EUMETSAT Satellite Application Facility on Climate Monitoring

Validation Report

Meteosat Solar Surface Radiation and effective Cloud Albedo Climate Data Record

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SARAH climate data records

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TABLE OF CONTENTS

List of Figures

List of Tables

Executive Summary

The solar irradiance (SIS = Surface Incoming Solar radiation) and the direct normal irradiance (DNI = Surface Incoming Direct Normal radiation) derived from the MVIRI and SEVIRI instruments on-board the Meteosat satellites (Meteosat 2 to 10, 1983-2013) have been validated using ground based observations from the Baseline Surface Radiation Network (BSRN) as a reference. The validation target values for the mean absolute difference between satellite-derived and surface-measured radiation is defined by the target accuracy for monthly/daily means of 10/20 W/m² for SIS and 15/25 W/m² for DNI plus an uncertainty of the ground based measurements of 5 W/m² for SIS and 10 W/m² for DNI.
The mean absolute differences of the monthly mean surface incoming solar (SIS) and surface incoming direct normal radiation (DNI) are 5.5 W/m^2 and 17.5 W/m^2, respectively, i. e., well below the respective targets of 15 and 25 W/m² for all sites. Moreover, nearly 95 % and almost 85 % of the monthly mean absolute difference values of the surface solar radiation and the direct normal irradiance are below the target / threshold values, respectively.
The daily mean data of the surface incoming solar radiation (global irradiance) have a mean absolute difference of 12.1 W/m², which is below the target value of 25 W/m². The mean absolute difference of the daily mean direct normal radiation (DNI) is 34.0 W/m^2, i. e. below the threshold value of 40 W/m². The target / threshold accuracy is therefore achieved for monthly and daily means.
A small negative decadal trend in the bias between the satellite-derived data set and surface irradiance observations in Europe has been found: [-1.5, -1.1, -0.6] W/m^2/decade, 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.

Applicable Documents

Reference	Title	Code
AD.1.	CM SAF Product Requirement Document	SAF/CM/DWD/PRD/2.4

Reference Documents

Reference	Title	Code
RD.1.	Algorithm Theoretical Baseline Document (ATBD) Meteosat Solar Surface Irradiance and effective Cloud Albedo Climate Data Sets METEOSAT_HEL	SAF/CM/DWD/ATBD/METEOSATI_HEL
RD.2.	Product User Manual: Meteosat Solar Surface Irradiance and effective Cloud Albedo Data Sets. METEOSAT_HEL	SAF/CM/DWD/PUM/METEOSAT_HEL
RD.3.	Requirements Review 2.1	SAF/CM/DWD/RR21

1 The EUMETSAT SAF on Climate Monitoring (CM SAF)

EUMETSAT has set up and operates a Network of ***Satellite Application Facilities*** (SAF), which together with the EUMETSAT central facilities constitute the EUMETSAT Application Ground Segments for MSG and EPS. The SAFs are located in a National Meteorological Service or other approved institute of a EUMETSAT member state. The scope of the SAF activities is to deliver products, at the level of geophysical parameters, based primarily on the satellite data.

Each SAF is developed and operated according to a Cooperation Agreement, signed between EUMETSAT and the Host Institute. Funding from the Host Institute and co-operating entities complements the EUMETSAT Contribution to the project.

Overview information on the CM SAF can be found at its web page under www.cmsaf.eu

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 31 year long (1983-2013) continuous surface radiation climate data record based on observations from the Meteosat First and Second Generation satellites: Surface Solar Radiation Data Set – Heliosat (SARAH). SARAH contains climate data records of the surface incoming solar radiation (SIS), the surface incoming direct normal radiation (DNI) and the effective cloud albedo (CAL). 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 and DNI CDR are processed using a climate version of the Heliosat algorithm to obtain information about 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 DNI data sets are presented in Figure 2-1. It is clear that these data sets 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 DNI) 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 sets are provided in the following sections.

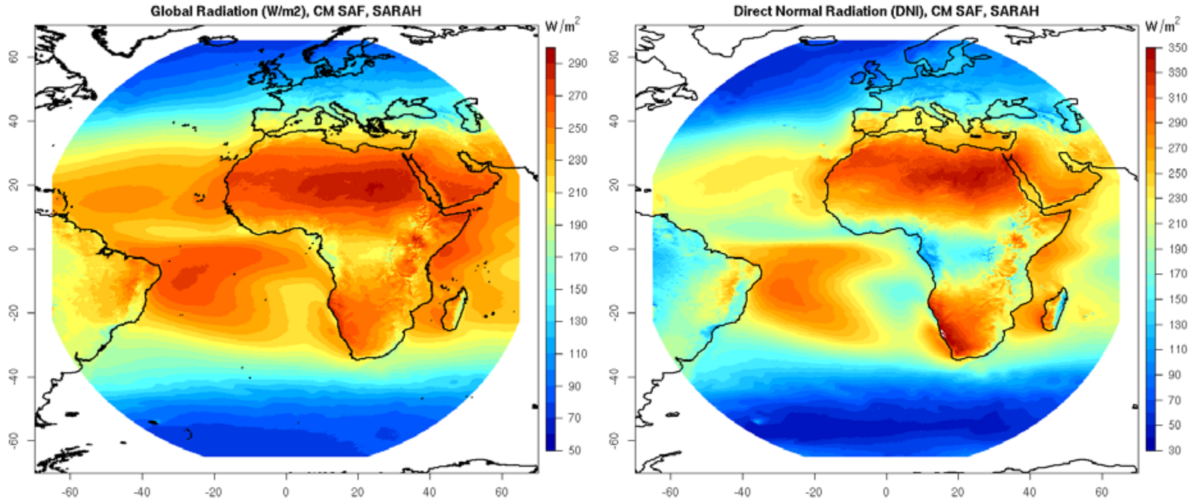


Figure 2-1: *Multiyear means of SIS (left) and DNI (right) for the whole CDR (1983-2013)*

3 Validation procedure

3.1 Validation data

The validation of the new data sets for the surface incoming solar radiation (SIS) and the surface incoming direct normal solar radiation (DNI) 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 (1992-2013) 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 set. However, it is feasible to assume the same data quality of the CM SAF data set for the years 1983 to 1992 than for the years that underwent validation against the BSRN reference measurements.

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

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 set, 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. 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 set 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 sets, long-term reference measurements should be employed. The Global Energy and Balance Archive (GEBA) contains monthly mean surface irradiance data sets from ground observations including stations reporting prior to 1983 (Gilgen et al. 2009). For about 50 European stations, the temporal homogeneity has been tested. Here we use these station measurements to assess the temporal stability of the monthly mean SIS data set from SARAH.

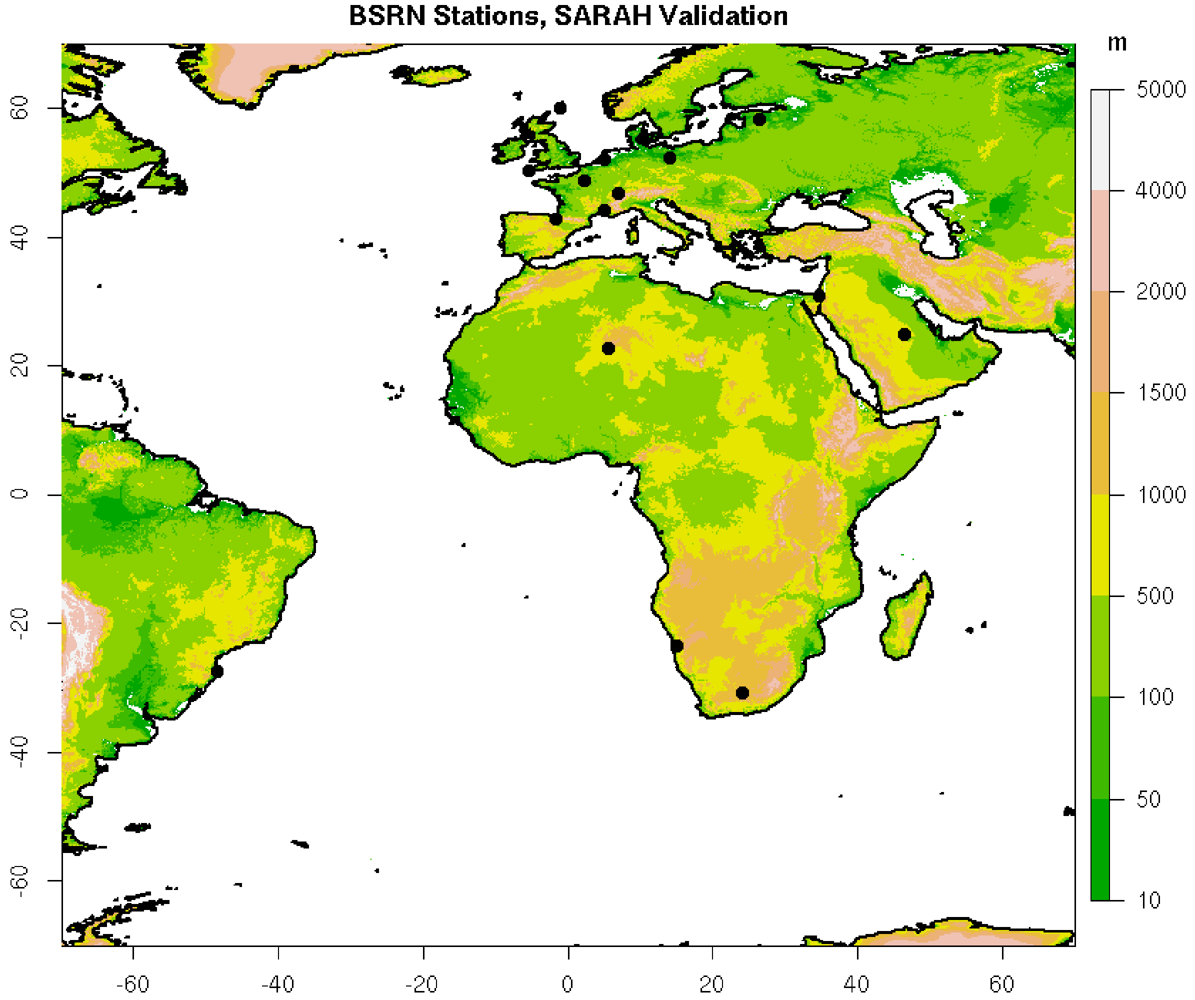


Figure 3-1: *Location of the BSRN stations used for the validation. Black dots are the locations of the stations. The underlying map shows the topography.*

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 and DNI are listed in Table 3-2. 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. We assume this additional uncertainty to be 5 W/m^2 for SIS and 10 W/m^2 for DNI.

Table 3-2: *Accuracy and decadal stability requirements (threshold, target and optimal) for monthly and daily averaged data from the SARAH data set (SIS, DNI, CAL)*

	SIS [W/m²]			**DNI [W/m²]**			**CAL**		
	Threshold	Target	Optimal	Threshold	Target	Optimal	Threshold	Target	Optimal
Monthly	15	10	8	20	15	12	0.15	0.1	0.05
Daily	25	20	15	30	25	20	0.2	0.15	0.1
Dec. Stability	4	2	1	6	4	3	0.15	0.1	0.08

3.2 Data set used for evaluation

In addition to the validation with surface measurements, the quality of the CM SAF SARAH data set 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 set 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). In that data set, the surface incoming direct radiation (SID) was generated and provided as a measure of the direct surface solar radiation. To allow a consistent comparison with the current release of the CM SAF surface radiation data set, here we also report the validation results of the SID data calculated from the SARAH data set.

