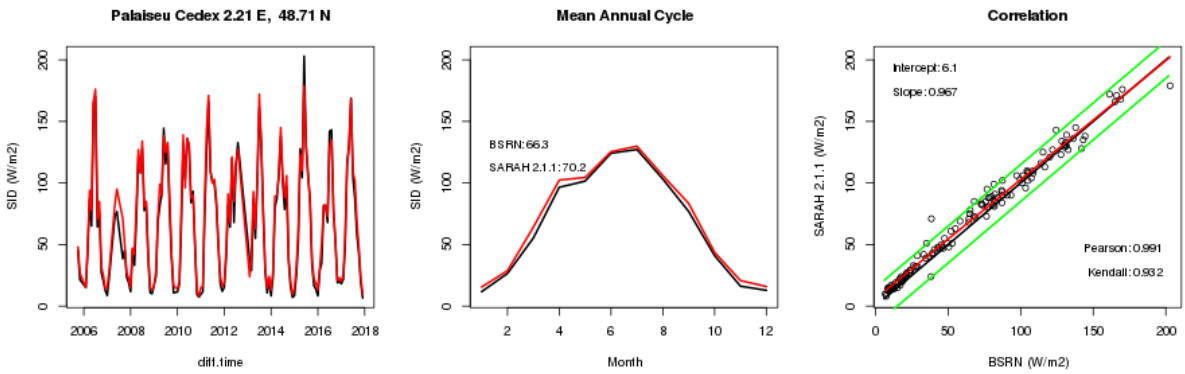

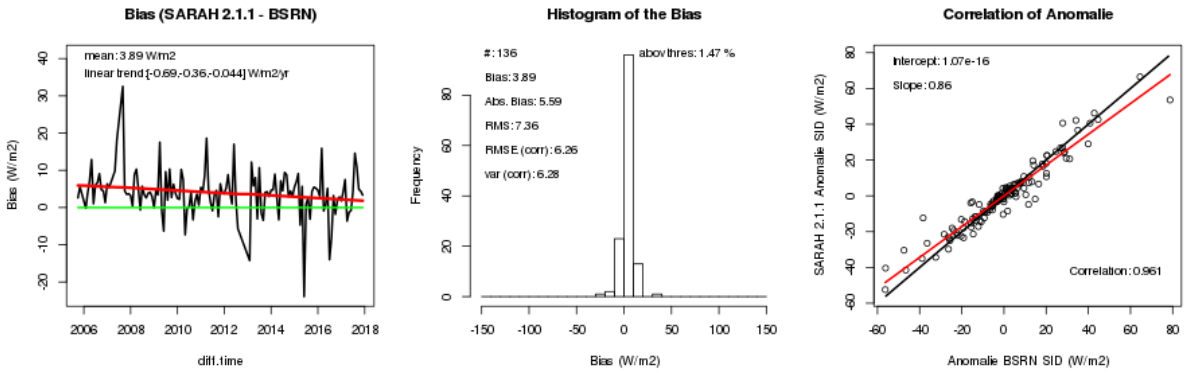

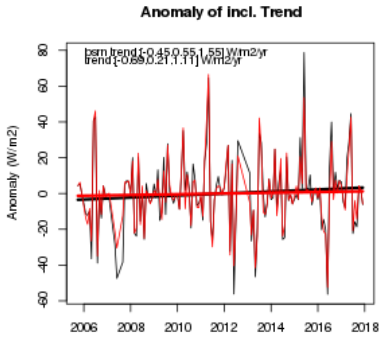

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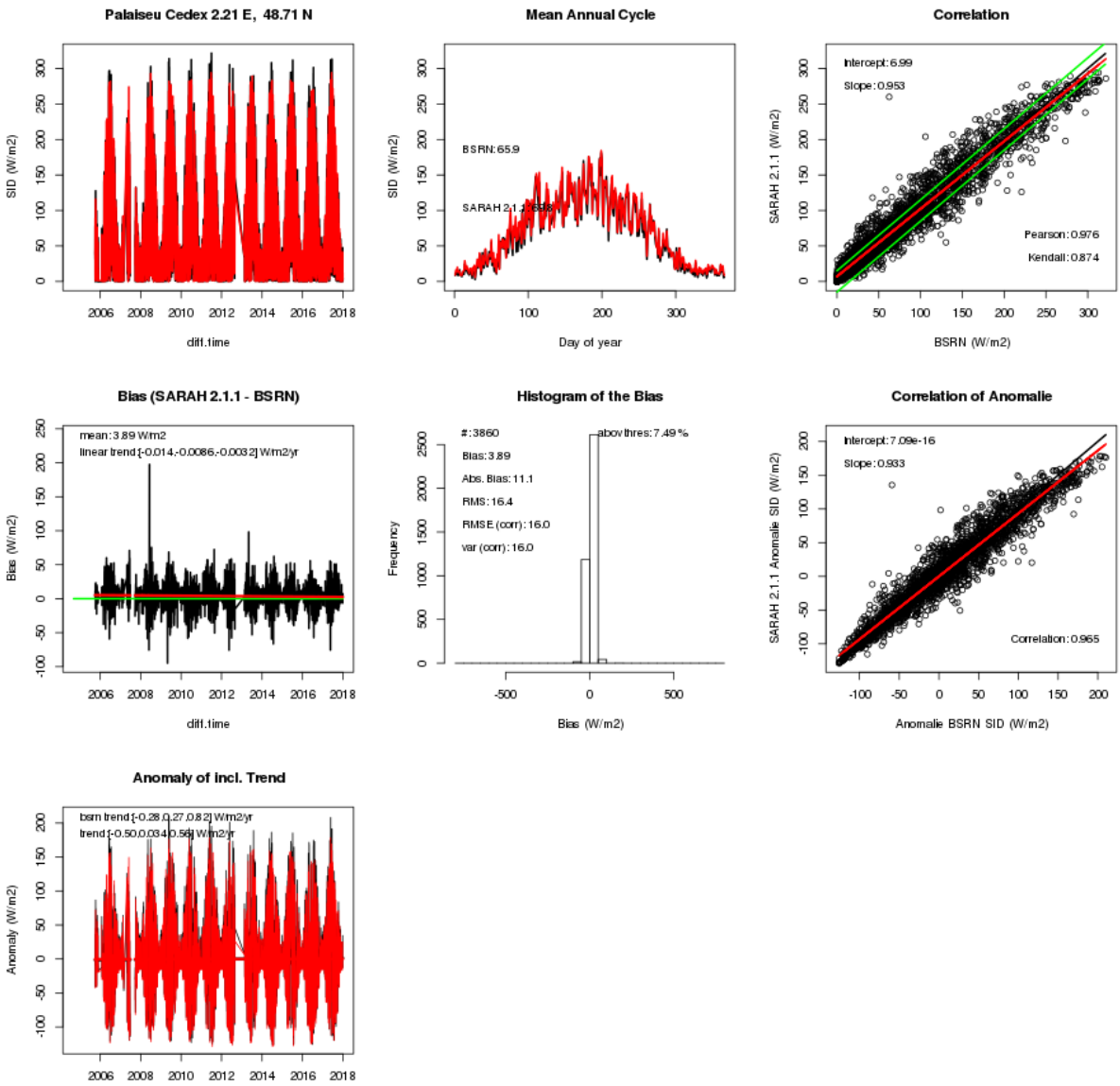

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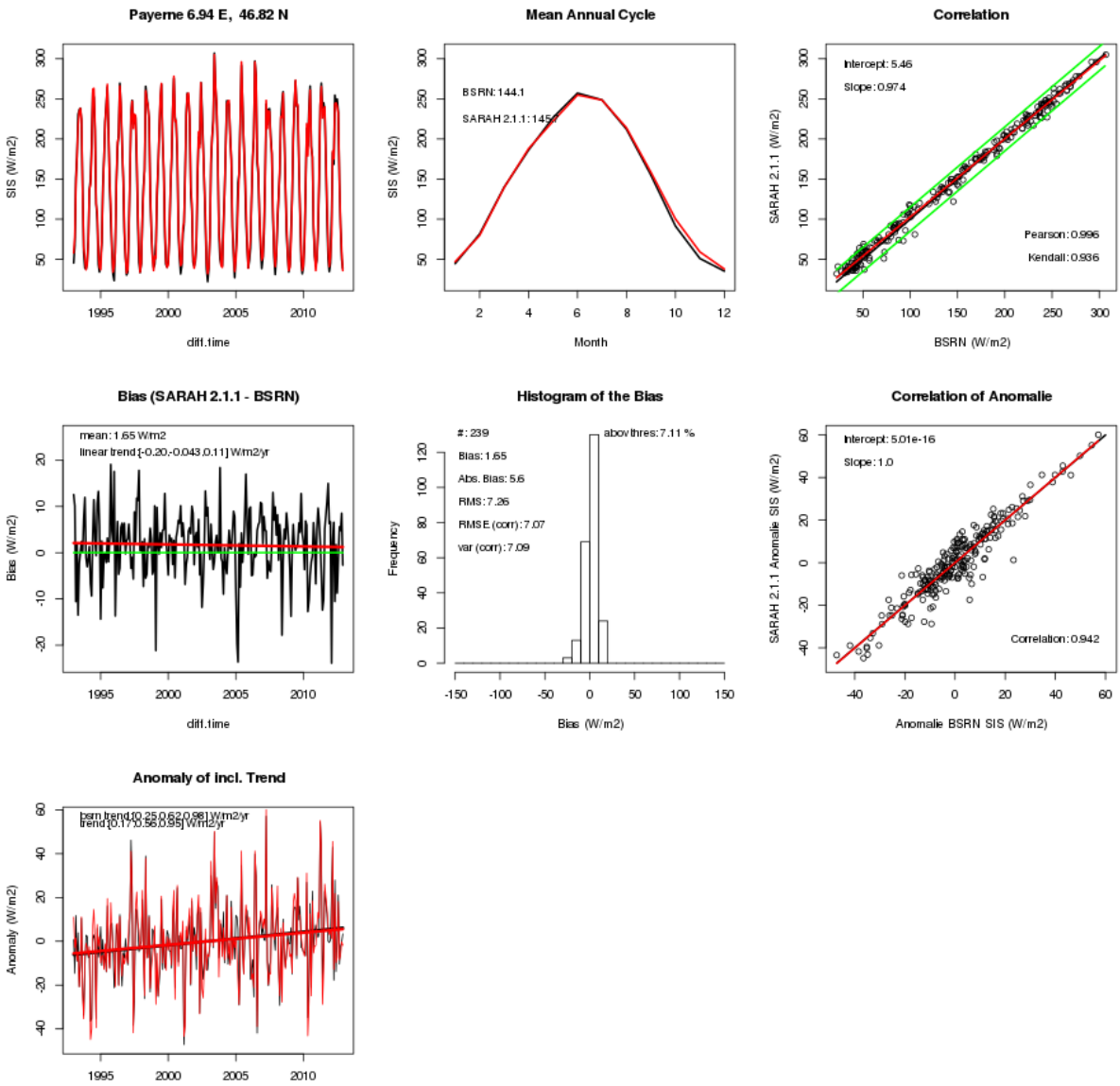

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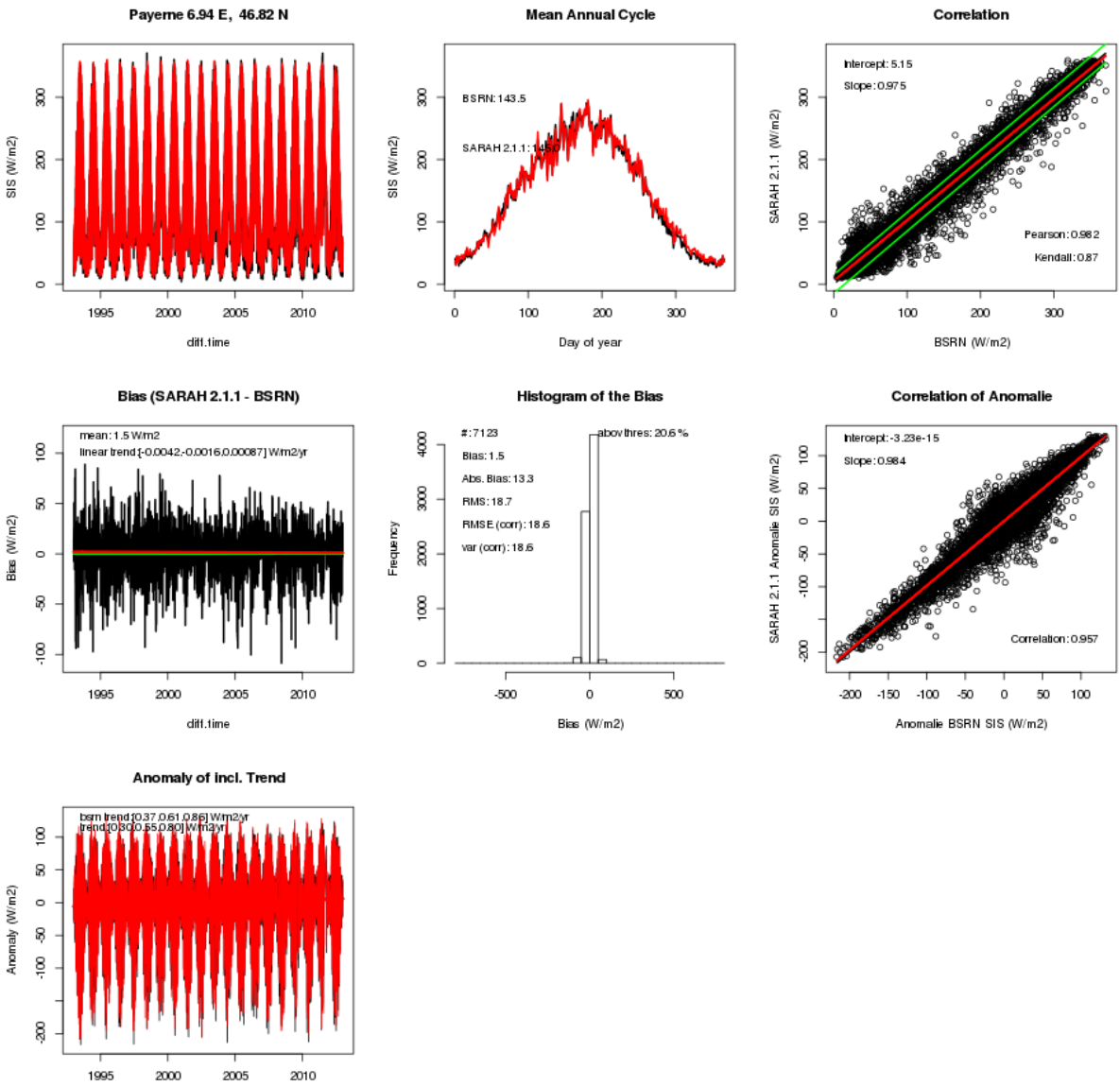

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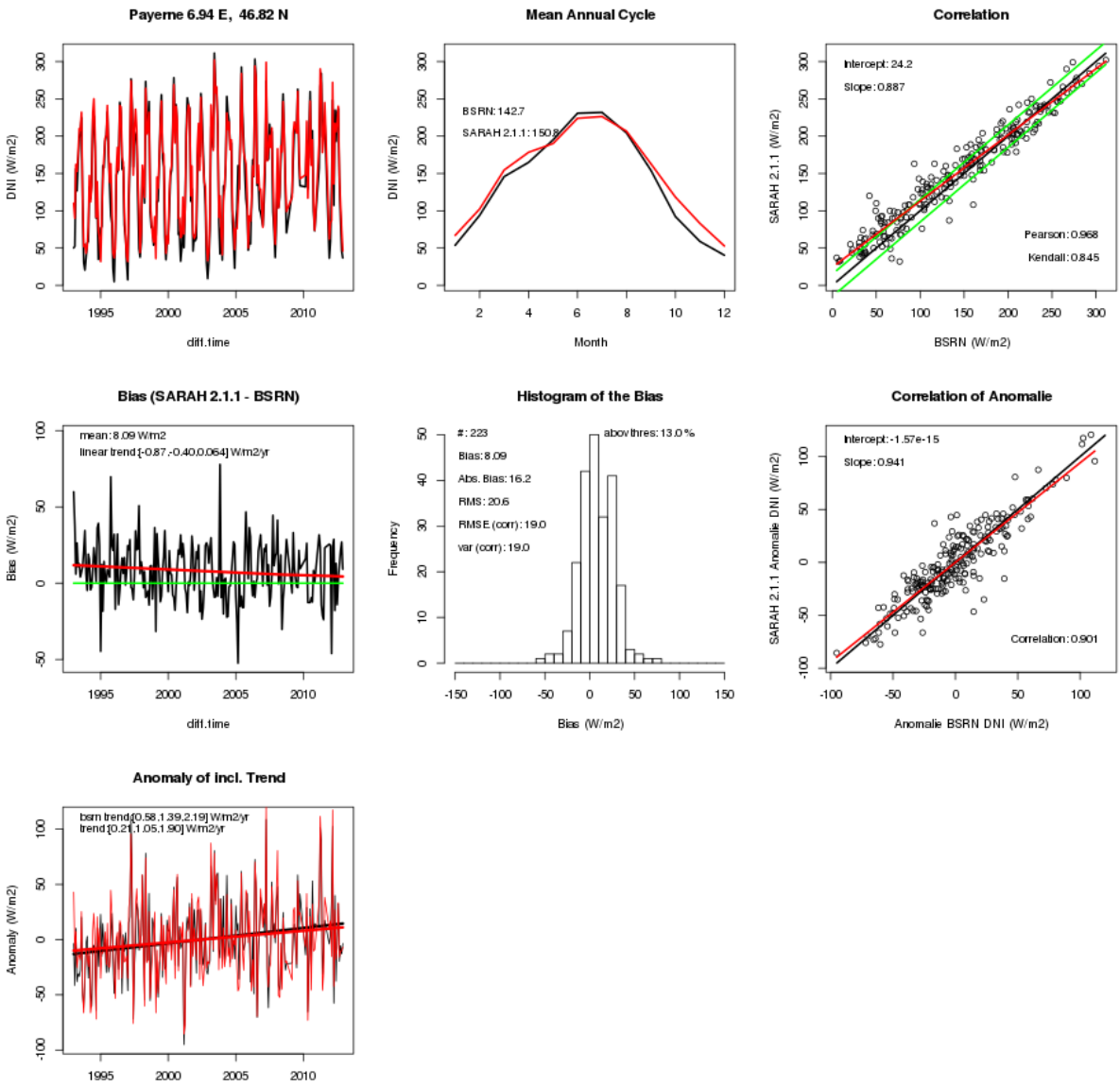

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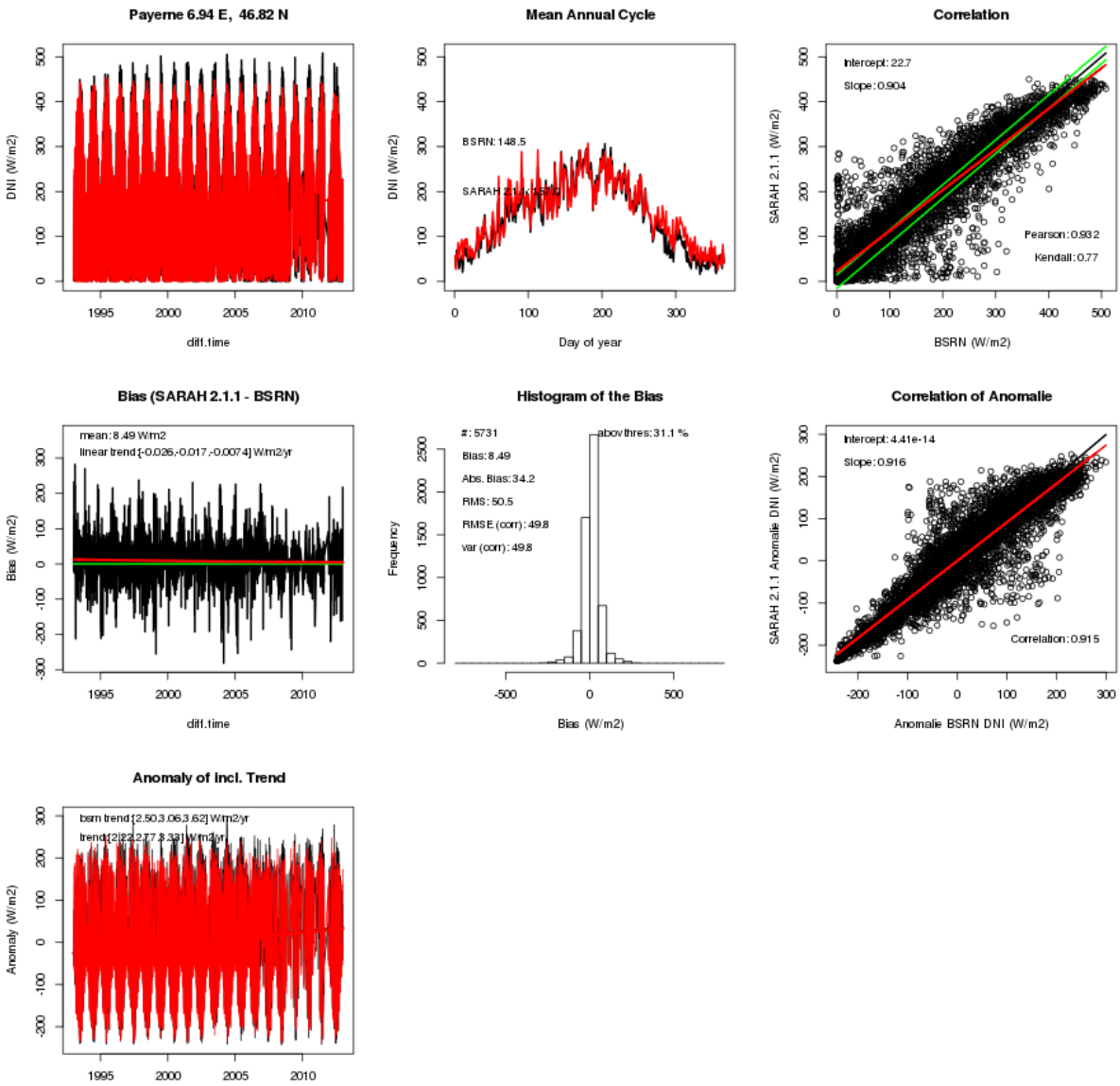

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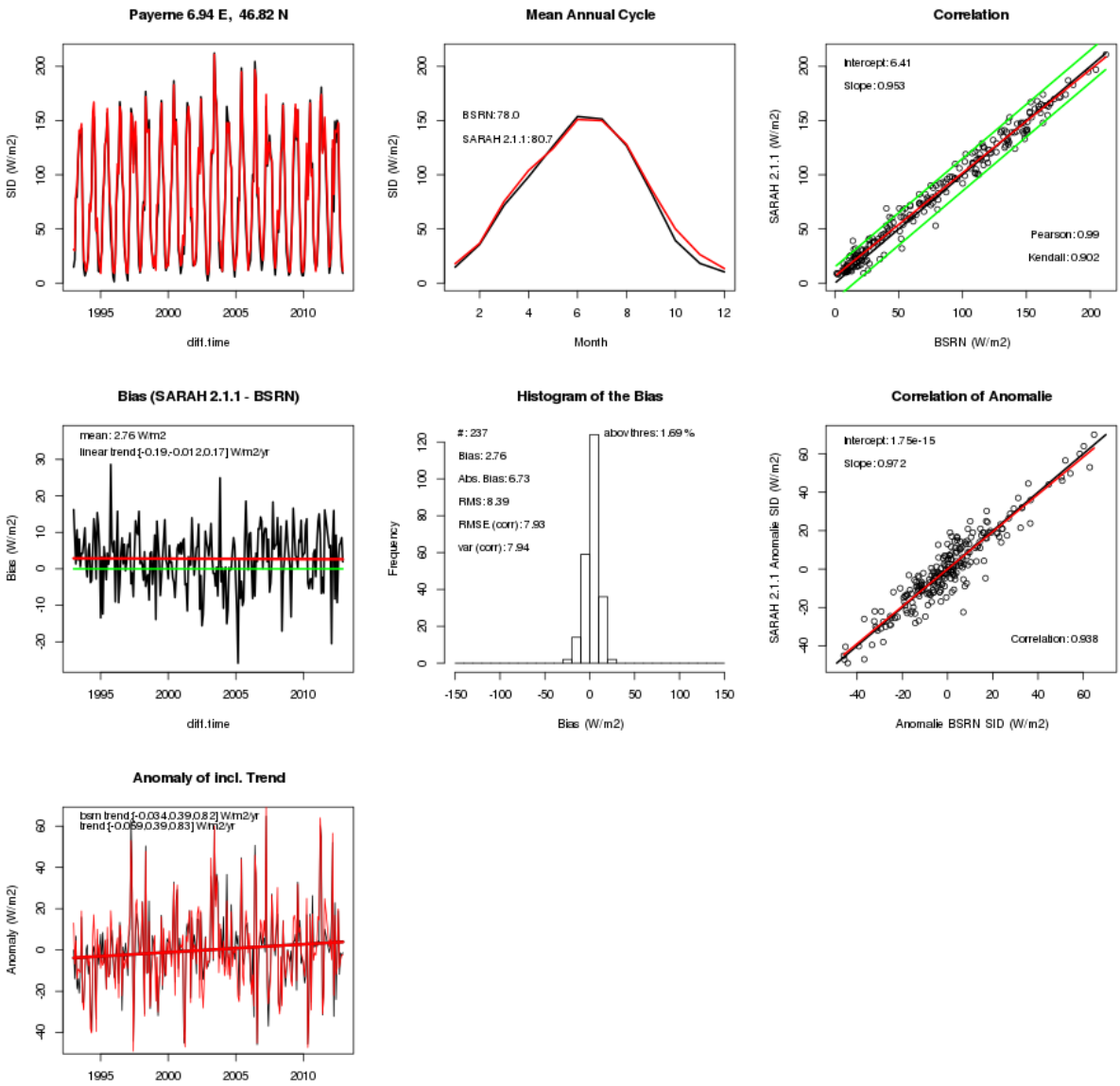

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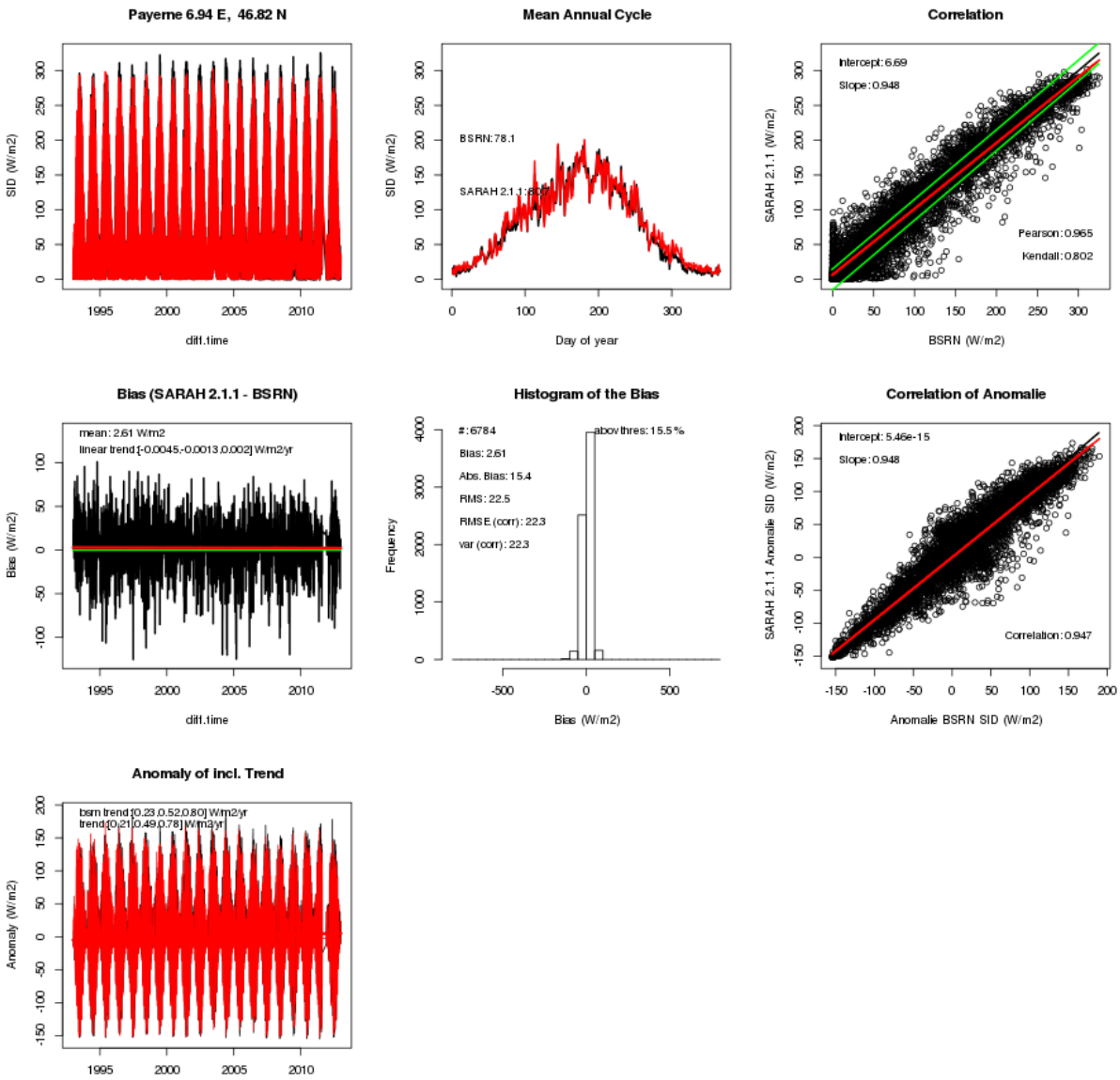
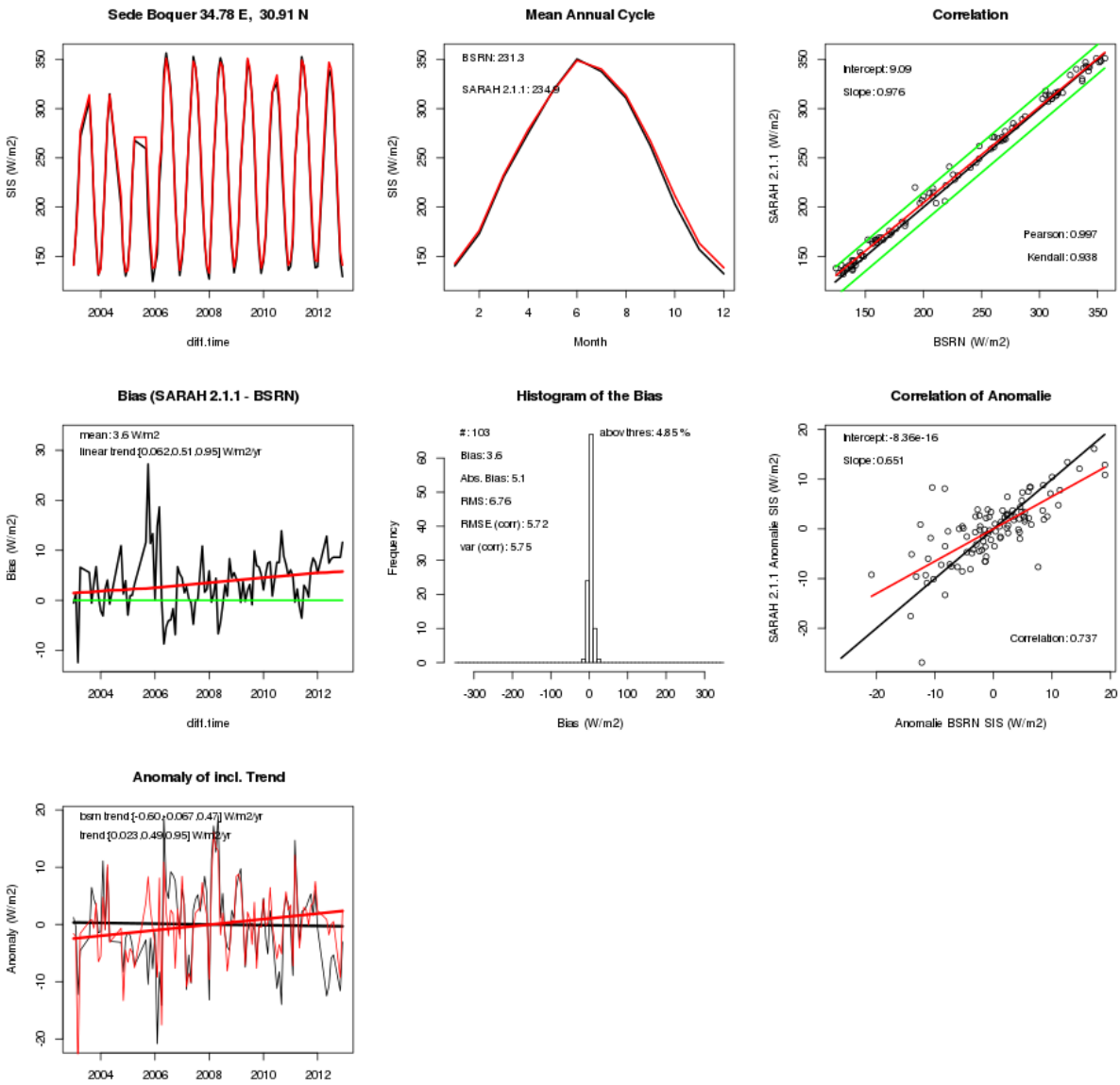