3.3 Statistical measures

The validation employs several statistical measures and scores to evaluate the quality of the SIS and DNI data sets. Beside the commonly used bias and standard deviation, we also use the (mean) absolute deviation and the correlation of the anomalies derived from the surface measurements and the CM SAF data set. Bias and standard deviation alone provide not sufficient information of the climate quality of a data record. For each data set we further provide the number of months that exceed the target accuracy to characterize the quality of the data sets. In the following chapters the applied quality measures are described. Thereby, the variable 'y' describes the data set to be validated (e. g., CM SAF) and 'o' denotes the reference data set (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 sets, resulting from the arithmetic mean of the difference over the members of the data sets. It indicates whether the data set on average over- or underestimates the reference data set.

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

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 set.

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

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 set.

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

Anomaly correlation

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

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

Here, for each station the mean annual cycle $\bar{y}$ and $\bar{o}$ 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 set is the fraction of the time steps that are outside the requested target value ‘T’. The target values are given by the threshold / target accuracies of the corresponding CM SAF product, plus the non-systematic error (uncertainty) of the BSRN measurements (Ohmura et al. 1998).

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

4 Validation results

In this section the validation results of the Surface Incoming Solar Radiation, SIS, the direct normal irradiance, DNI, and the effective cloud albedo, CAL, are presented. For the evaluation of the quality of the SARAH data set with the previous release of the CM SAF surface radiation data set we also report the validation results of the surface direct irradiance (SID).

For the comparison with the BSRN data the daily and monthly means from the SARAH data set 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 in a mean bias, mean absolute difference, anomaly correlation, standard deviation and fraction of months above a given limit for each individual station and for all stations together. In addition to the results presented in the section 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 SIS data set are summarized in Table 4-1. It shows that the mean absolute difference (MAD) of the data set is significantly better than the requested limit for the target accuracy of 10 W/m^2 and even fulfils the optimal accuracy requirement of 8 W/m^2. In total only about 5 % of the monthly mean data exceed the target accuracy, assuming an uncertainty of the surface measurement of 5 W/m^2. The data set 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 release of the CM SAF surface radiation data set based on observations from the MVIRI instruments. It is clear that the quality of the new CM SAF data set is substantially improved compared to the previous CM SAF data set.

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 sets.*

SIS	N_{mon}	Bias [W/m^2]	MAD [W/m^2]	SD [W/m^2]	AC	$Frac_{mon}$ > 15 W/m^2 [%]
SARAH	1672	1.27	5.46	7.34	0.92	5.6
MVIRI	878	4.24	7.76	8.23	0.89	10.71

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 surface radiation data set has a substantially reduced bias and a lower MAD compared to the MVIRI CM SAF Surface radiation data set at each BSRN stations. Particular improvements can be found compared at Lerwick, Carpentras, and Sede Boquer.

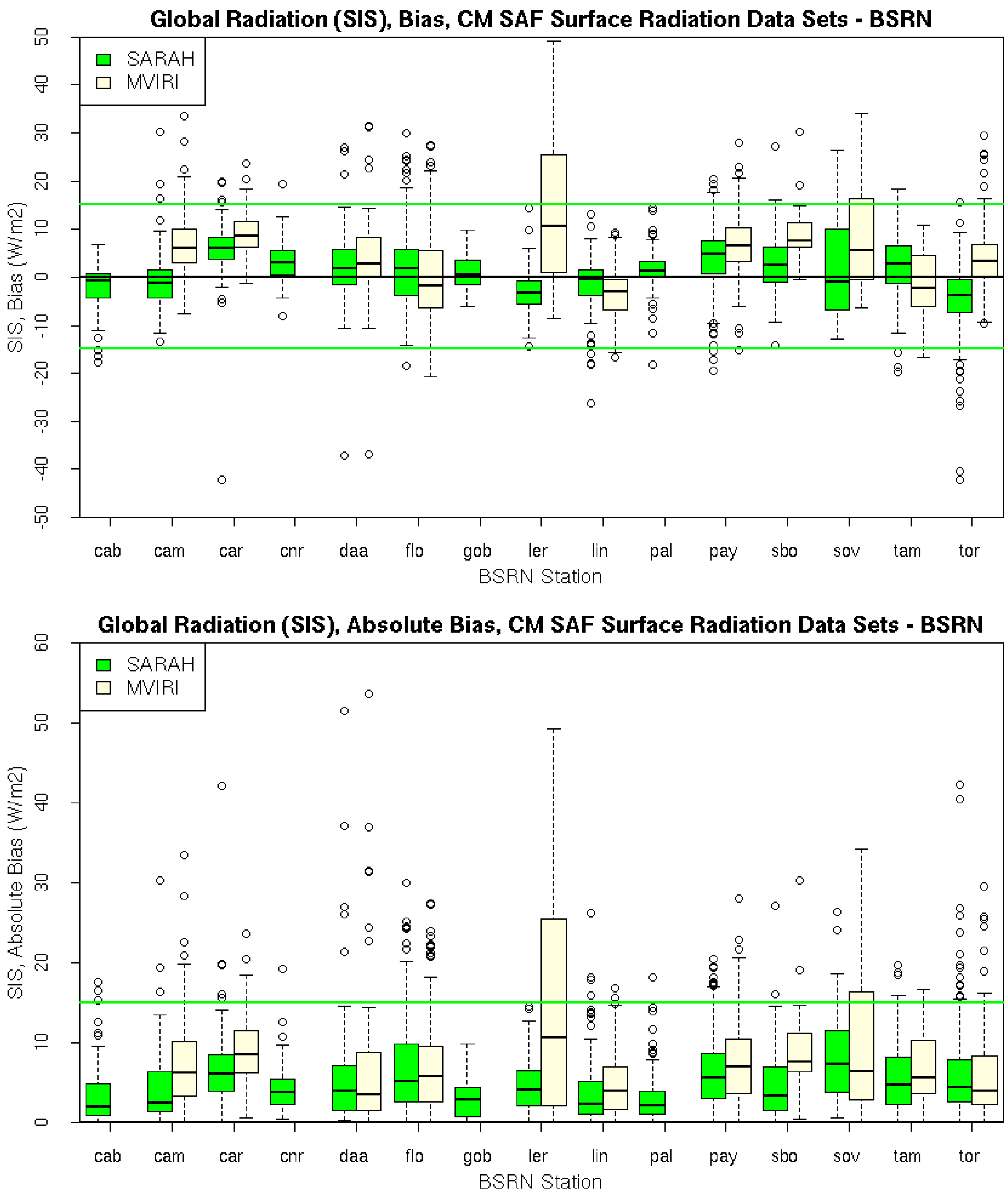


Figure 4-1: *(Top) Bias and (bottom) absolute bias (MAD: mean absolute difference) between the monthly mean BSRN surface measurements and the (green) SARAH SIS data set and the (yellow) MVIRI CM SAF Surface Radiation data set for each considered BSRN station. The green lines indicate the target value of 15 W/m^2.*

Daily means

Table 4-2 provides the validation result for the daily means of the new SARAH SIS data set and the previous CM SAF MVIRI SIS climate data record. 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 CM SAF SIS daily mean data set (i. e., 12.1 W/m^2) is well below the target value of 25 W/m² and even below the optimal accuracy of 15 W/m^2. Nearly 90 % of the MAD values meet the accuracy requirement. Thus, the accuracy requirement is fulfilled for the daily means. As for the monthly mean validation, the SARAH SIS data set shows improved performance for each quality measure compared to the CM SAF MVIRI SIS data set.

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 sets.*

SIS	N_{day}	Bias [W/m^2]	MAD [W/m^2]	SD [W/m^2]	AC	$Frac_{day}$ > 25 W/m^2 [%]
SARAH	48605	1.12	12.1	17.9	0.95	11.3
MVIRI	29790	4.41	15.05	23.36	0.92	16.3

The bias and the MAD of the SIS daily mean from the SARAH data set for the individual BSRN stations are shown in Figure 4-2. Generally, the CM SAF SARAH 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.

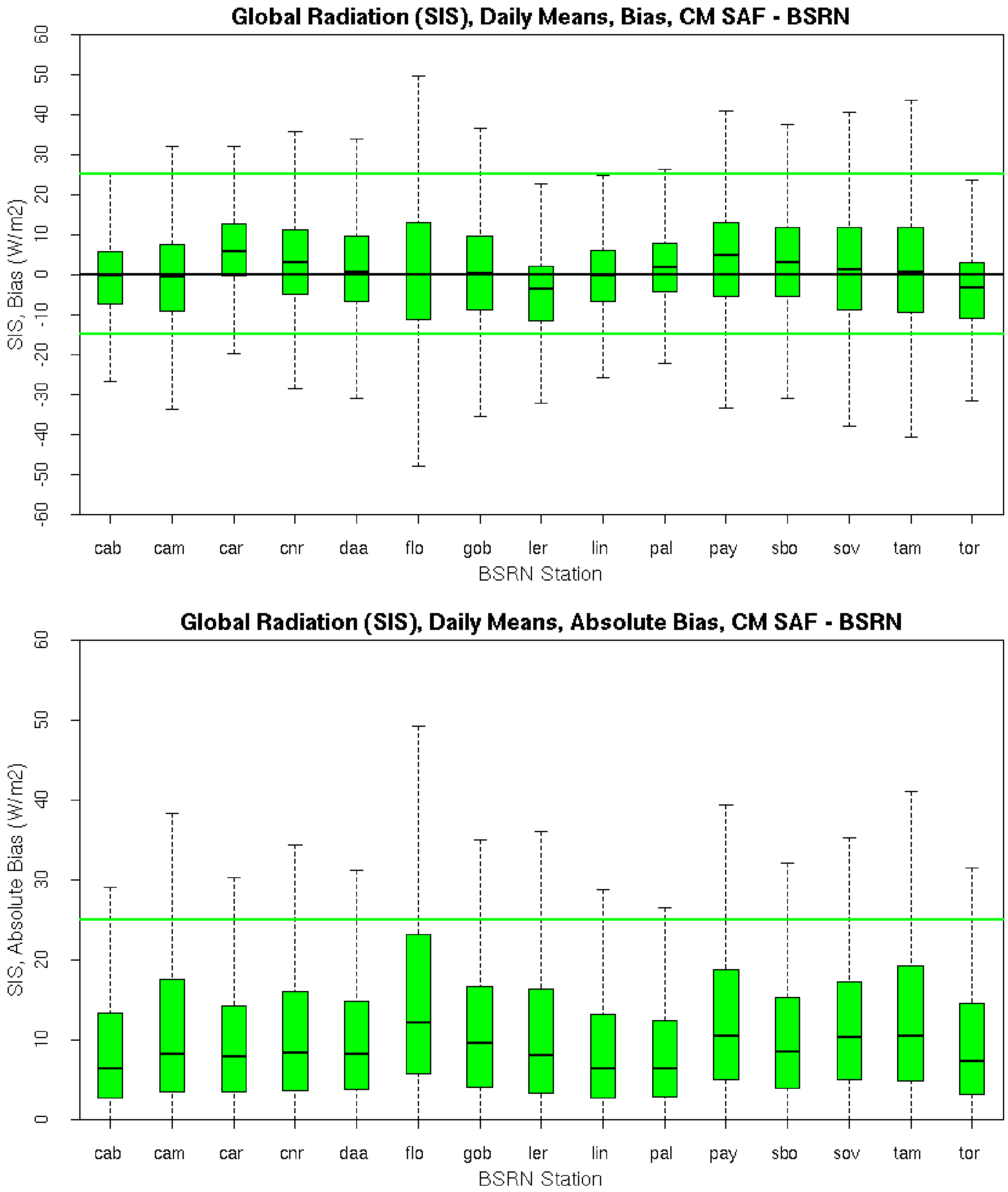


Figure 4-2: *(Top) Bias and (bottom) absolute bias for the comparison of daily mean SIS between the BSRN stations and the SARAH Surface radiation data set. No outliers are shown here.*

4.2 Surface Direct Normal radiation: DNI

This section presents the validation results of the SARAH DNI data set compared to the BSRN surface reference observations.