Sede Boquer, SIS, monthly mean



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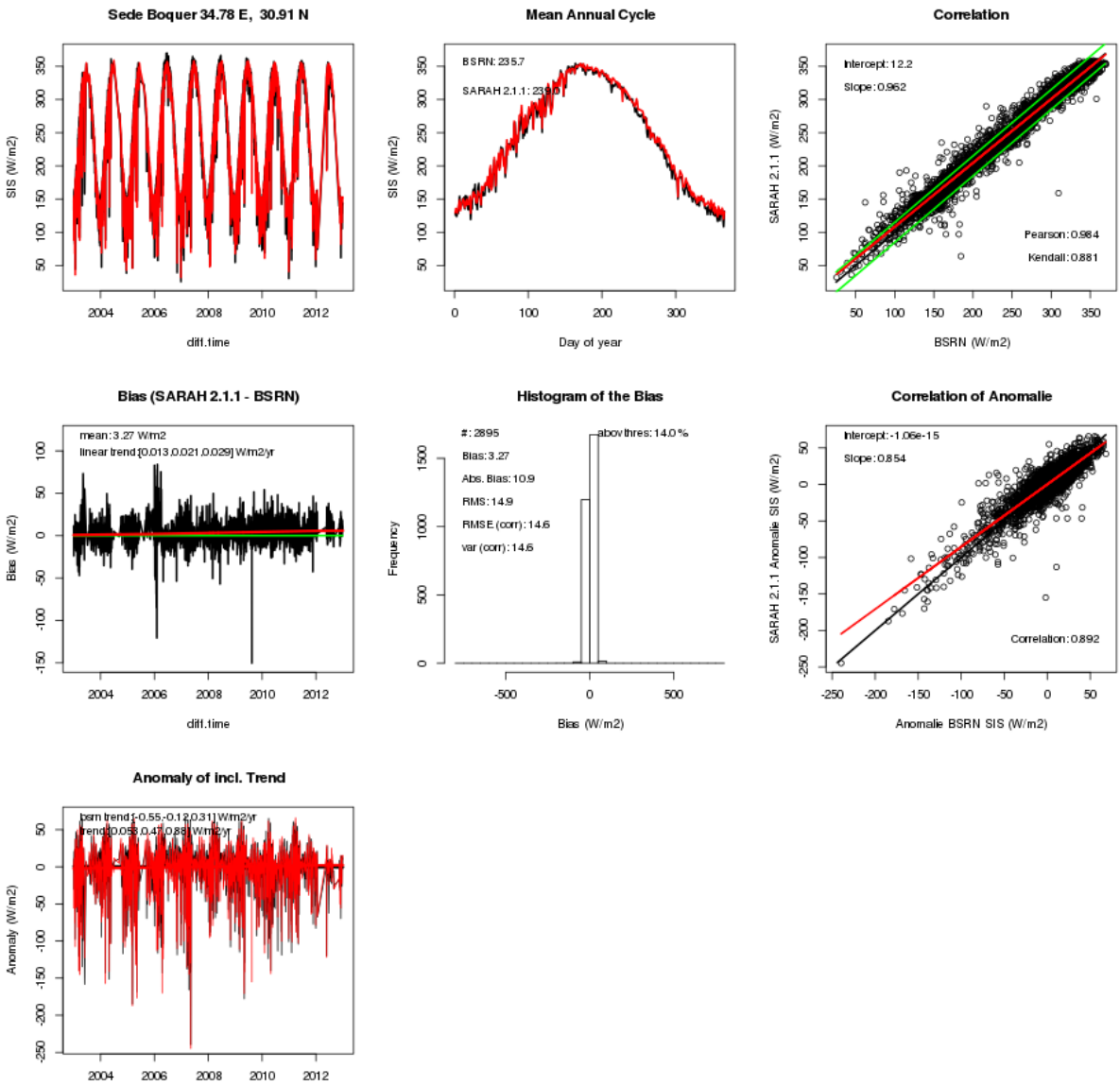

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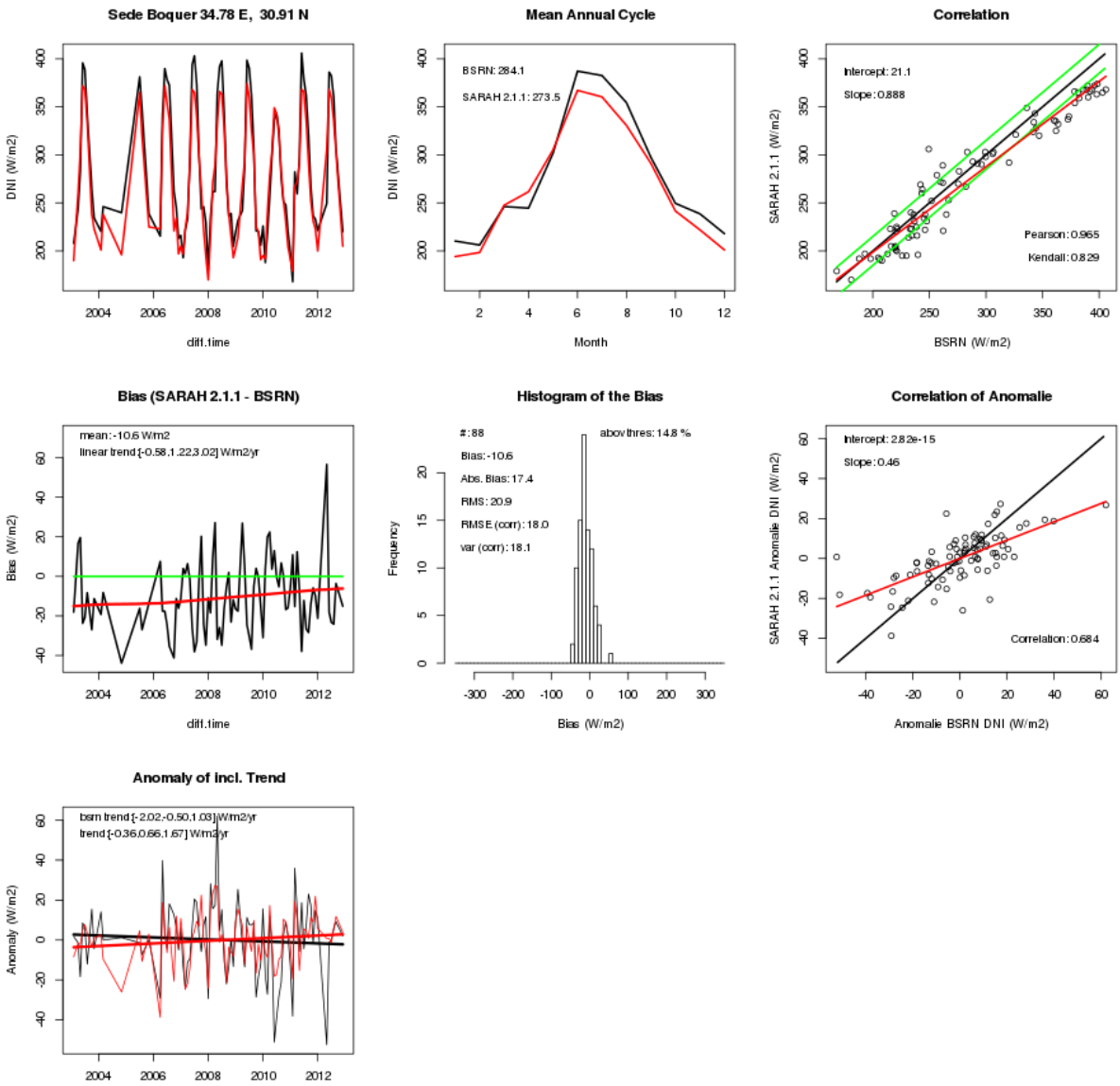

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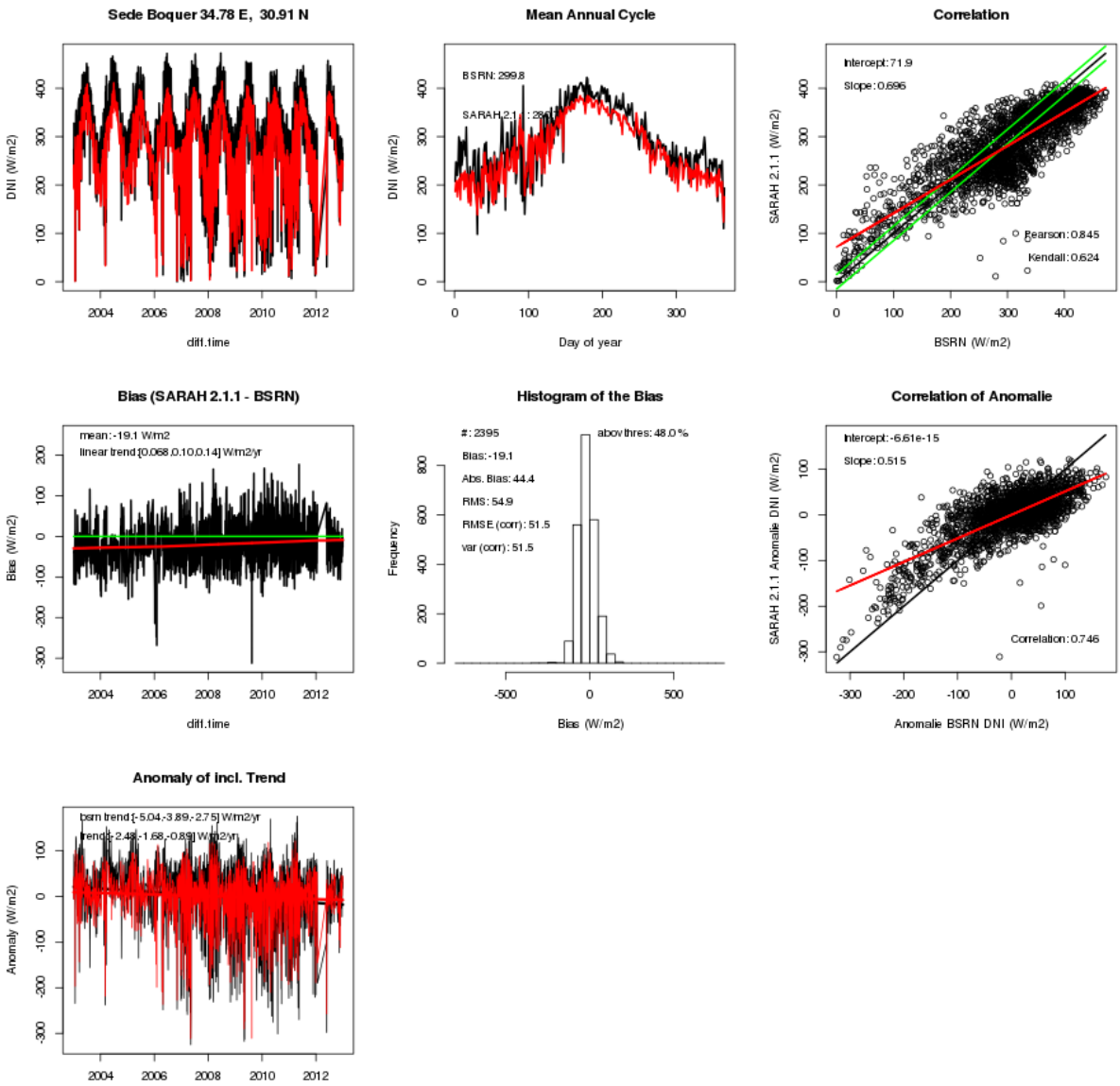

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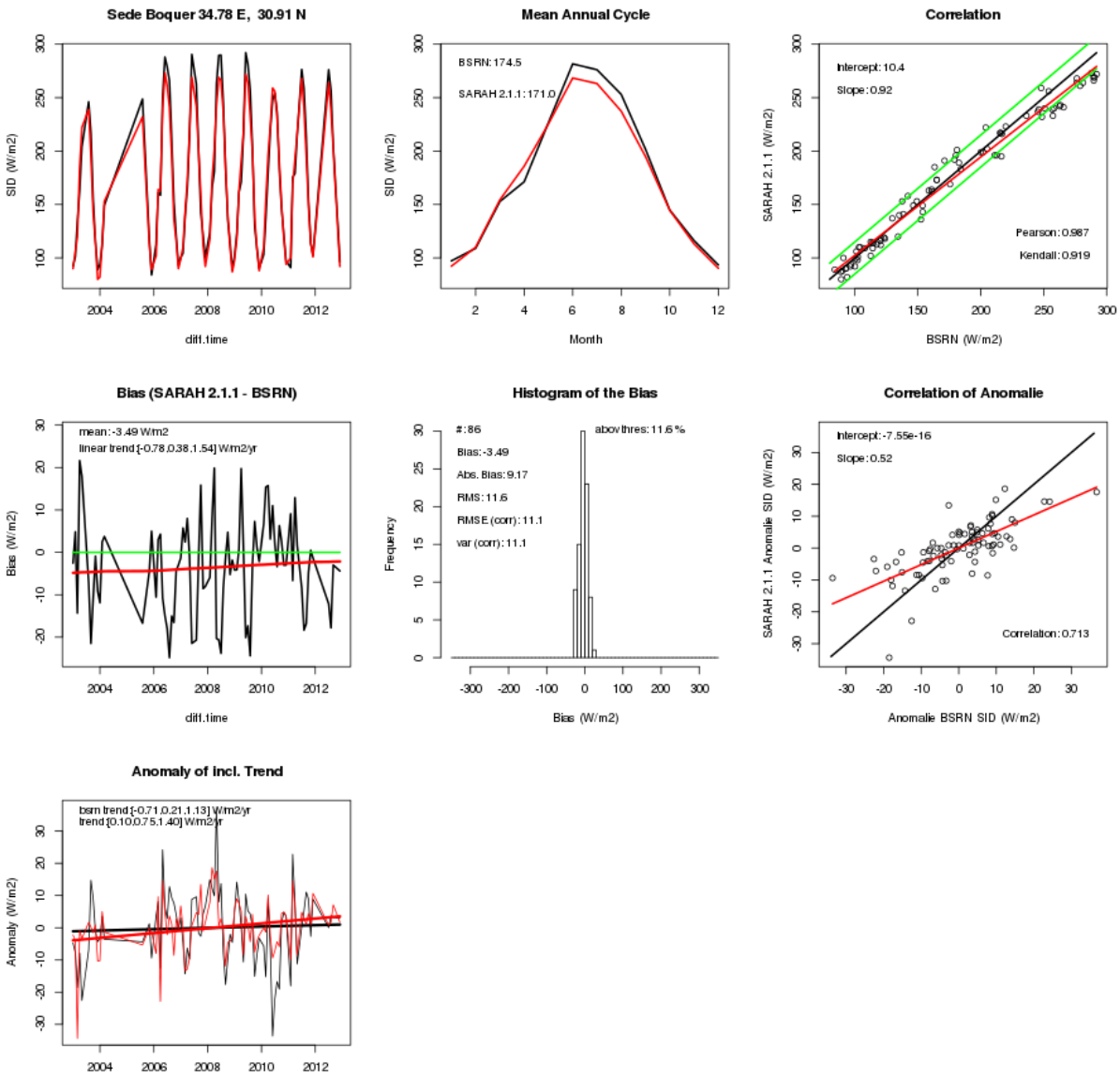

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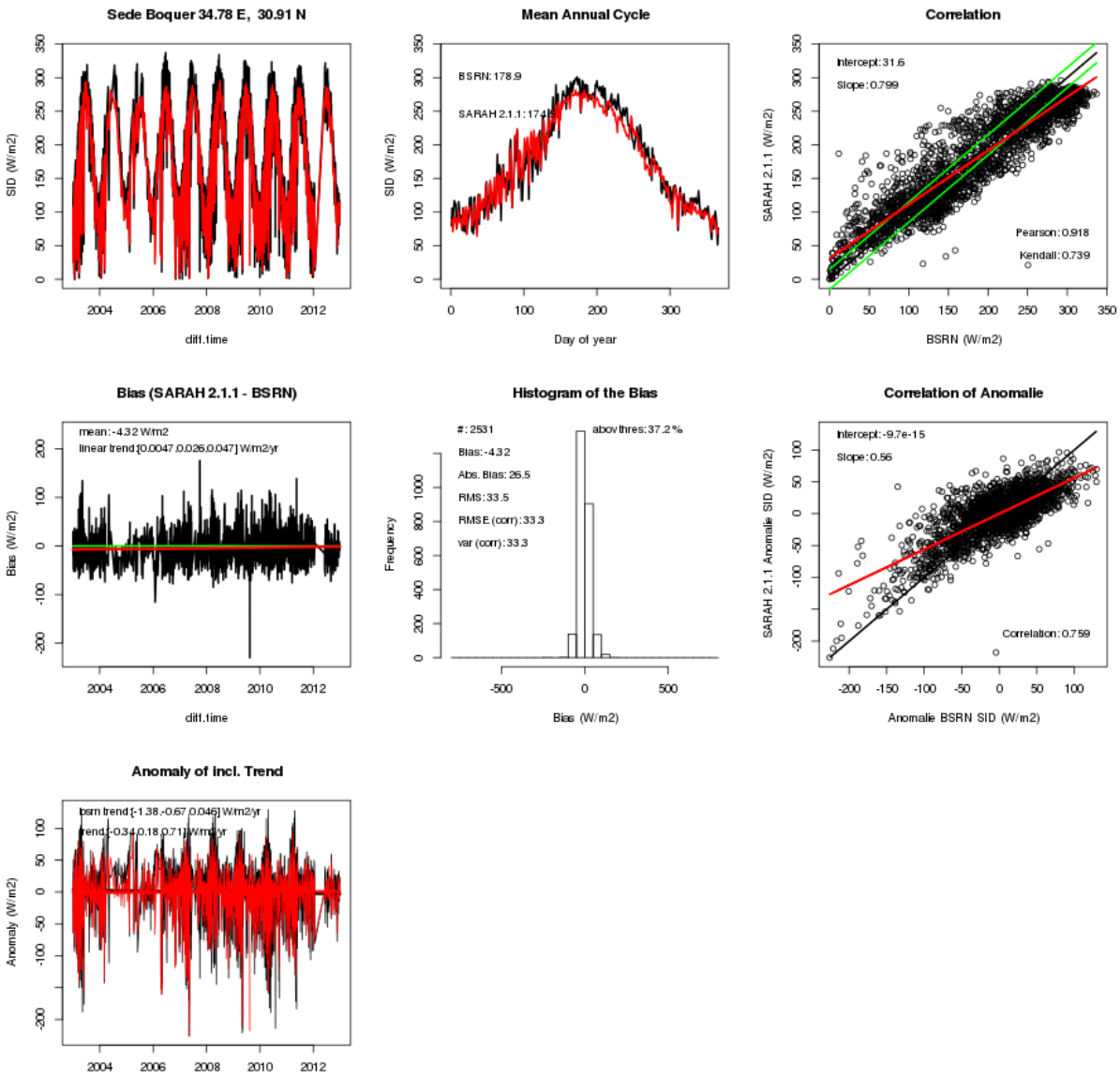
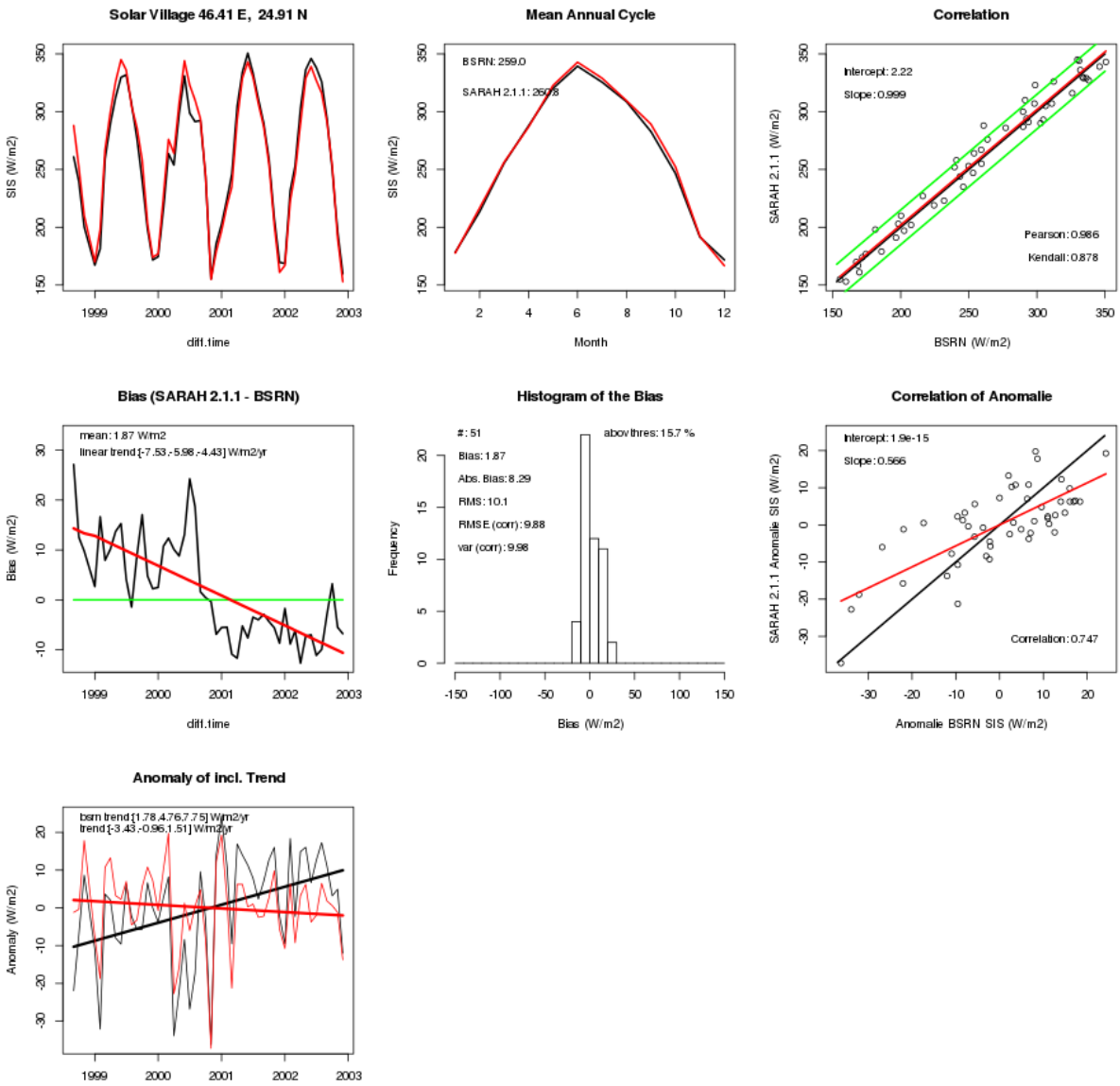


Solar Village, SIS, monthly mean



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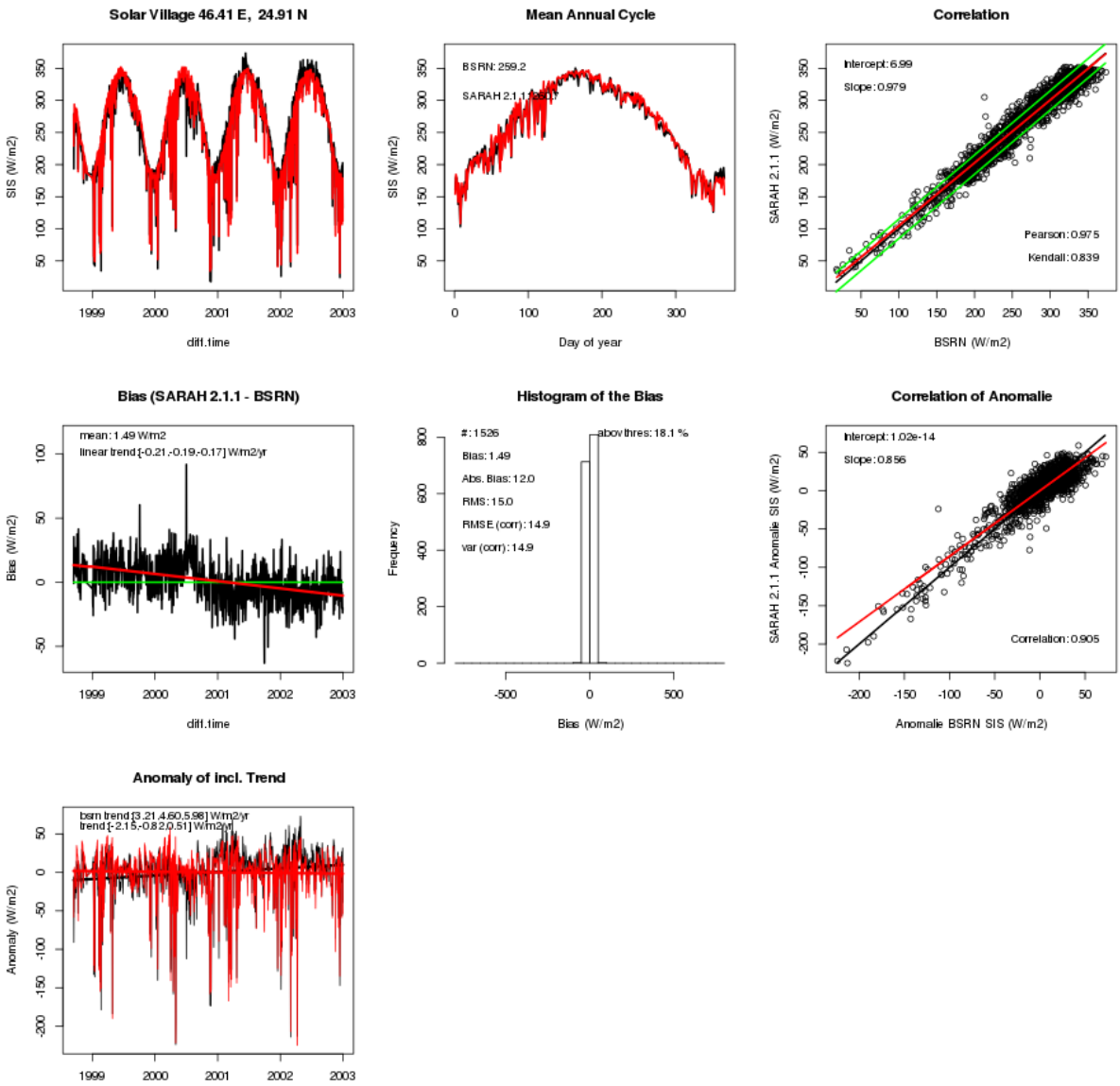