Monthly means

Table 4-3 shows the validation results of the monthly mean direct normal surface radiation (DNI) from the new CM SAF SARAH surface radiation data set compared to the observations from the BSRN measurements. A small bias of 3.25 W/m^2 is found in the SARAH DNI data set. The mean absolute difference is 17.5 W/m^2 and hence, between the target and the threshold accuracy of 15 W/m^2 and 20 W/m^2, respectively. Considering the uncertainty of the surface measurement of 10 W/m^2, the accuracy requirement is fully fulfilled. The standard deviation and, thus, the spread is slightly larger for DNI than for SIS (22.9 W/m^2 compared to 7.3 W/m^2). Nearly 85 % of the monthly mean values are better than the threshold value. The anomaly correlation is very good with a value of 0.87.

Table 4-3: *Results of the comparison between the monthly mean surface solar direct normal radiation derived from BSRN measurements and the SARAH DNI surface radiation data set. Also shown are the results of the comparison between the monthly mean surface solar direct radiation derived from BSRN measurements and the two CM SAF surface radiation data sets.*

DNI	N_{mon}	Bias [W/m^2]	MAD [W/m^2]	SD [W/m^2]	AC	$Frac_{mon}$ > 30 W/m^2 [%]
SARAH	1541	3.25	17.5	22.9	0.87	16.4

SID	N_{mon}	Bias [W/m^2]	MAD [W/m^2]	SD [W/m^2]	AC	$Frac_{mon}$ > 20 W/m^2 [%]
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 version of the CM SAF surface radiation data set, Table 4-3 also shows the results of the validation of the surface direct radiation (SID) for both, SARAH and the previous CM SAF MVIRI, data sets. Here the substantial improvement of the new data set of the direct surface solar radiation is obvious with improved performance in all aspects of this evaluation.

The results for the individual BSRN stations are shown in Figure 4-3. With the exception of the BSRN station at Toravere substantially more than 50 % of the monthly mean DNI data are within the threshold value at each station. In Toravere, the SARAH DNI data has a negative offset of about -27 W/m^2, which corresponds to a negative offset in SID of about 10 W/m^2. For comparison with the MVIRI CM SAF Surface Radiation data set, which does not contain a DNI data set, Figure 4-3 also presents the bias and the absolute bias of the monthly means of SID from SARAH and from the CM SAF MVIRI data set for each station. For most stations, the accuracy of SID from SARAH has improved compared to the previous CM SAF MVIRI data set.

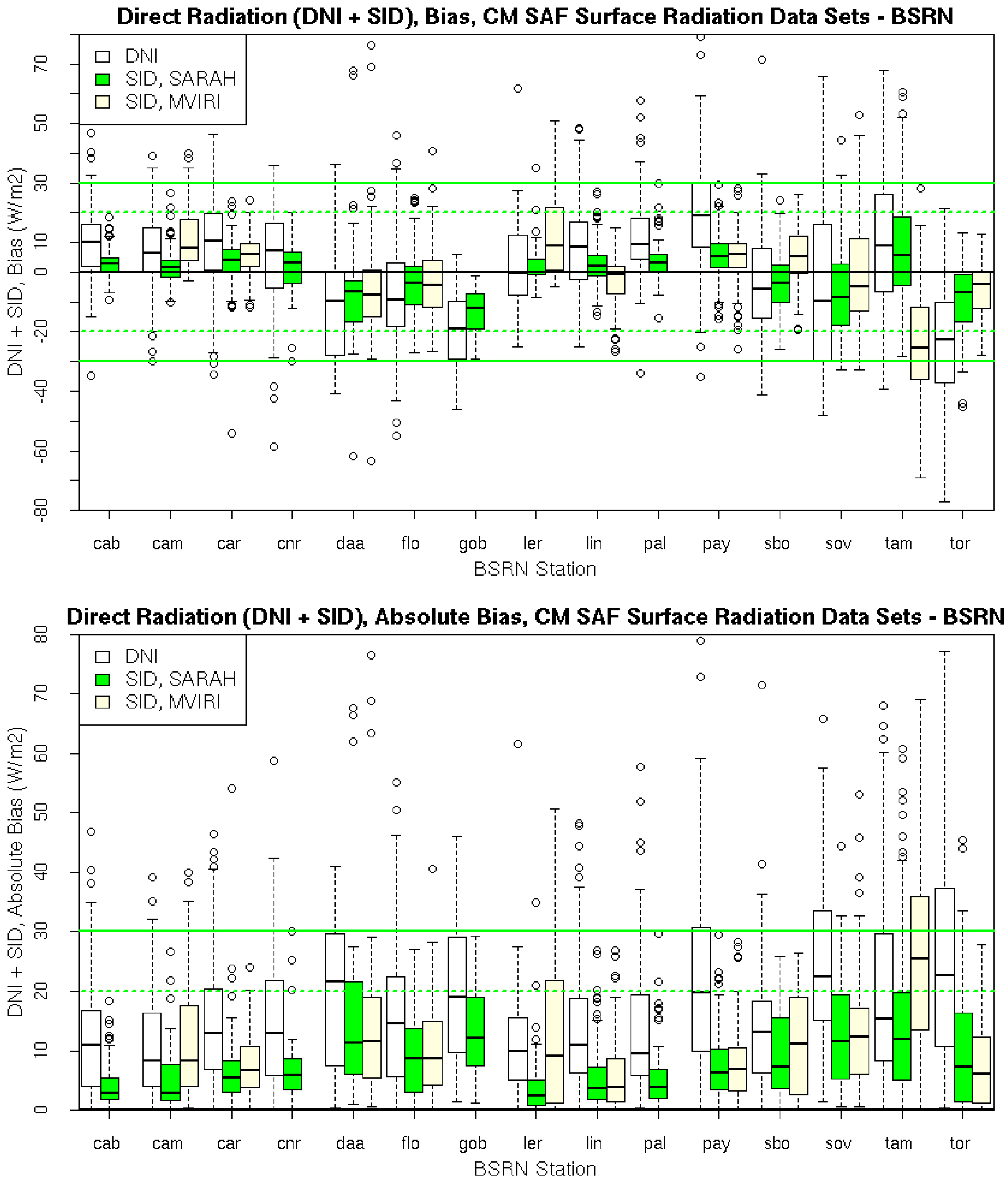


Figure 4-3: *(Top) Bias and (bottom) absolute bias (MAD: mean absolute difference) between the monthly mean BSRN surface measurements and the (white) SARAH DNI data set, the (green) SARAH SID data set, and the (yellow) MVIRI CM SAF SID data set for each considered BSRN station. The solid / dashed green lines indicate the target value of 30 W/m² / 20 W/m² for DNI and SID, respectively.*

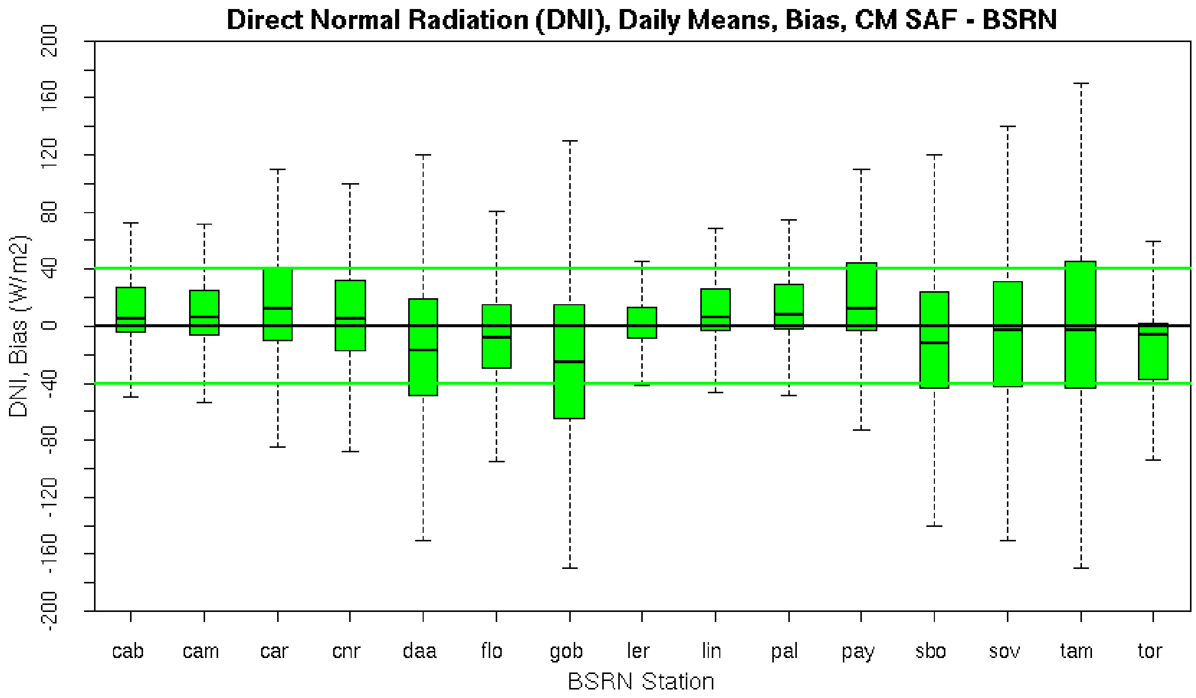
Daily means

The validation results for the daily means of the CM SAF SARAH DNI are shown in Table 4-4. The mean absolute difference is slightly larger than for the daily mean SIS data set (34.0 W/m^2 compared to 12.2 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 CM SAF MVIRI surface radiation data set, the evaluation results for the surface direct irradiance (SID) from the SARAH data set are also reported in Table 4-4. As for SIS, the substantially improved performance of SARAH compared to the CM SAF MVIRI data set can be seen in all aspects of the validation.

Table 4-4: *Results of the comparison between the daily mean surface solar direct normal radiation derived from BSRN measurements and the SARAH DNI surface radiation data set. Also shown are the results of the comparison between the monthly mean surface solar direct radiation derived from BSRN measurements and the two CM SAF surface radiation data sets.*

DNI	**N_{day}**	**Bias [W/m^2]**	**MAD [W/m^2]**	**SD [W/m^2]**	**AC**	**$Frac_{day}$ > 40 W/m^2 [%]**
SARAH	41253	3.8	34.0	48.4	0.91	32.8
SID	**N_{day}**	**Bias [W/m^2]**	**MAD [W/m^2]**	**SD [W/m^2]**	**AC**	**$Frac_{day}$ > 30 W/m^2 [%]**
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 in Figure 4-4 show the same features as for the monthly mean SID. Exceptionally large mean absolute differences are found at the mostly sunny, cloud free desert stations of Gobabeb, Sede Boqer, Solar Village and Tamanrasset. For most other stations, at least 50 % of the daily mean bias difference of DNI is within the threshold value.



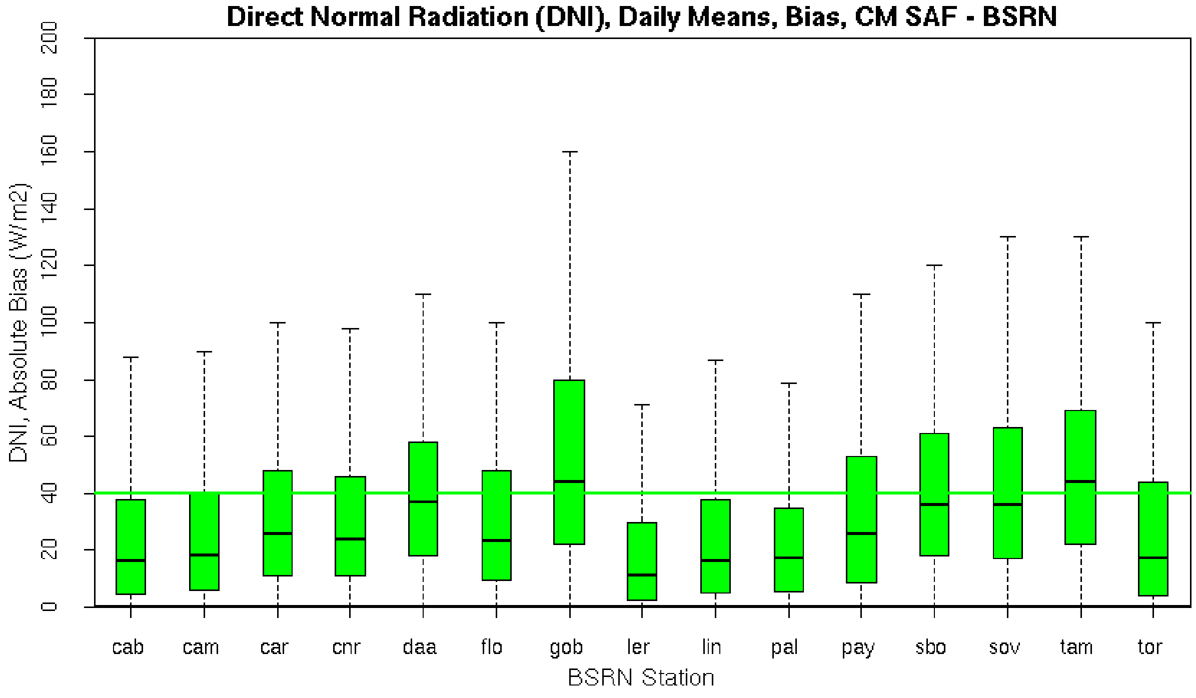


Figure 4-4: *(Top) Bias and (bottom) absolute bias for the comparison of daily mean DNI between the BSRN stations and the SARAH Surface radiation data set. No outliers are shown here.*

4.3 Effective cloud albedo CAL

The effective cloud albedo is derived from the satellite observations using Equation 4.1

$$n = \frac{\rho - \rho_{srf}}{\rho_{\max} - \rho_{srf}}$$ **(Equation 4.1)**

Here, ρ is the observed reflection ρ_{srf} is the clear sky reflection and ρ_{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 we assume a perfect clear sky irradiance (no errors), 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:

$$SIS = (1 - CAL) \cdot SIS_{clear}$$ **(Equation 4.2)**

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 4-5 shows the maximum error in the cloud index, 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

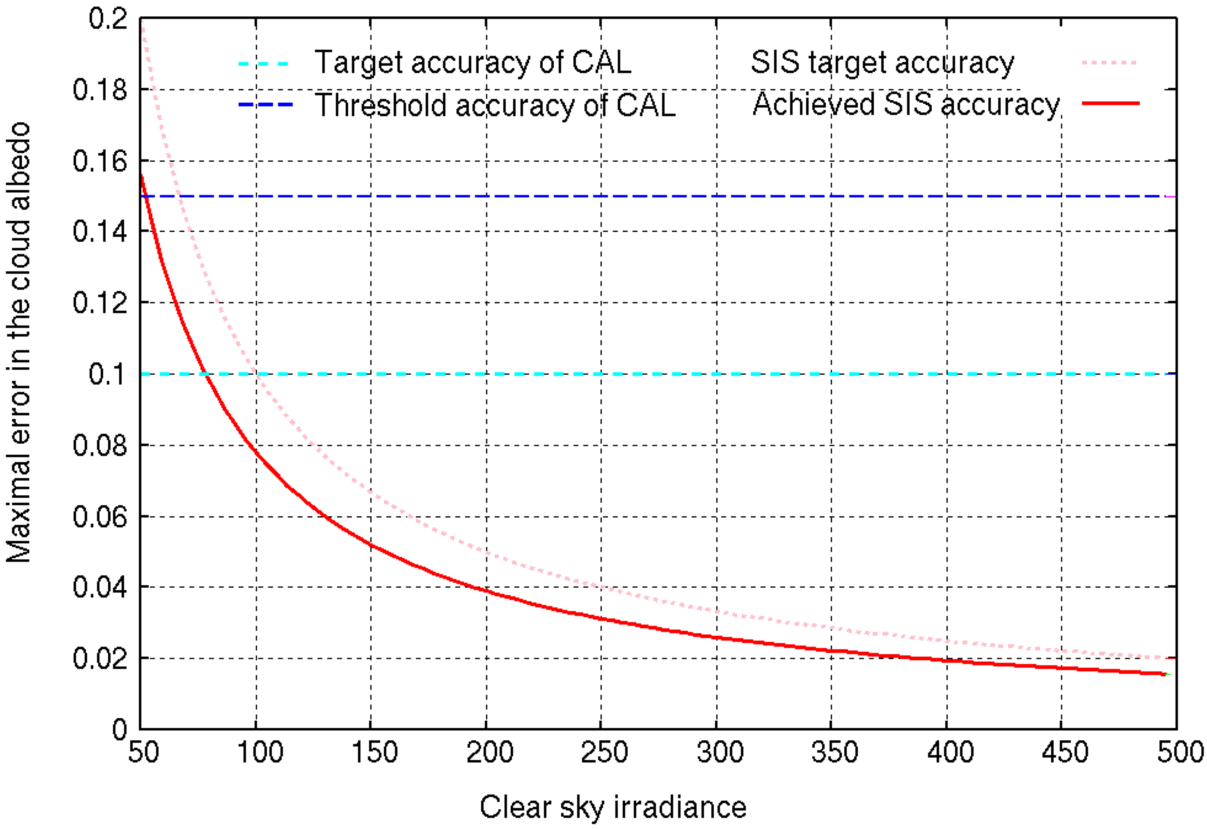


Figure 4-5: *Maximum error of the monthly mean effective cloud albedo in dependency of the clear sky irradiance based on the derived SIS accuracy. The target accuracy is 10 W/m². For the achieved SIS accuracy the mean absolute difference given in Table 4-1 has been used.*

Figure 4-5 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 4-6. 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.

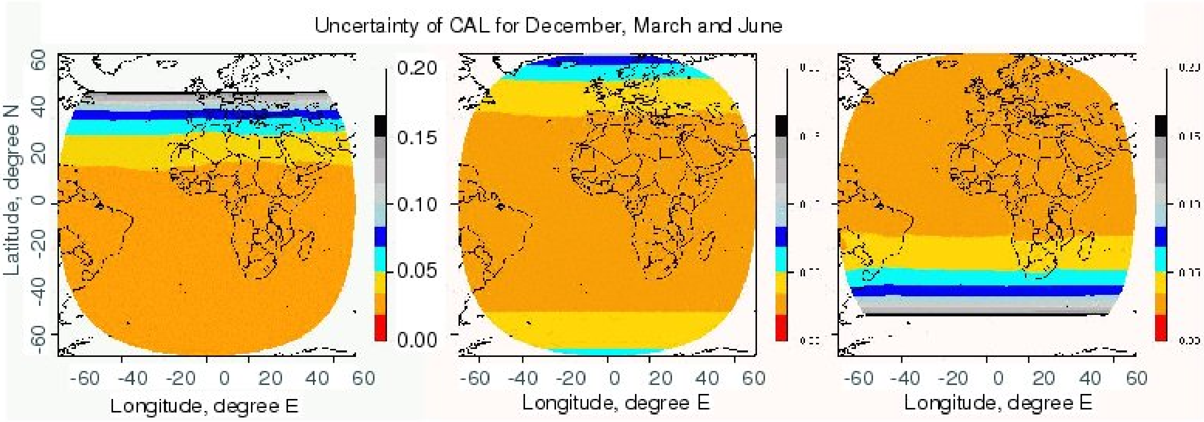


Figure 4-6: *Uncertainty of the effective cloud albedo for winter, spring and summer months. The applied method fails to provide the accuracy of the method for the white regions followed by the black colored "border".*

Daily means

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

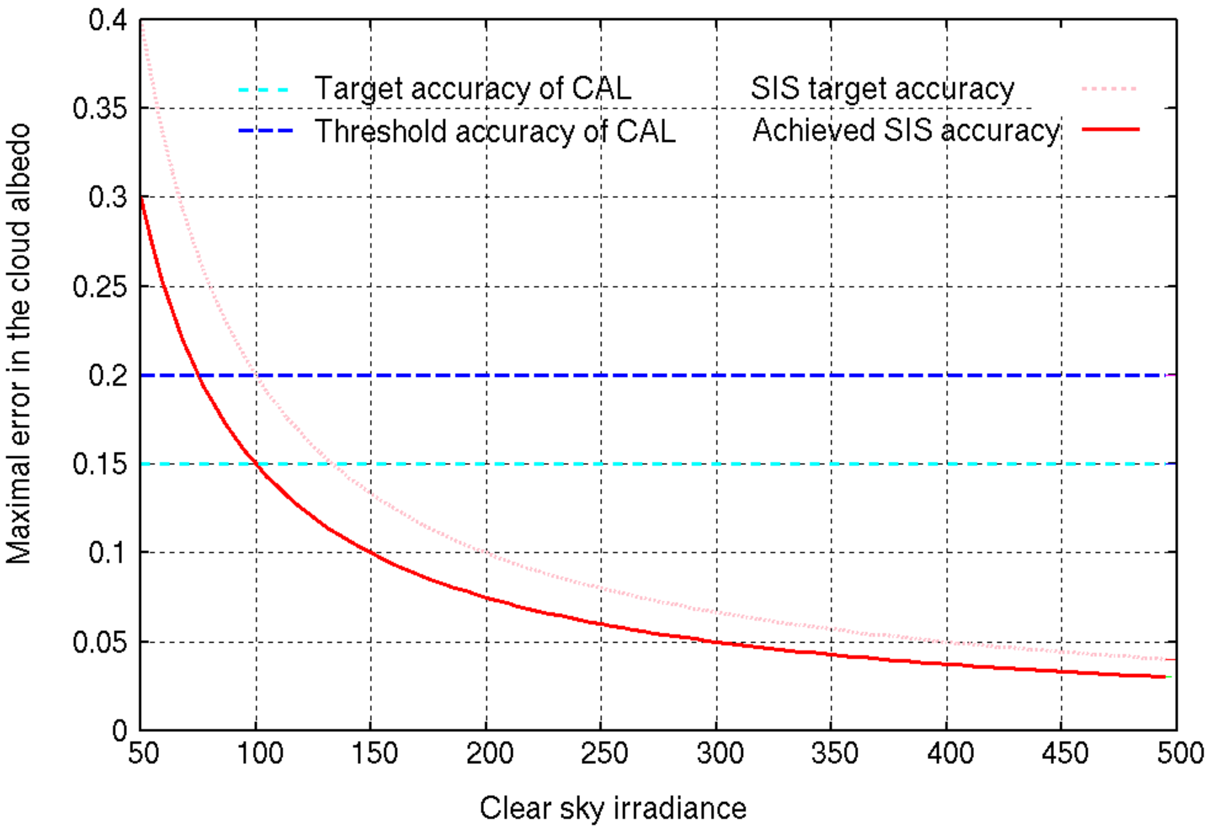


Figure 4-7: *Maximal error of the effective cloud albedo (daily mean) for different clear sky irradiance values based on the derived SIS accuracy for daily means. The target accuracy is 20 W/m². For the achieved SIS accuracy the mean absolute difference given in Table 4-2 has been used.*

In Figure 4-7 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.