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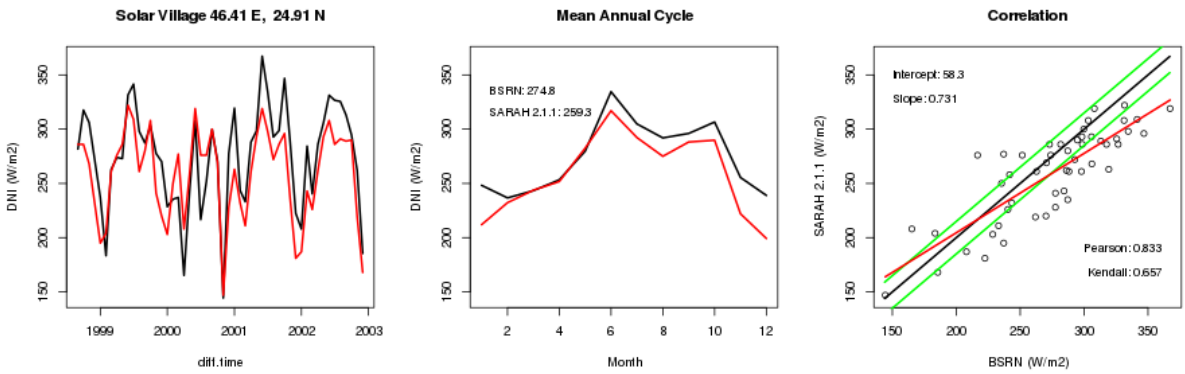

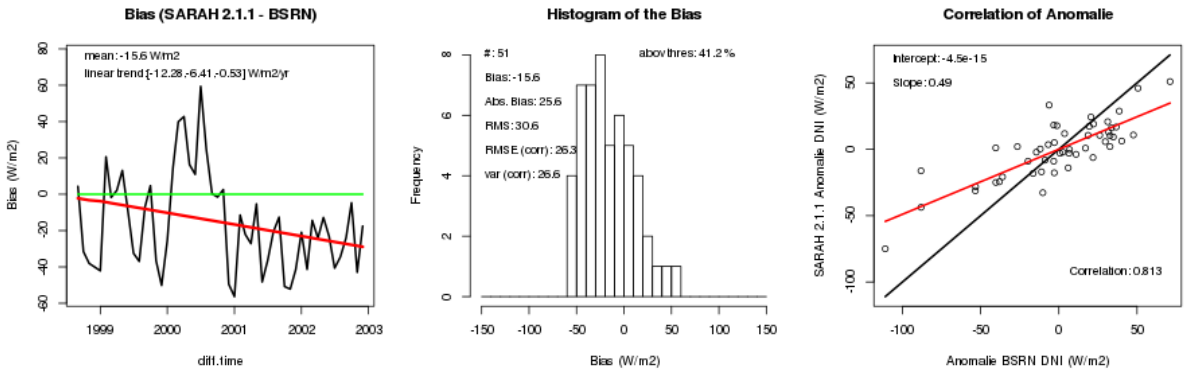

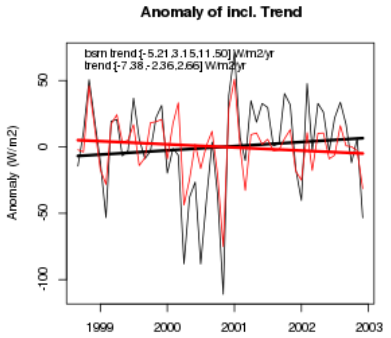

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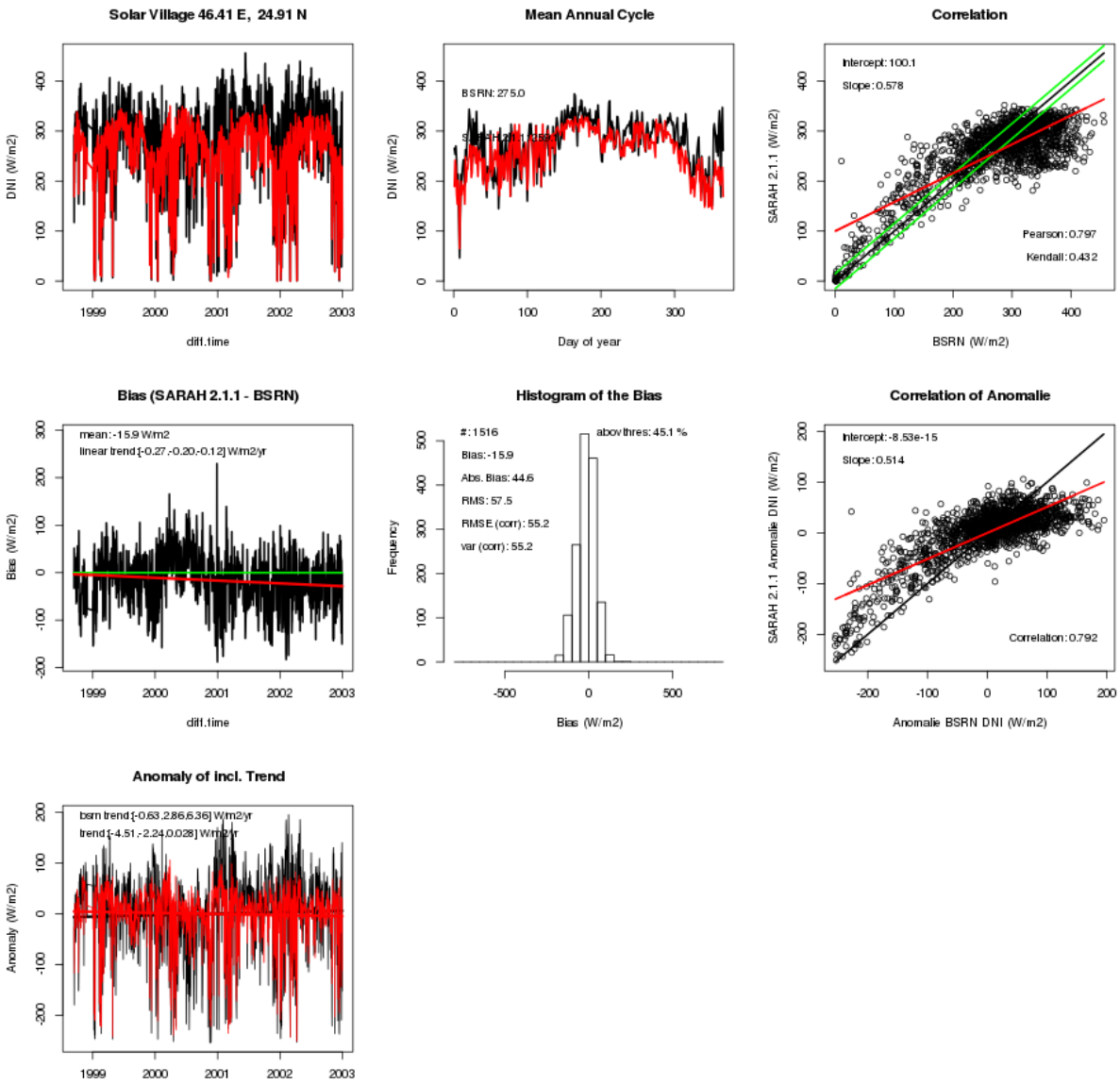

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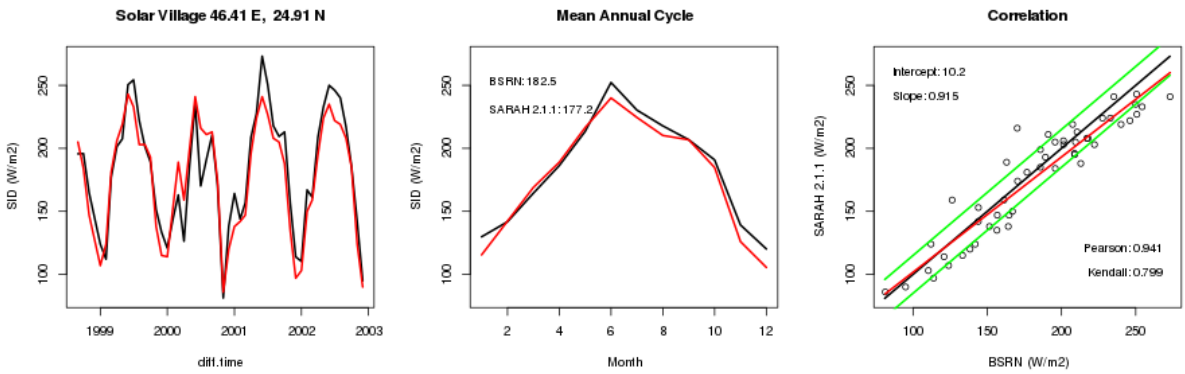
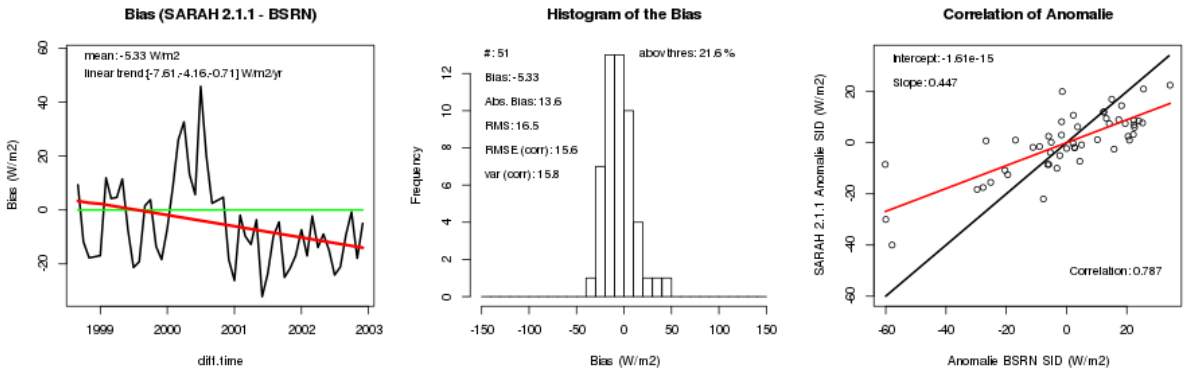
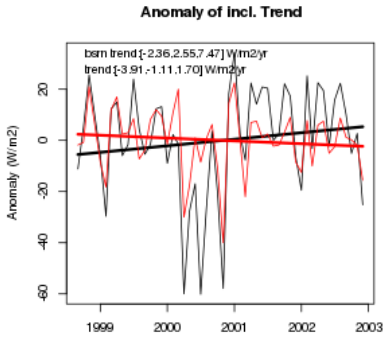
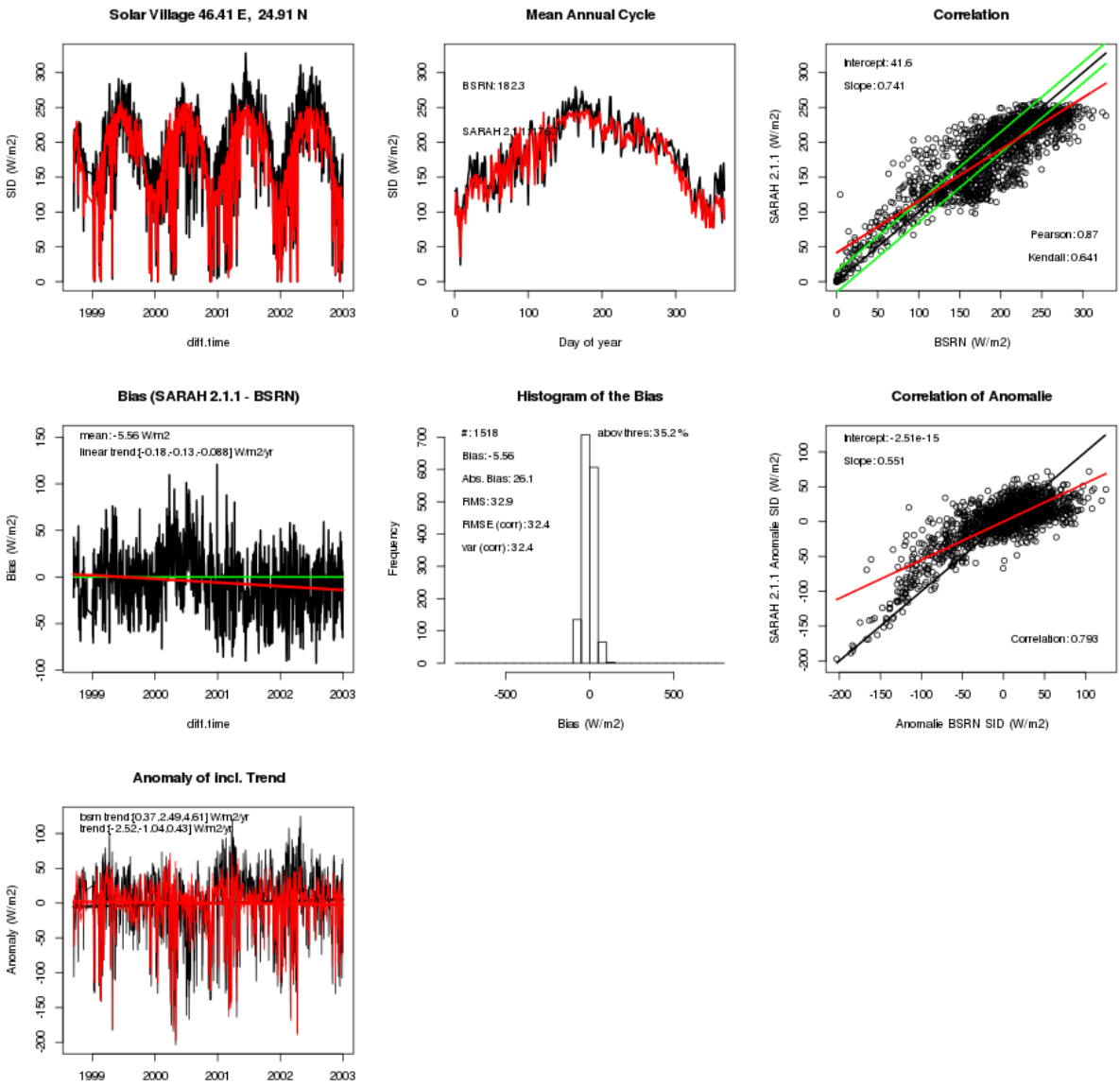