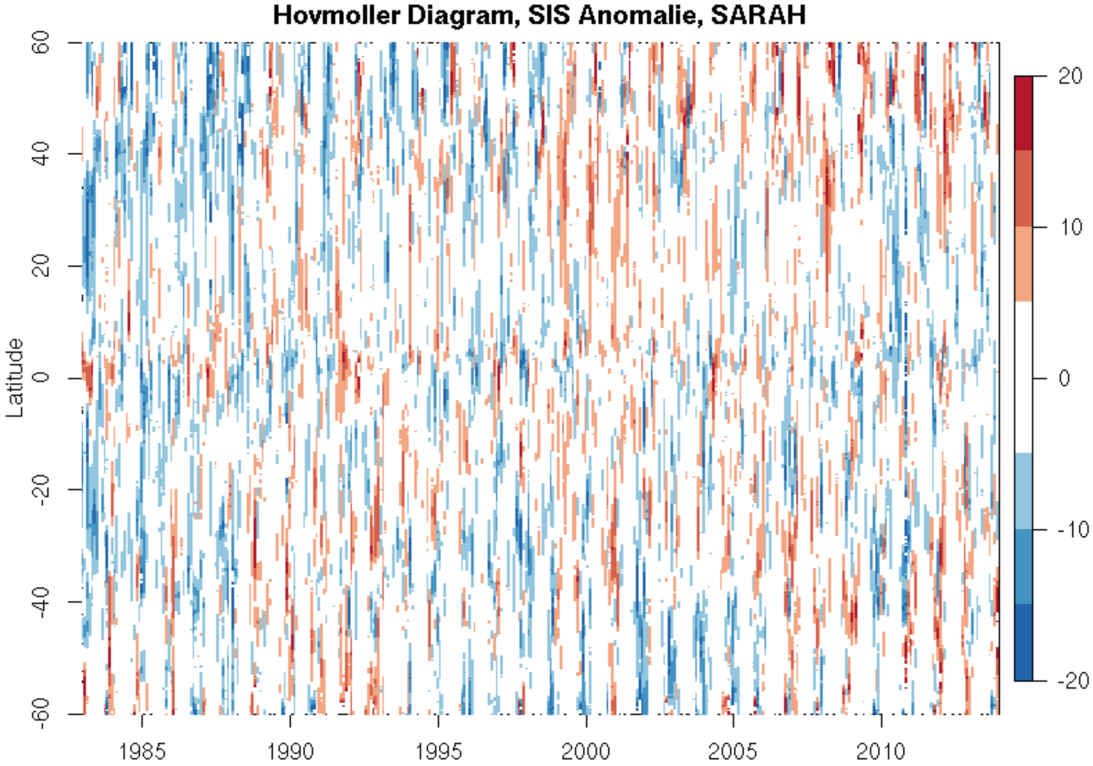
5 Homogeneity of the solar surface irradiance data sets

The definition of a climate data record requests that the time series is homogeneous over time, so that it can be meaningfully statistically evaluated by, for instance, performing a trend analysis. Artificial steps and/or temporal trends in the data set, 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 5-1 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 5-1: *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 2013

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 5-1 shows the Hovmoeller diagram of the monthly mean anomalies of SIS and DNI. The time range contains the full time period of the SARAH data set starting with Meteosat 2 in 1983 until Meteosat 10 in 2013. No obvious step is present in the time series of the anomaly for the whole time range, pointing to the high stability of the SARAH data sets.



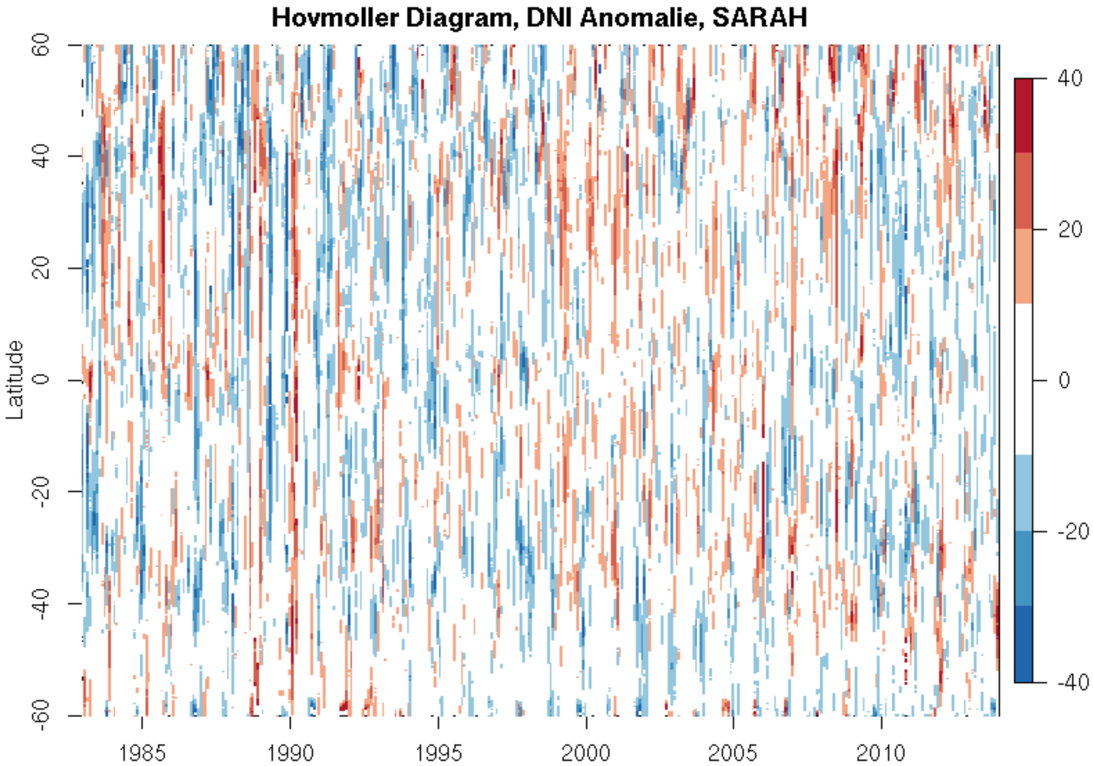


Figure 5-1: *Hovmoeller diagrams of the monthly mean anomaly of (top) SIS and (bottom) DNI.*

To evaluate and quantify the stability of the SARAH data set, 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 adjusted to ensure their homogeneity (Sanchez-Lorenzo et al. 2013), only these stations are considered here.

Figure 5-2 shows the temporal evolution of the average bias between the monthly mean SARAH SIS data set and the measurements from the GEBA stations. Only stations with more than 95% available monthly means between 1983 and 2011 are considered to avoid artificial shifts in the mean time series due to changes in data availability.
A negative decadal trend of -1.1 W/m^2/decade of the bias is detected. This trend is found to be statistically significant, but is below the CM SAF target accuracy (2 W/m^2/decade). In addition, Figure 5-2 shows the corresponding time series of the bias of the CM SAF MVIRI SIS data set, which exhibits a significant negative trend of -1.2 W/m^2/dec compared to the GEBA surface observations between 1983 and 2005. For this period the SARAH SIS data set does not show a significant trend documenting the enhanced stability of the SARAH data set compared to the previous CM SAF MVIRI surface radiation data set.

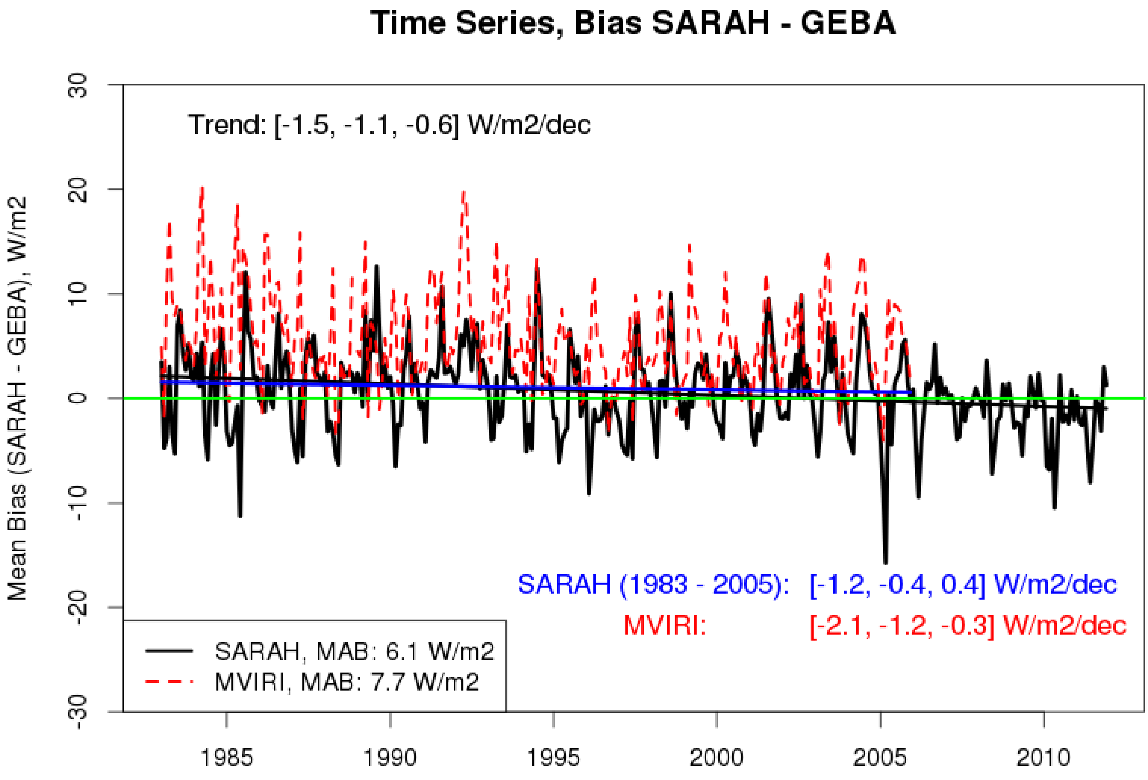


Figure 5-2: *Temporal evolution of the normalized differences between the CM SAF data set and the GEBA data. The green line represents the zero line, the black and the blue straight lines represent the linear regression of the time series for the time periods 1983 to 2011 and 1983 to 2005, respectively.*

6 Conclusion and Recommendation

6.1 Conclusion

The satellite-derived data sets of the surface incoming solar and direct normal radiation (SIS and DNI) from CM SAF have been validated by comparison with observations from 15 high-quality ground-based stations of the BSRN network. The applied validation limit or target value 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 systematic error of the BSRN surface measurements.
Prior to 1992 no BSRN measurements are available. Thus, the data set 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 data set the mean absolute difference (MAD) of the monthly means (5.5 W/m^2) and the daily means (12.1 W/m^2) is significantly better than the required target accuracy of 10 W/m² and 20 W/m². The validation target is also reached at all considered stations..
For the surface solar direct normal radiation (DNI) from the SARAH data set the mean absolute difference (MAD) of the monthly means (17.5 W/m^2) and the daily means (34.0 W/m^2) is in the range of the required threshold accuracy of 20 W/m² and 30 W/m². Including the uncertainty of the surface observations (estimated to be 10 W/m^2) in the assessment the target value is reached for the monthly mean DNI data and the threshold value is reached for the daily mean DNI data set from SARAH. The threshold value is reached at all stations for the monthly averaged DNI data, while it is achieved at most stations for the daily means.
The evaluation of the CM SAF SARAH SIS CDR with the current CM SAF MVIRI surface radiation data set shows that the monthly and daily mean CM SAF SARAH SIS CDR has a higher quality than the previous CM SAF Surface radiation data set. This also holds for the surface direct radiation (SID), which has been additionally evaluated for the SARAH data set to allow a comparison with the previous version of the CM SAF Surface radiation data set.

The stability of the SARAH SIS data set has been validated against European surface measurements. A significant negative linear trend of -1.1 W/m^2/dec was found, which is below the target stability requirement of 2 W/m^2/dec. Compared to the previous CM SAF SIS data set the stability from 1983 to 2005 has increased significantly; no significant trend in the bias between the SARAH SIS data set and surface observations is detected between 1983 and 2005.

Overall, it is shown that the target / threshold accuracy is achieved for monthly and daily means of the surface incoming solar (SIS) and direct normal radiation (DNI), respectively, of the CM SAF SARAH CDR.

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 0.05 (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. More over, for slant geometries (border of Heliosat coverage) 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, DNI and CAL higher uncertainties are expected over regions with long lasting snow cover and desert regions with bright surfaces. For DNI higher uncertainties are also expected in regions with high temporal and spatial variability in aerosol properties.

Table 6.1 summarizes the validation results obtained for the SARAH data sets.

Table 6-1: *Achieved validation results for SIS, DNI and CAL.*

Product	Summary on mean error (absolute)
DNI: Direct Normal Irradiance at Surface.	*Mean absolute Difference below 18 W/m² and 85 % of (monthly) absolute difference values below 20 W/m² (+ uncertainty of ground based measurements) for monthly means.* *Higher bias values occur in the Alpine and other mountainous regions, e. g. due to uncertainties in area to point comparison and snow coverage.*
SIS: Solar Incoming Solar Radiation.	*Mean Absolute Difference below 6 W/m² and 95 per cent of (monthly) absolute difference values below 10 W/m² (+ uncertainty of ground based measurements) for monthly means and 13 W/m² for daily means respectively.* *Higher bias values occur in the Alpine and other mountainous regions, e. g. due to uncertainties in area to point comparison and snow coverage.*
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.* *Higher bias values might occur during wintertime above +/- 55 degree latitude.* *Higher bias values occur for slant viewing geometries at the border of the Heliosat coverage throughout the year.* *Higher bias values occur also for snow covered regions.*

6.2 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 and DNI, ongoing activity. Significant improvements have already gained for the current SARAH release. The further evaluation is aimed for CDOP-2. If further improvements of the aerosol information are possible they will be implemented as soon as possible. Due to the complex matter of the task a potential implementation of new aerosol information will probably take place in CDOP-3.
b. Study to investigate the effect of a higher temporal resolution of water vapour, e. g. the use of daily means instead of monthly means, CDOP-2. If a higher resolution leads to significant improvements in the accuracy of surface radiation an updated water vapour input will be implemented in CDOP-3 (2018).

- Improvement of algorithms.

c. Development and evaluation of methods for the correction of broken clouds effect for the direct beam irradiance. The implementation is aimed for CDOP-2 and the SARAH Edition 2, which is planned to be released end of 2016 (DRR is foreseen for summer 2016).
d. Evaluation of potential improvements in the retrieval of clear sky reflection in order to minimise cloud contamination. The evaluation is aimed for CDOP-2, but the implementation will probably take place in CDOP-3 (2018).

- Analysis and evaluation of benefits and drawbacks of modifications with minor or regional effect on accuracy.

e. Evaluation of potential to improve the cloud detection over snow. The evaluation is aimed for CDOP-2, but the implementation will probably take place in CDOP-3 (2018).
f. Develop a correction for the determination of the cloud albedo under high viewing angles (slant viewing geometries). This effect could result in a small overestimation of the cloud albedo due to larger pixel sizes and enhanced likelihood of clouds in the satellite pixel. This effect can be estimated by comparison of the cloud albedo derived from the Meteosat Prime satellite and the Meteosat East satellite. It is aimed to implement this correction in the next Edition of SARAH in CDOP-2, end 2016.
g. 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. However, this is a item for CDOP-3

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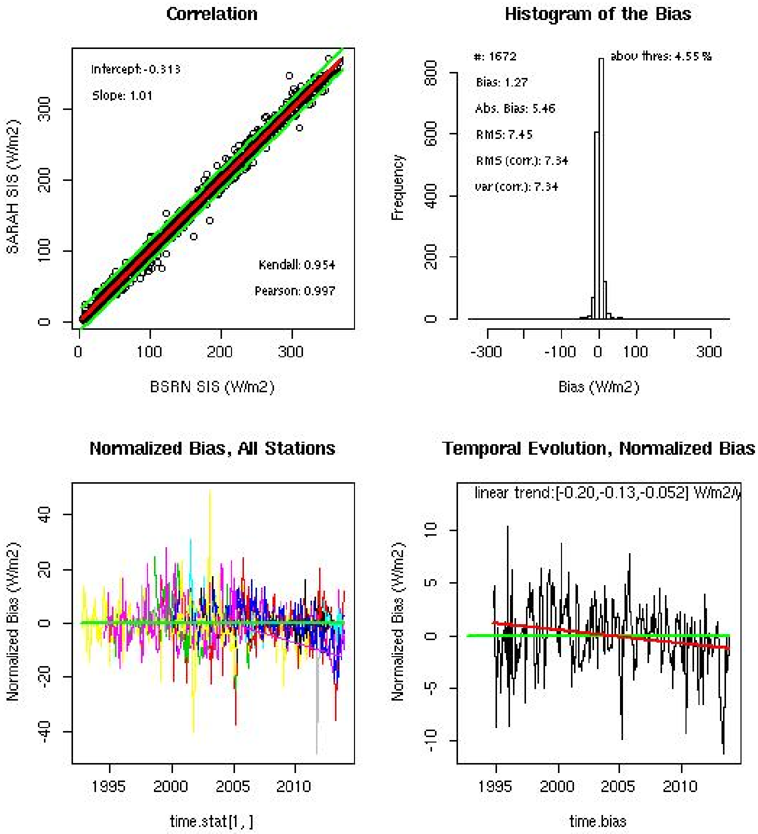
7 Appendix A: Validation figures of results for all BSRN station

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 SIS and DNI data sets, respectively. Shown is the correlation between the SARAH 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.

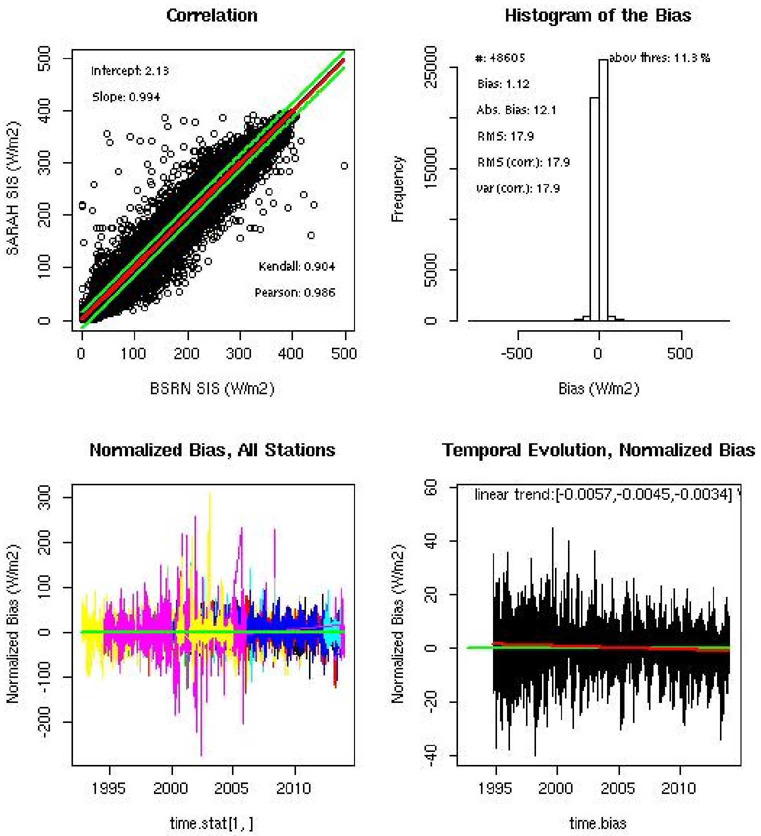
The subsequent figures present for each BSRN station the comparison of the monthly and daily SIS and DNI data from the SARAH data set and the BSRN observation. Shown are the time series (black: surface observations, red: SARAH data set), the mean annual cycle, the correlation, the time series and the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