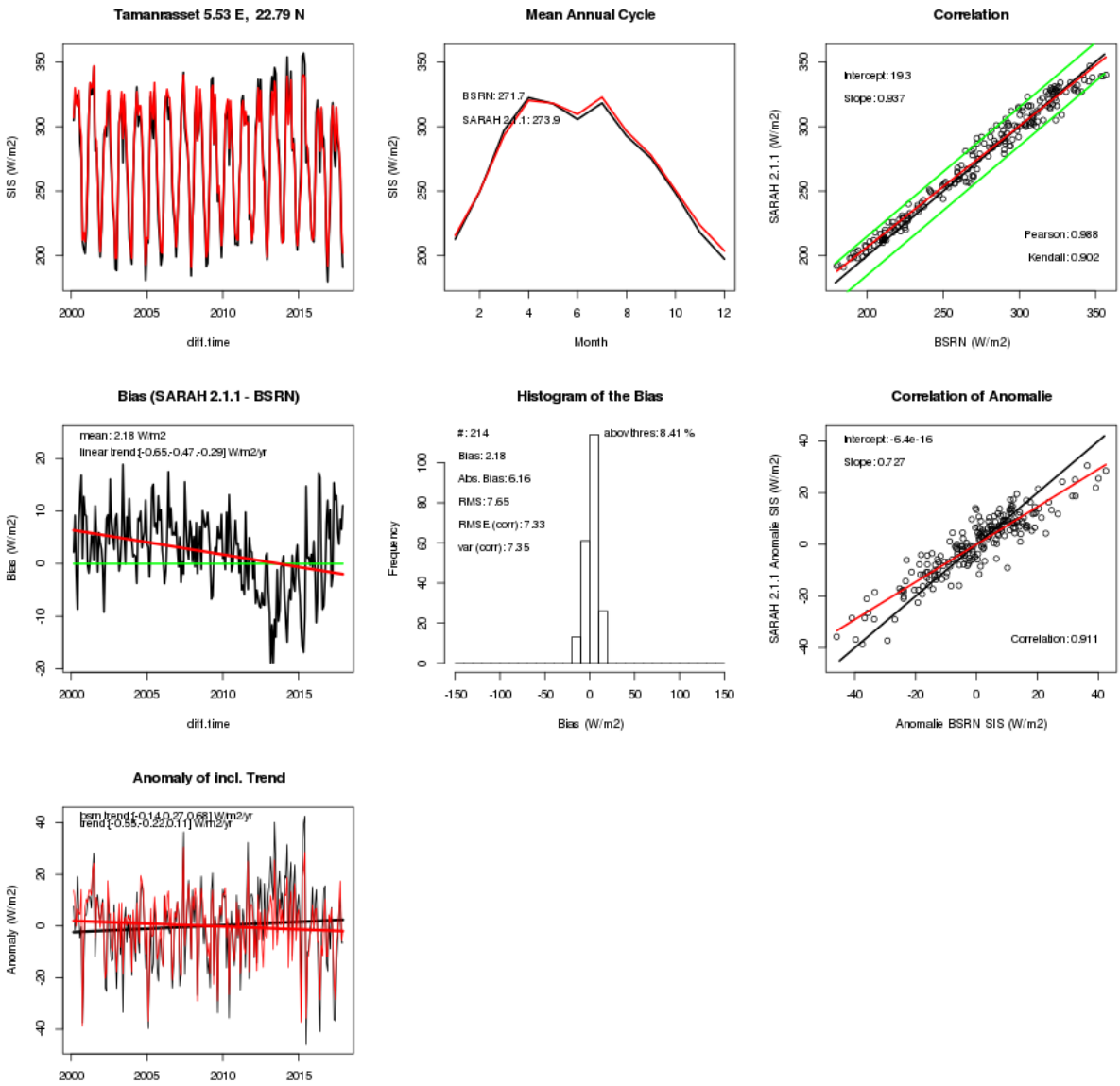




Solar Village, SID, daily mean



Tamanrasset, SIS, monthly mean



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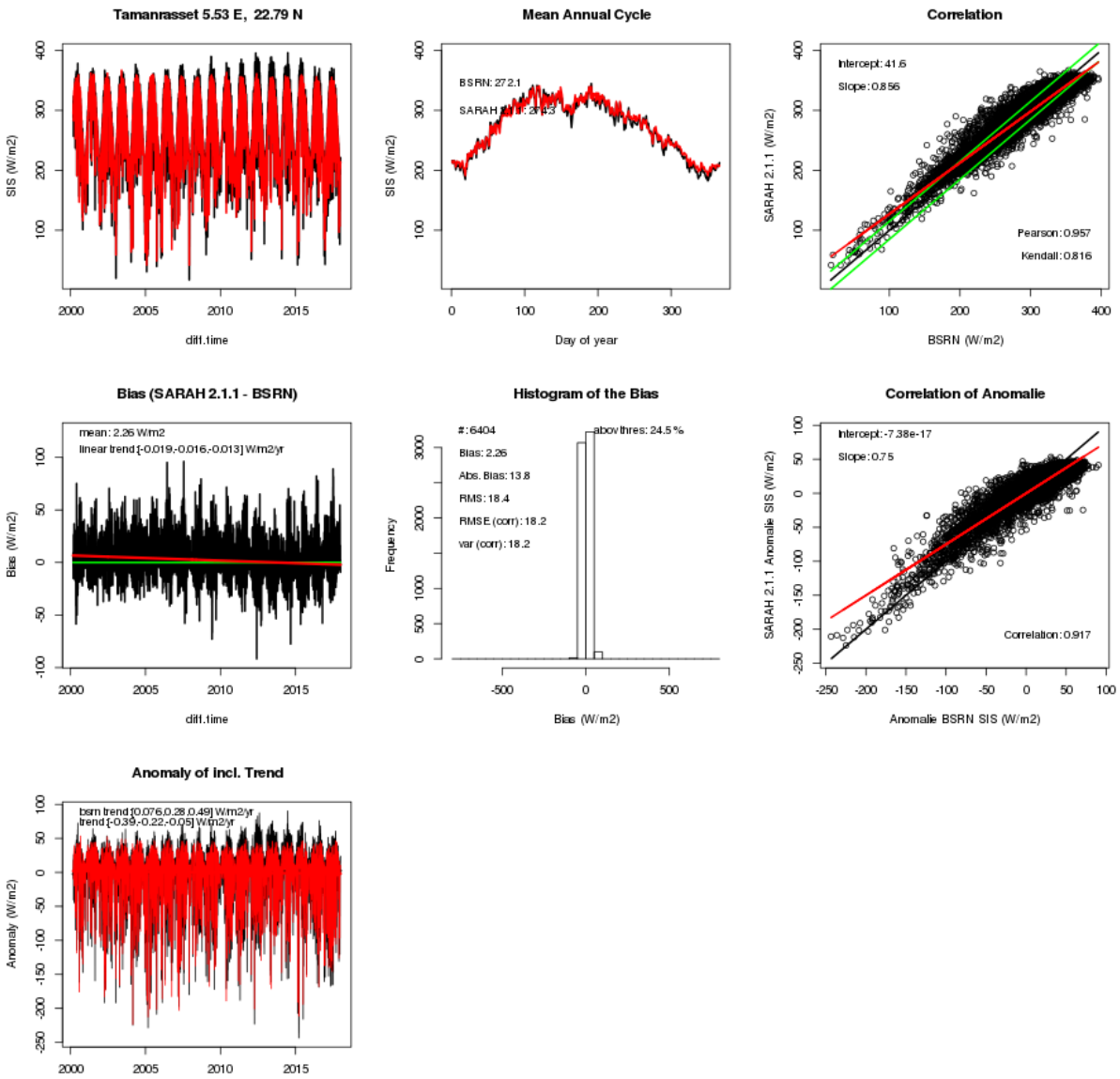

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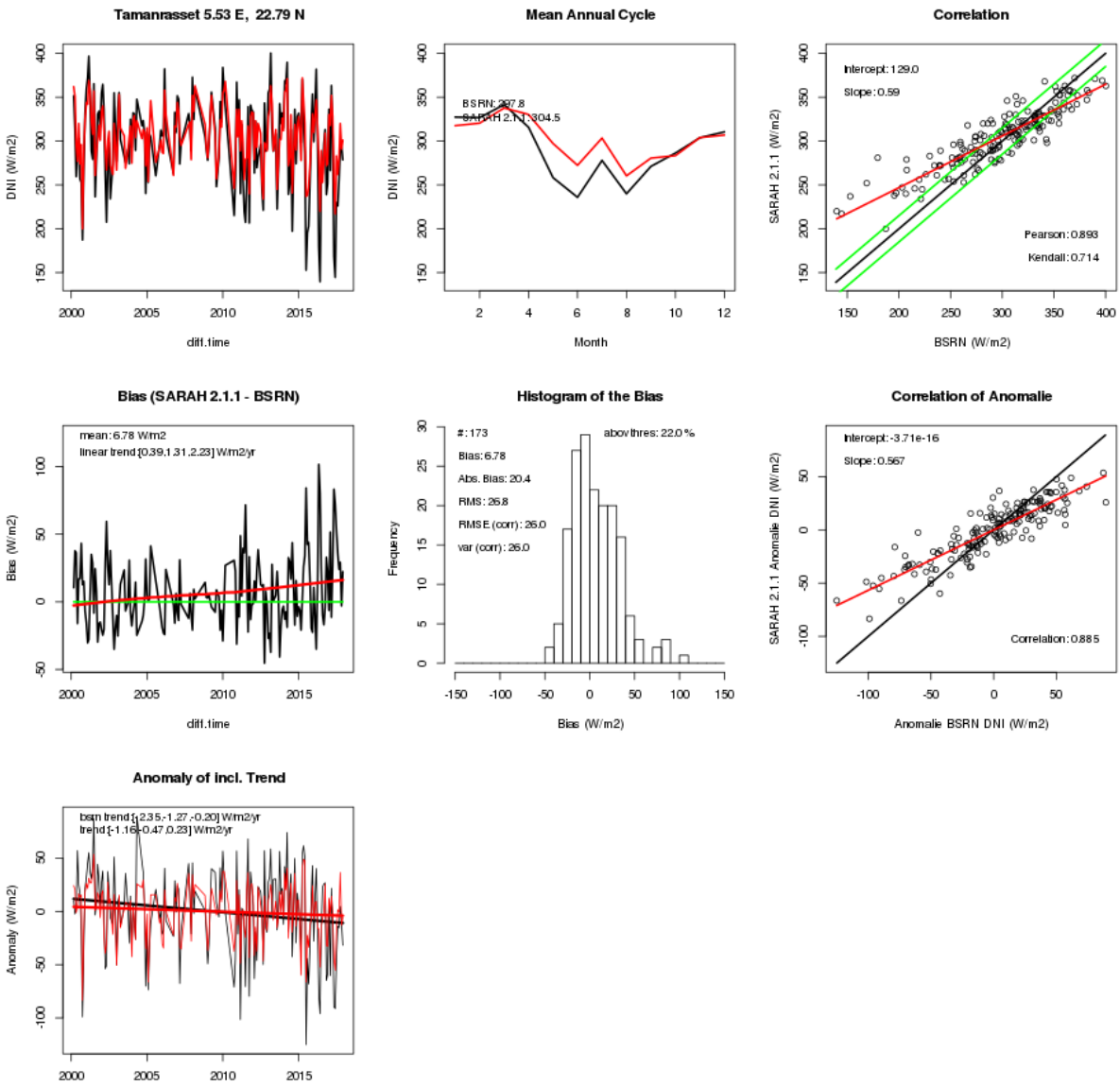

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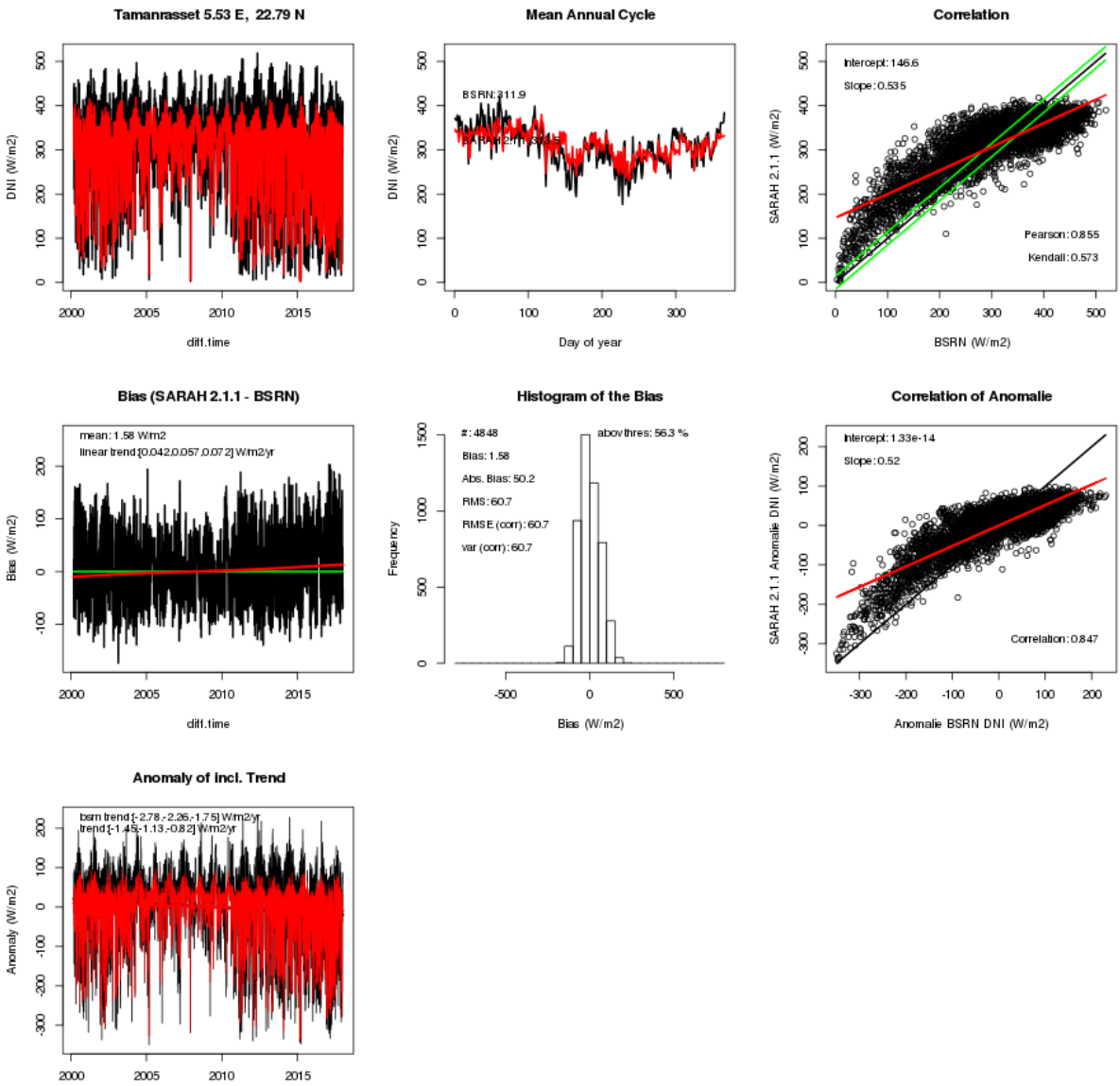