Complete Validation Results for SIS

Monthly means

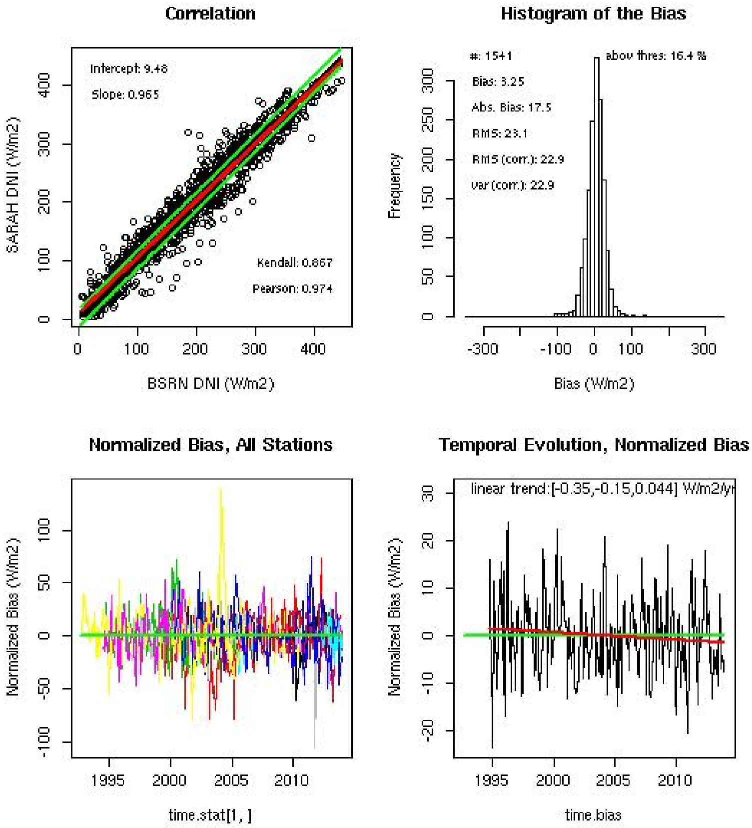


SIS, Daily means

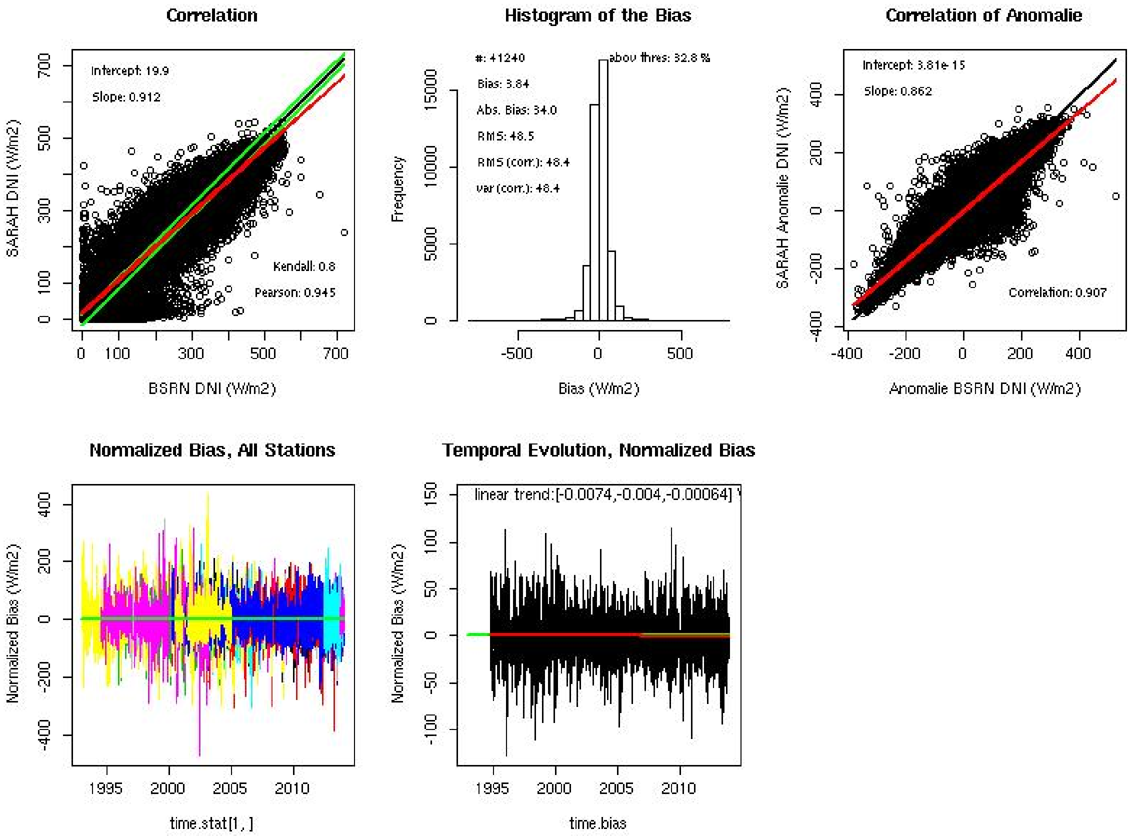


Complete Validation Results for DNI

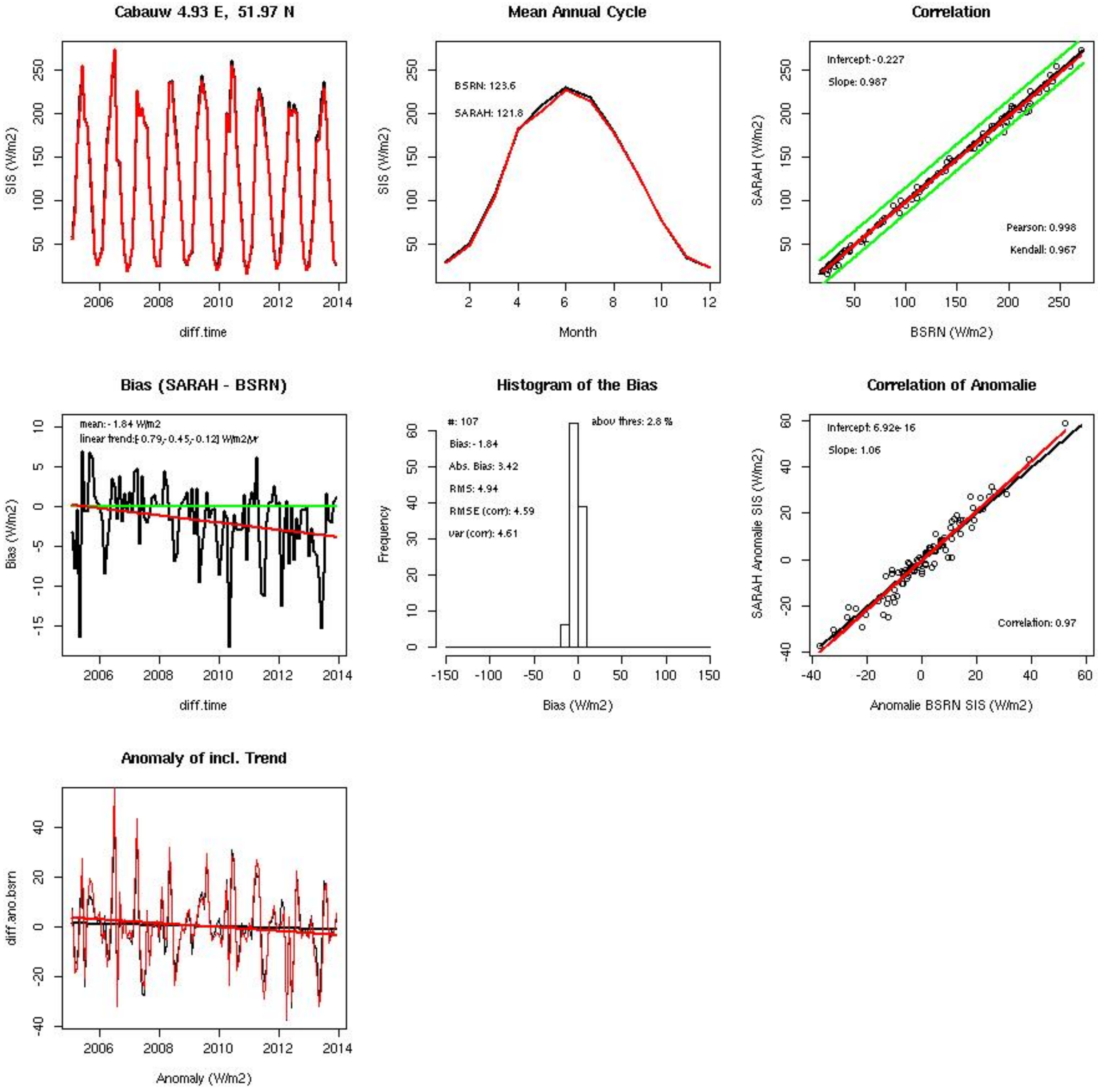
Monthly means



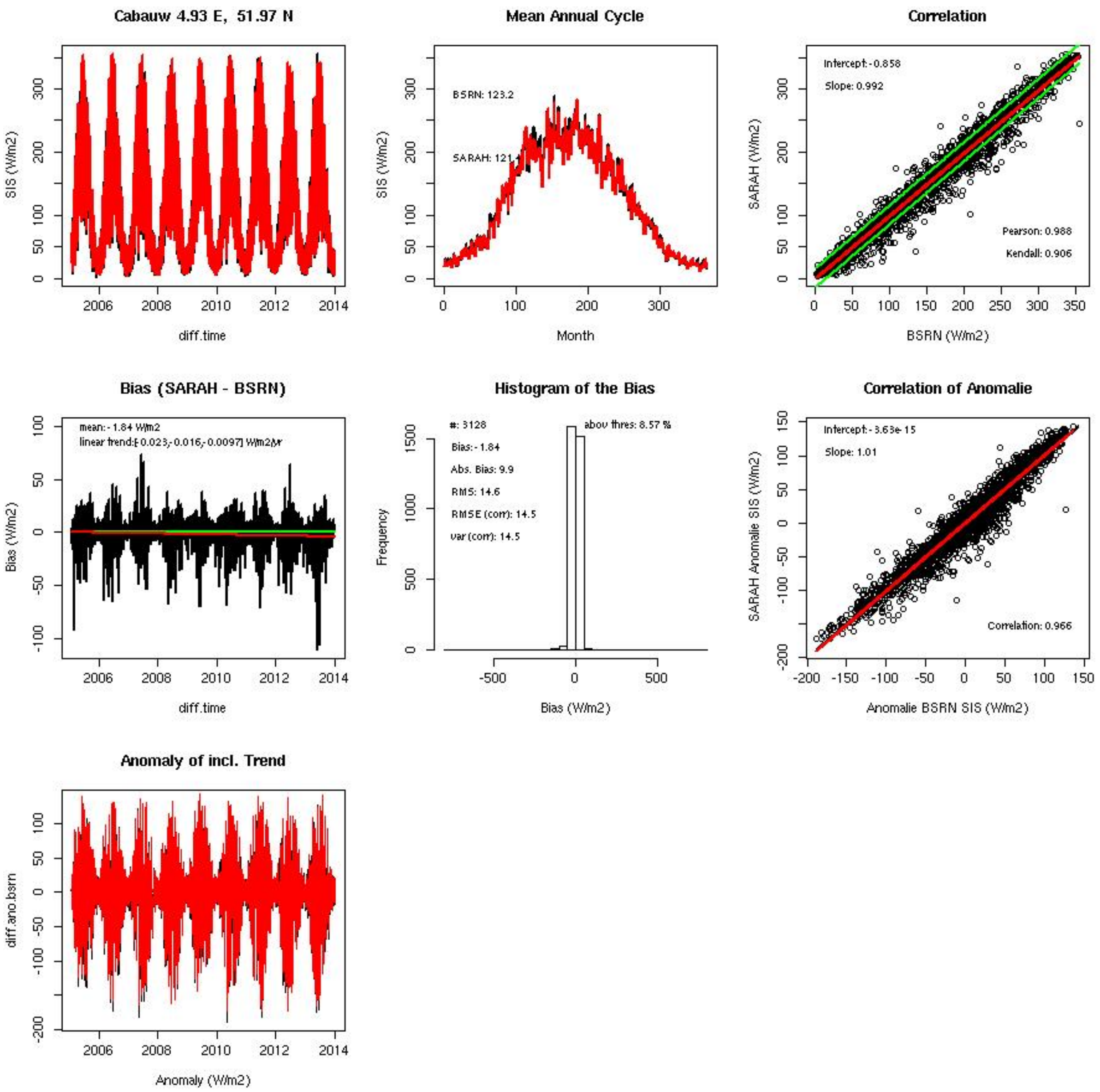
DNI, Daily means