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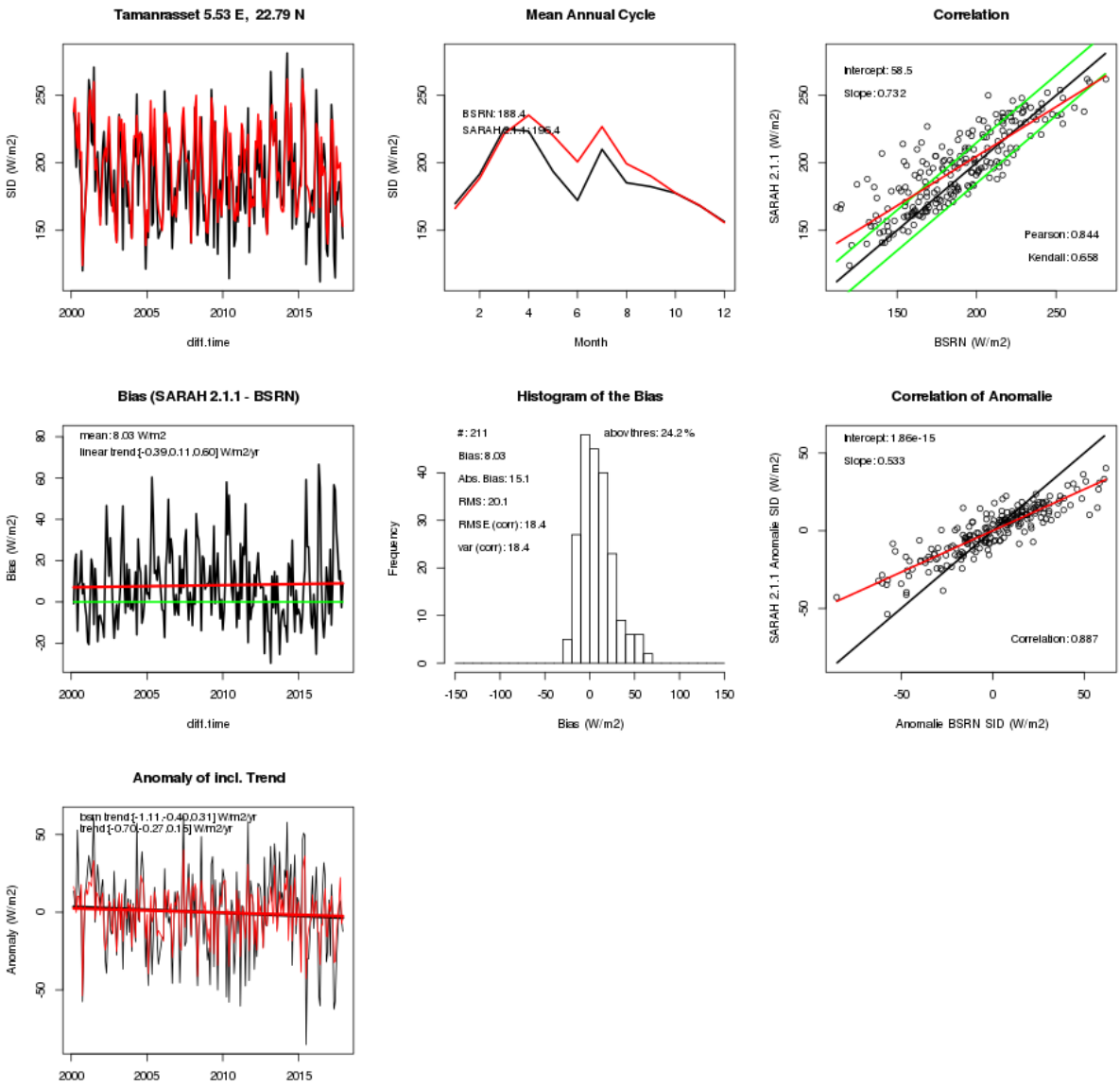

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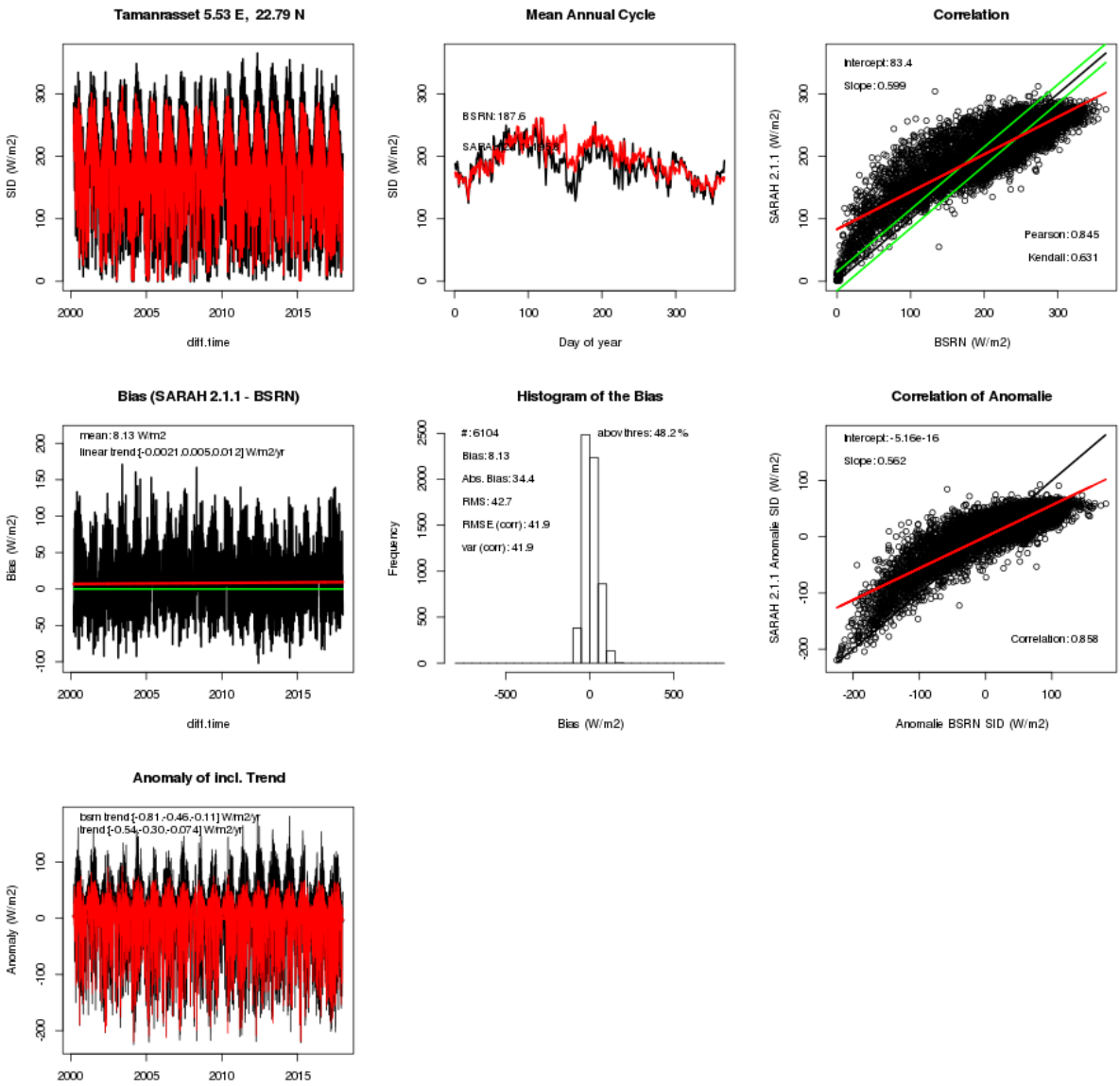

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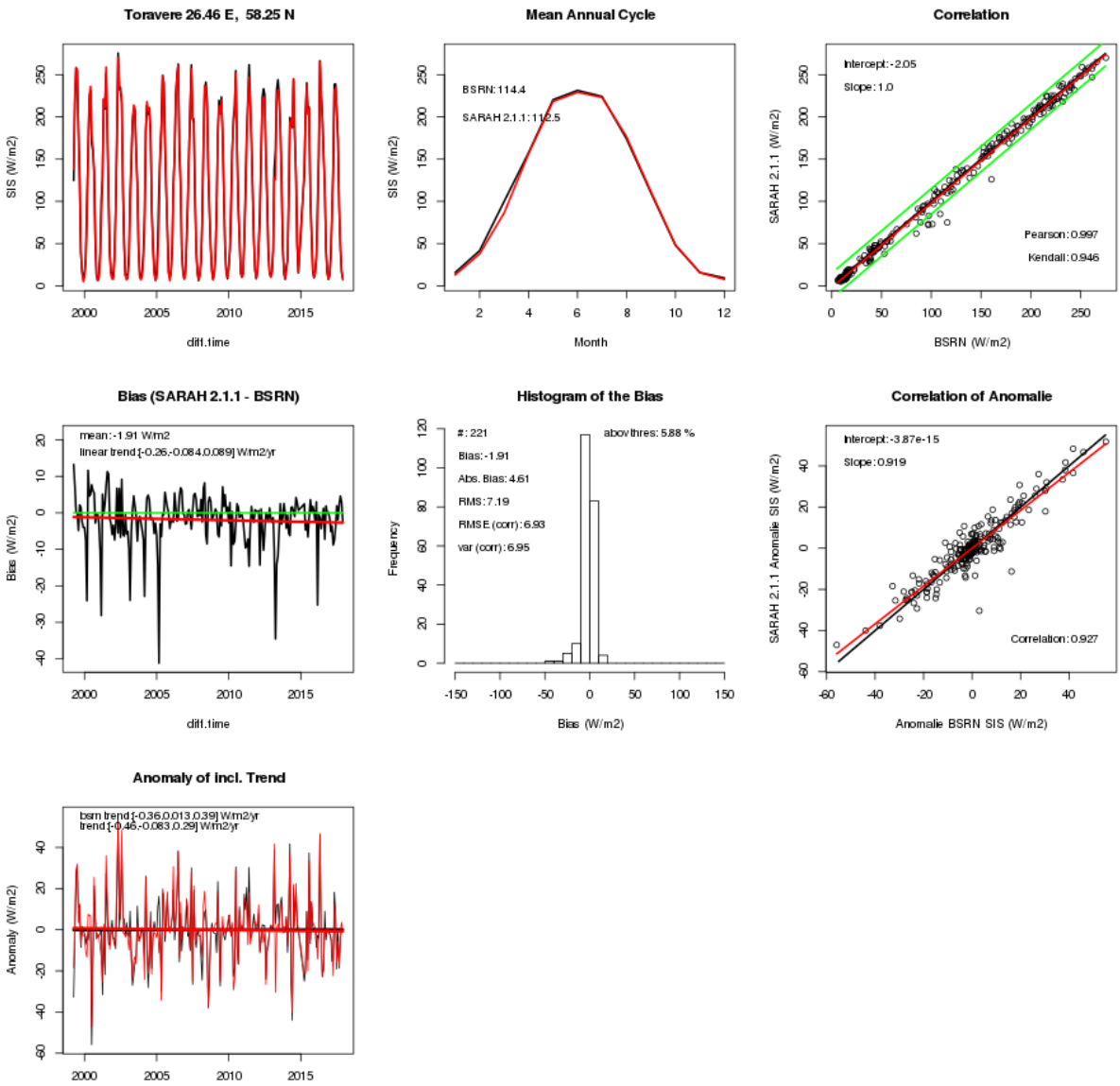

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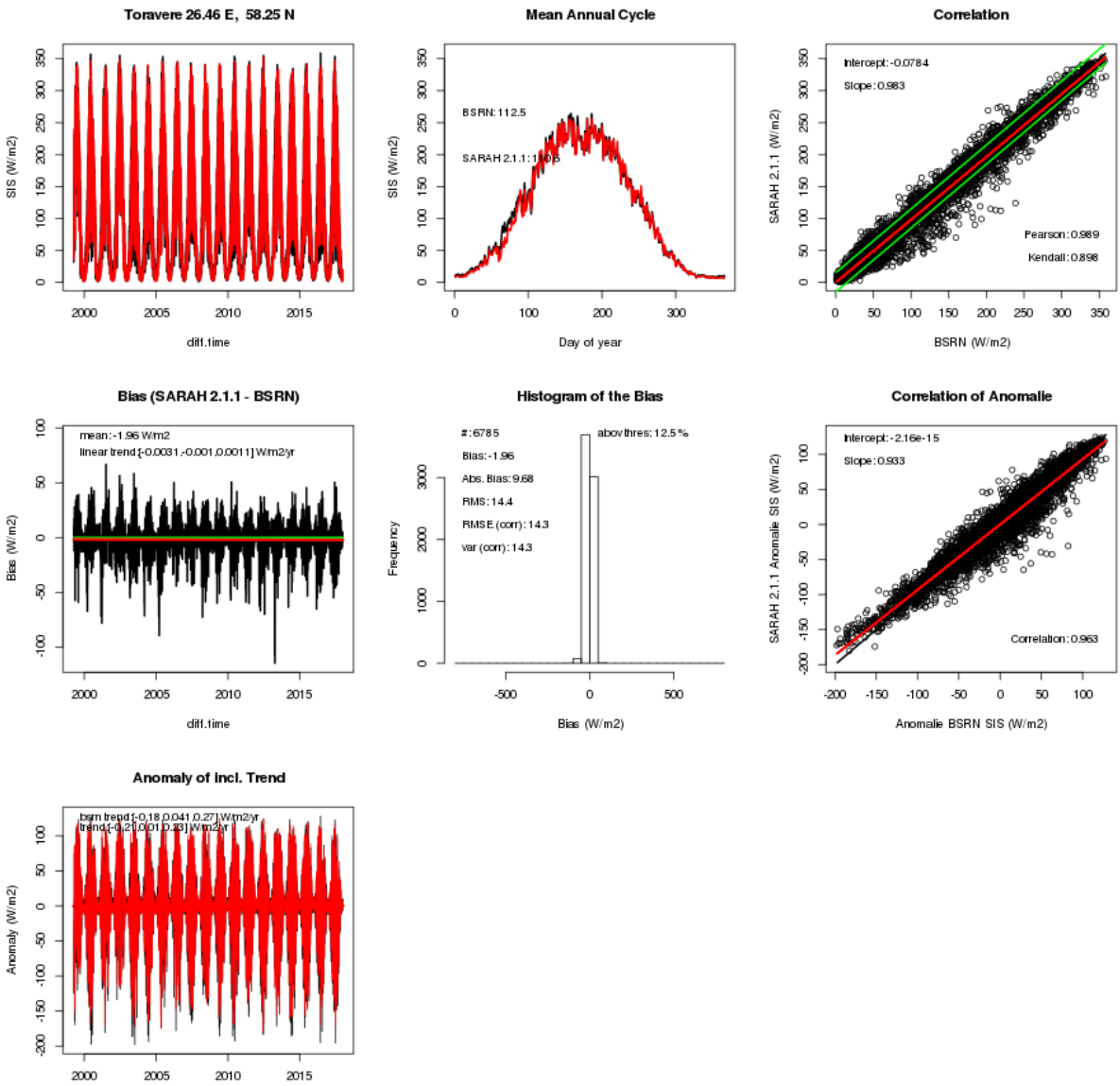

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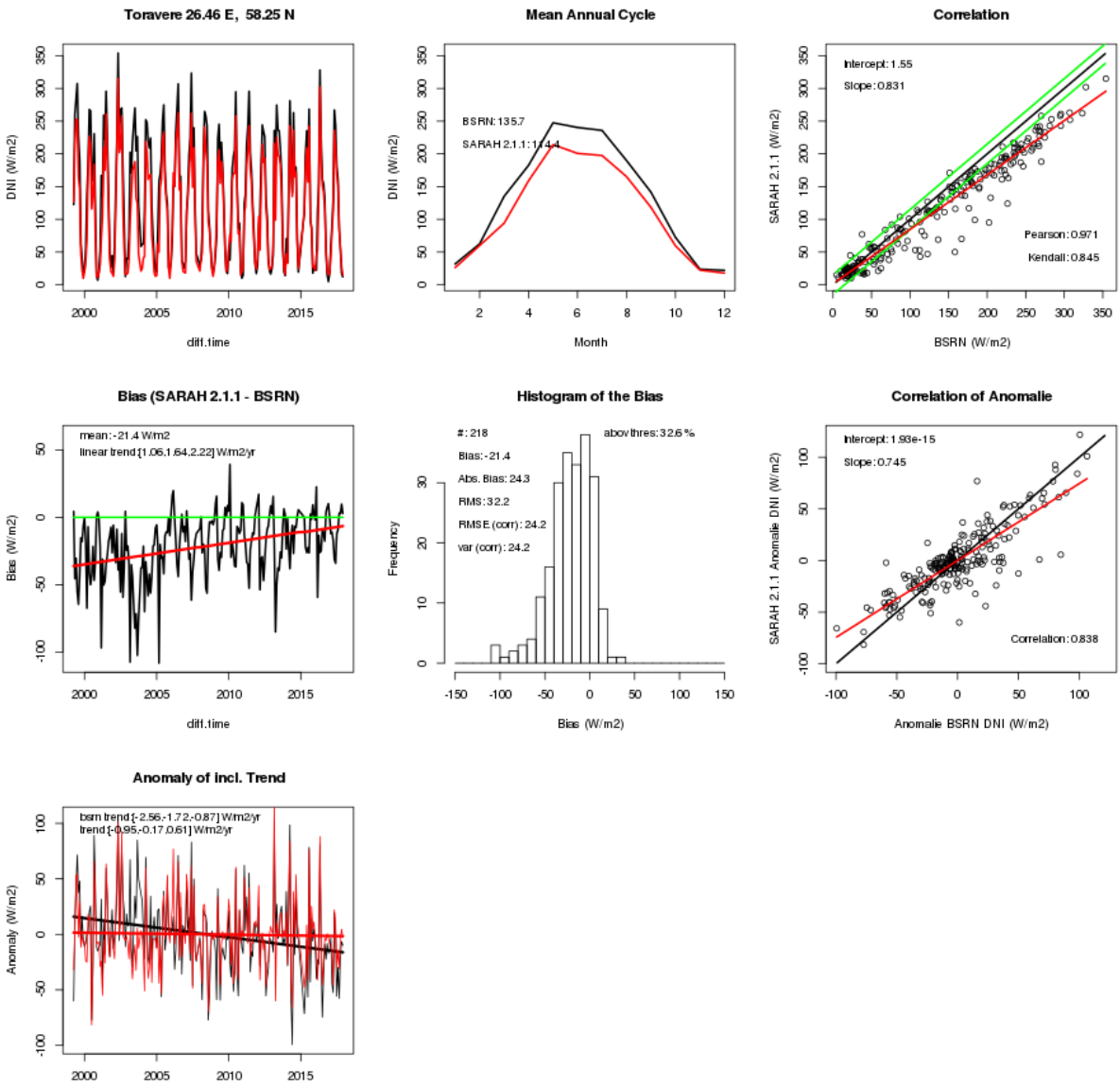

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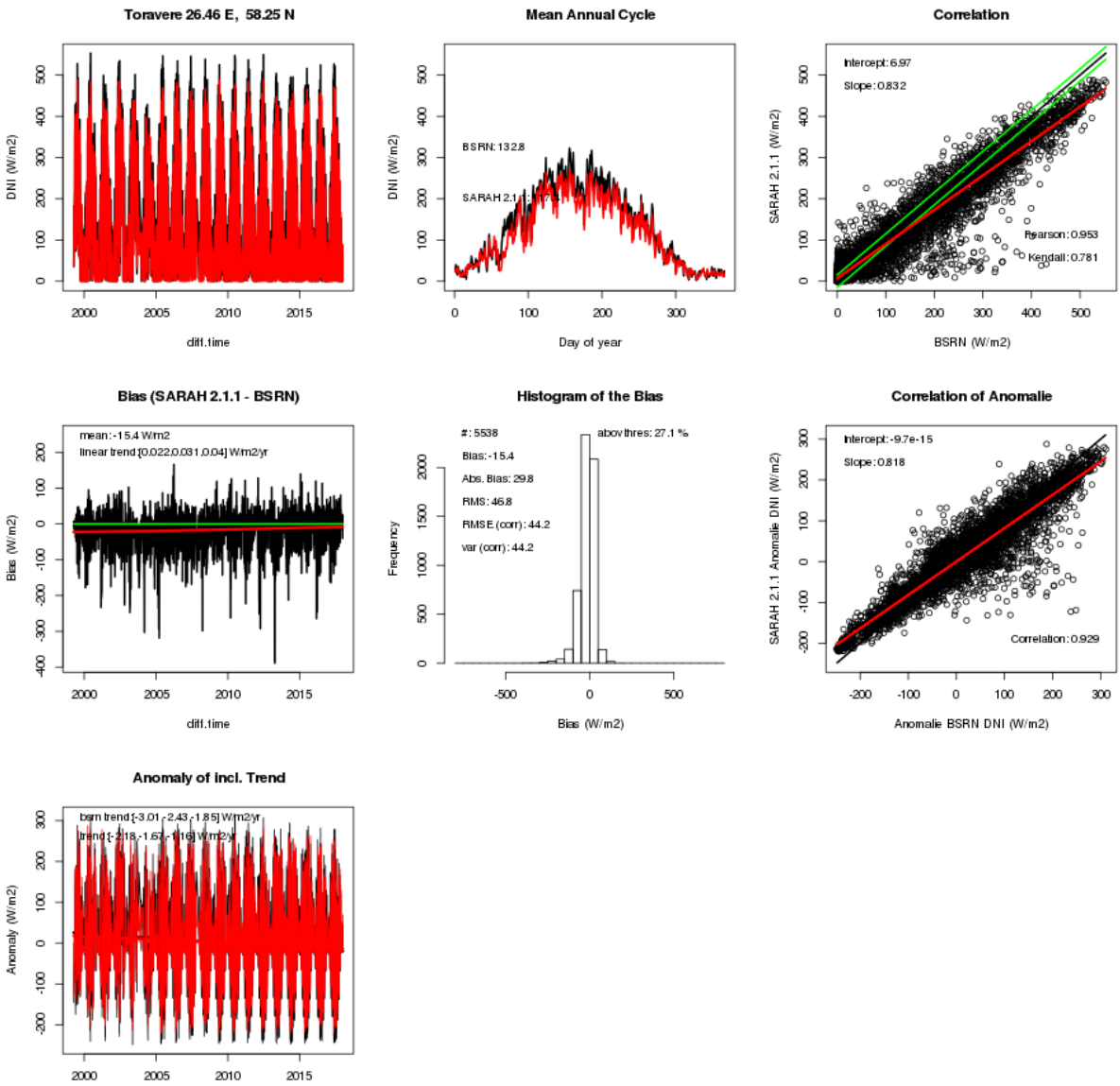

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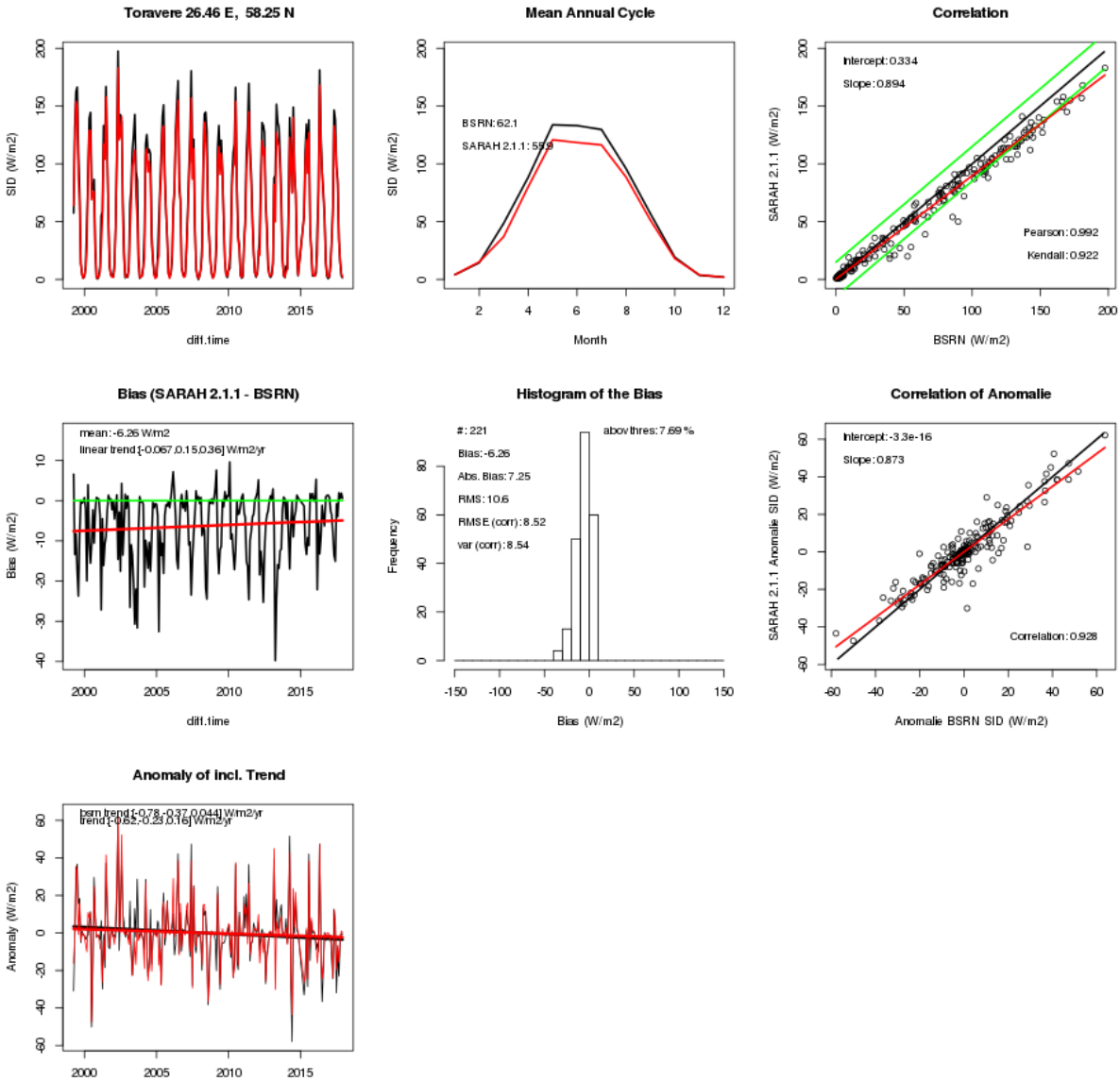

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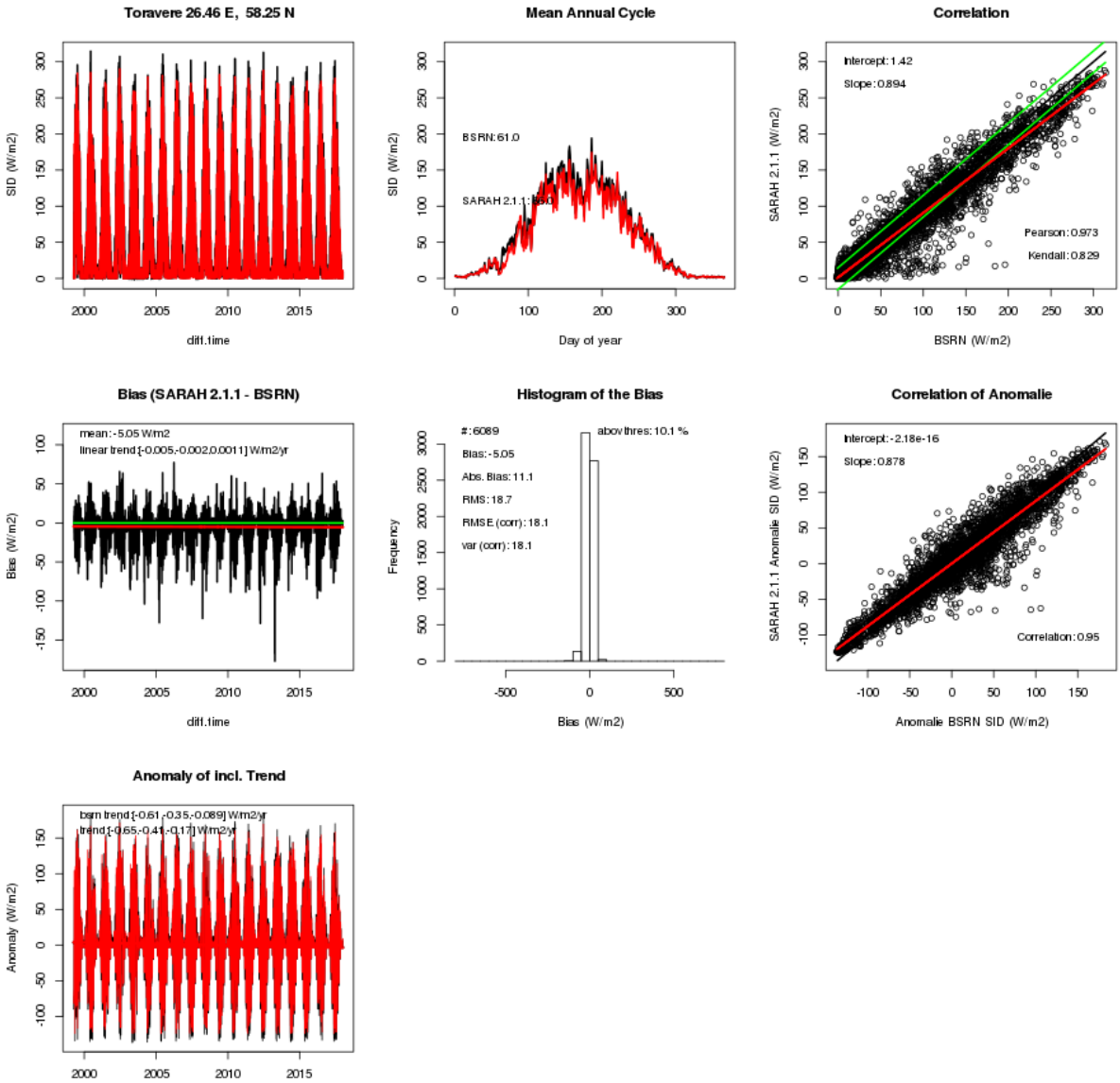

9 Appendix B: Glossary

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
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
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
SRI	Spectral Resolved Irradiance
WMO	World Meteorological Organisation