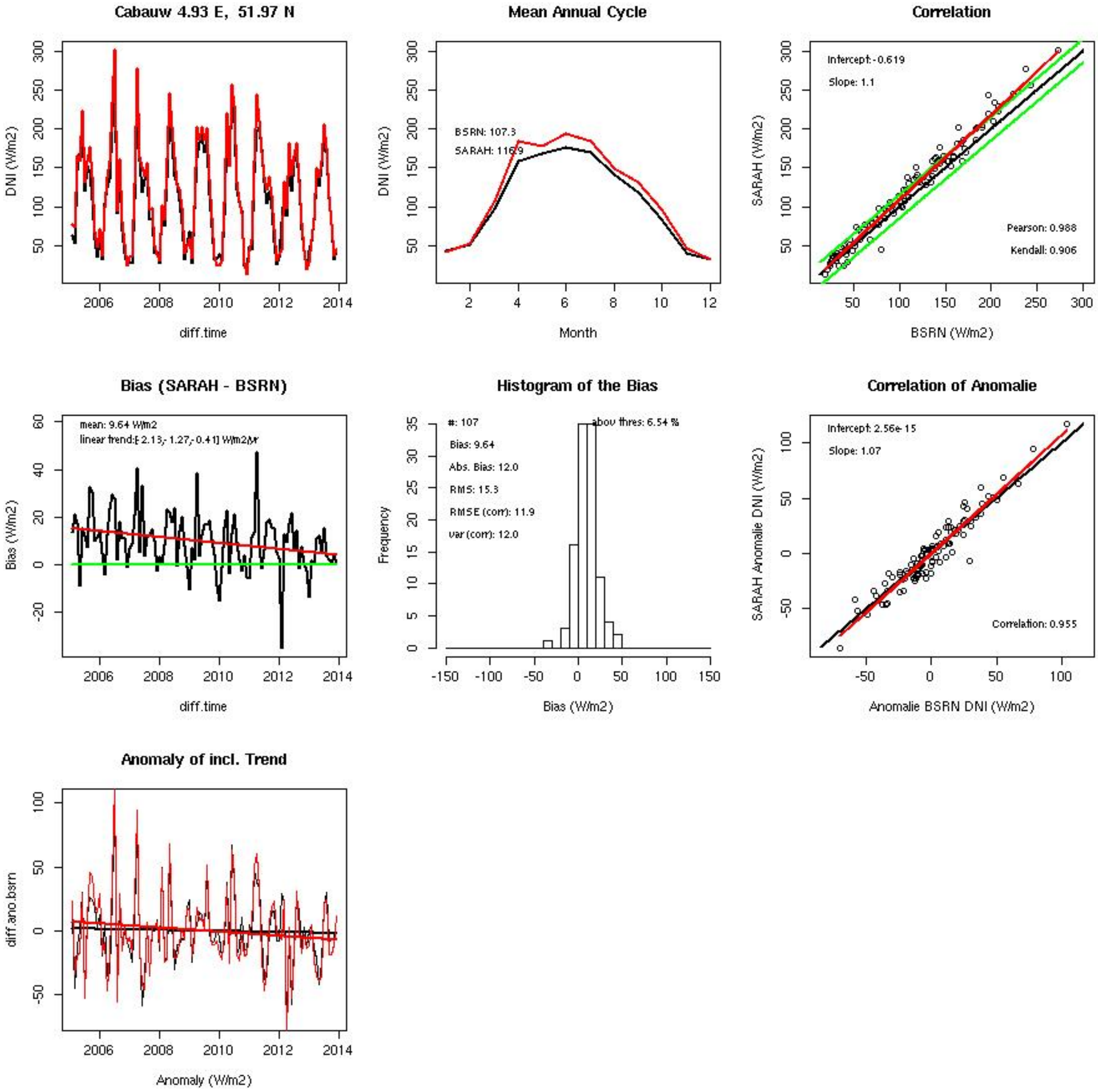
Cabauw, SIS, monthly mean



Cabauw, SIS, daily mean



Cabauw, DNI, monthly mean



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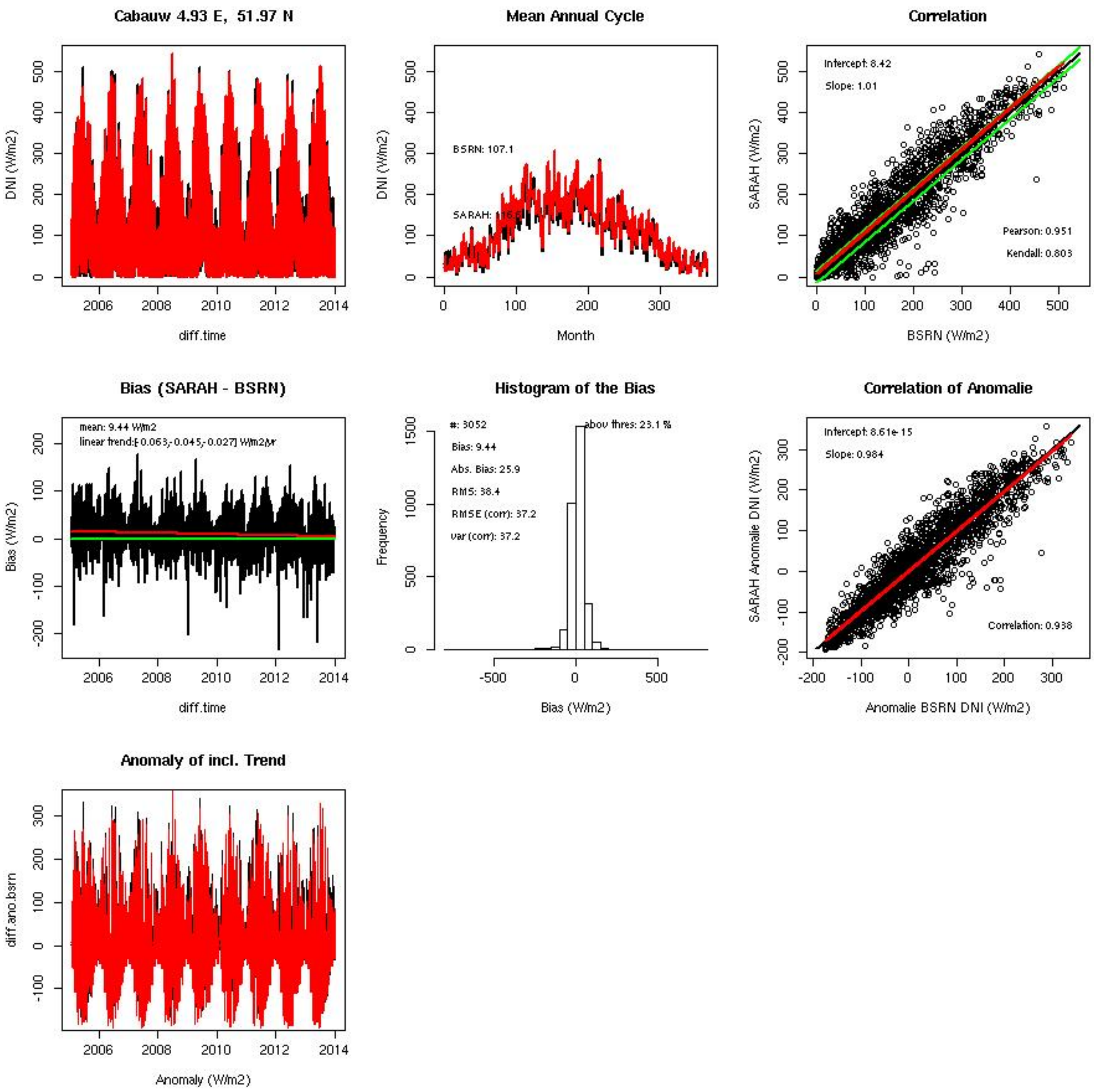
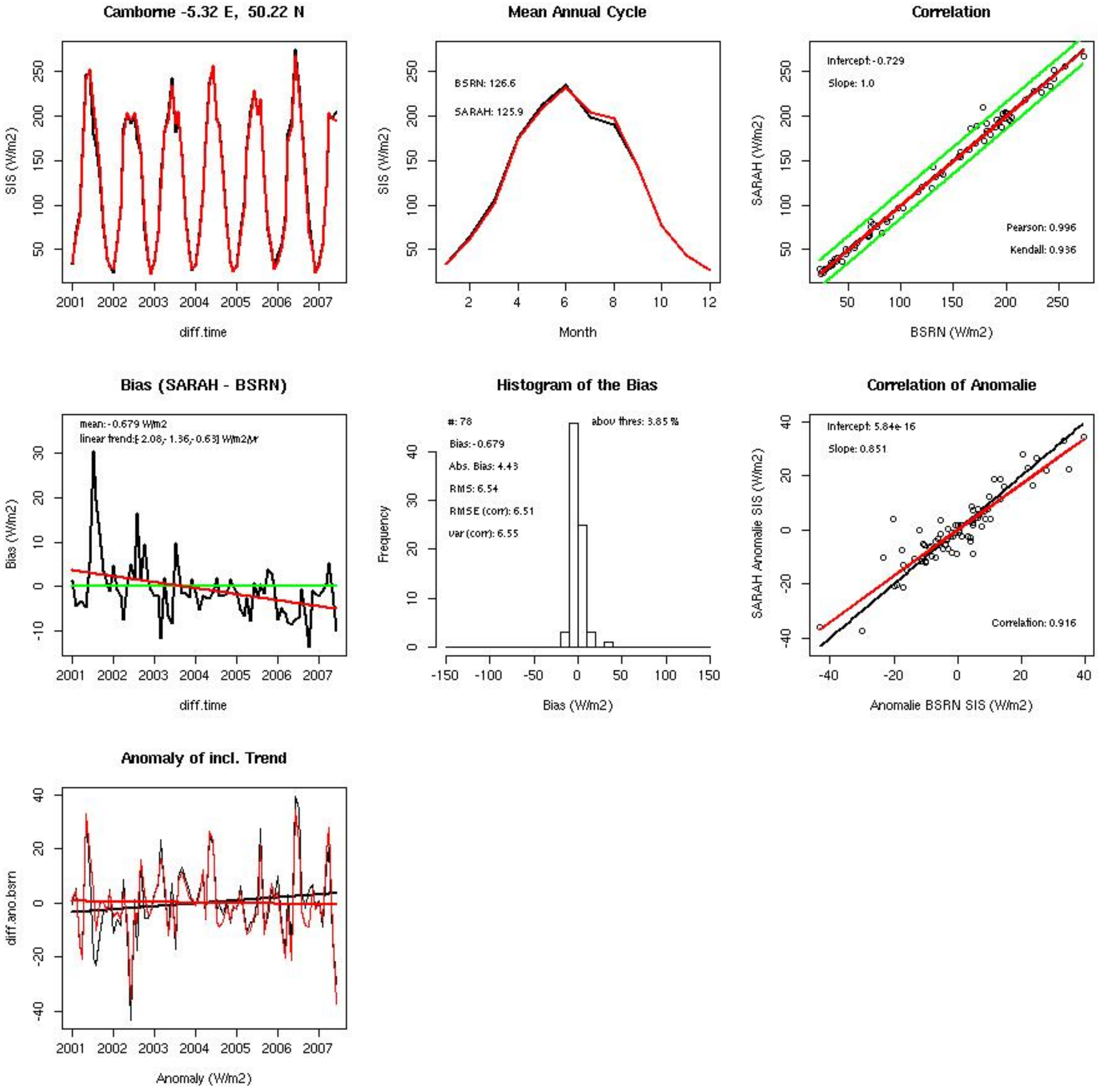
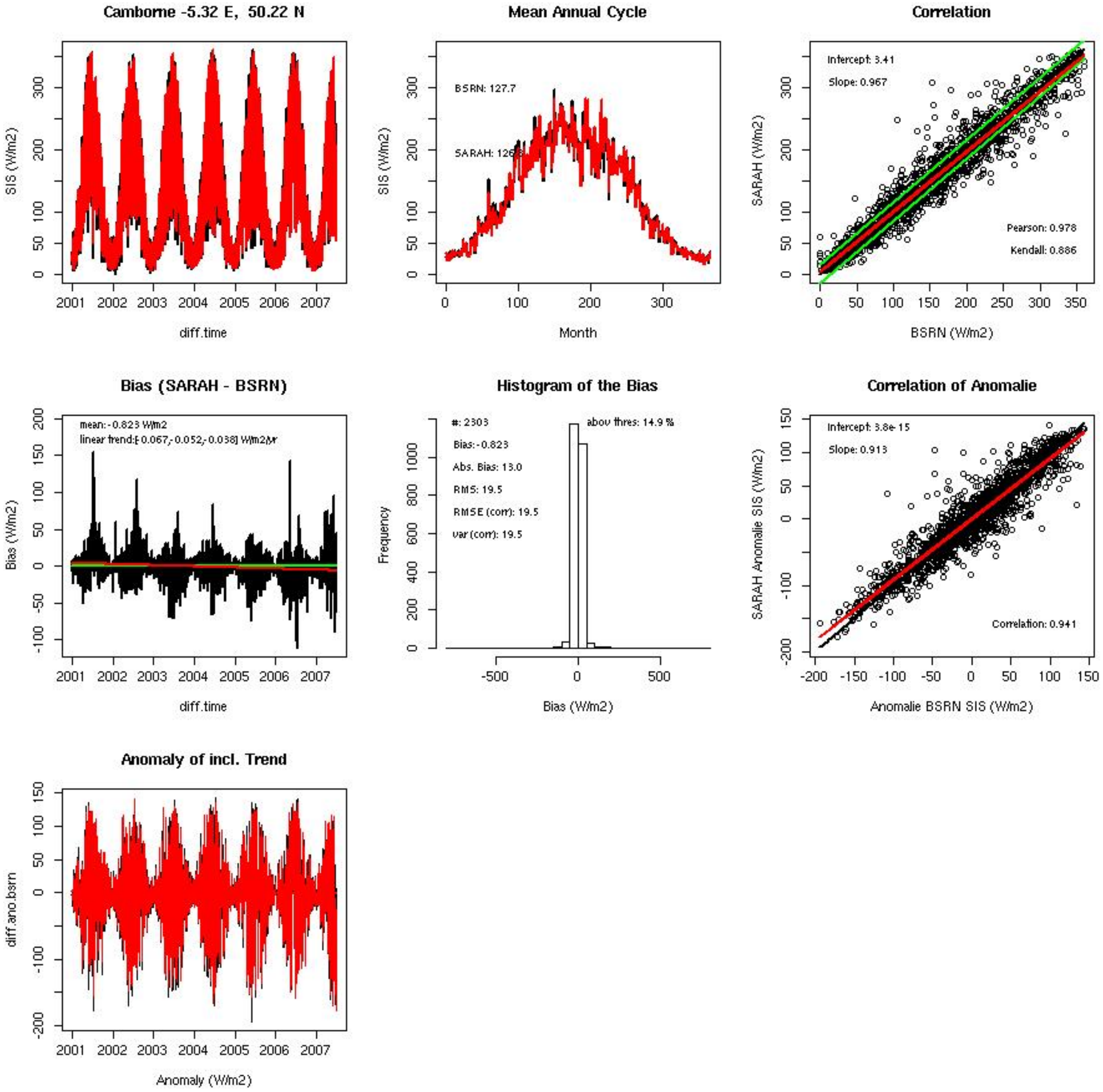


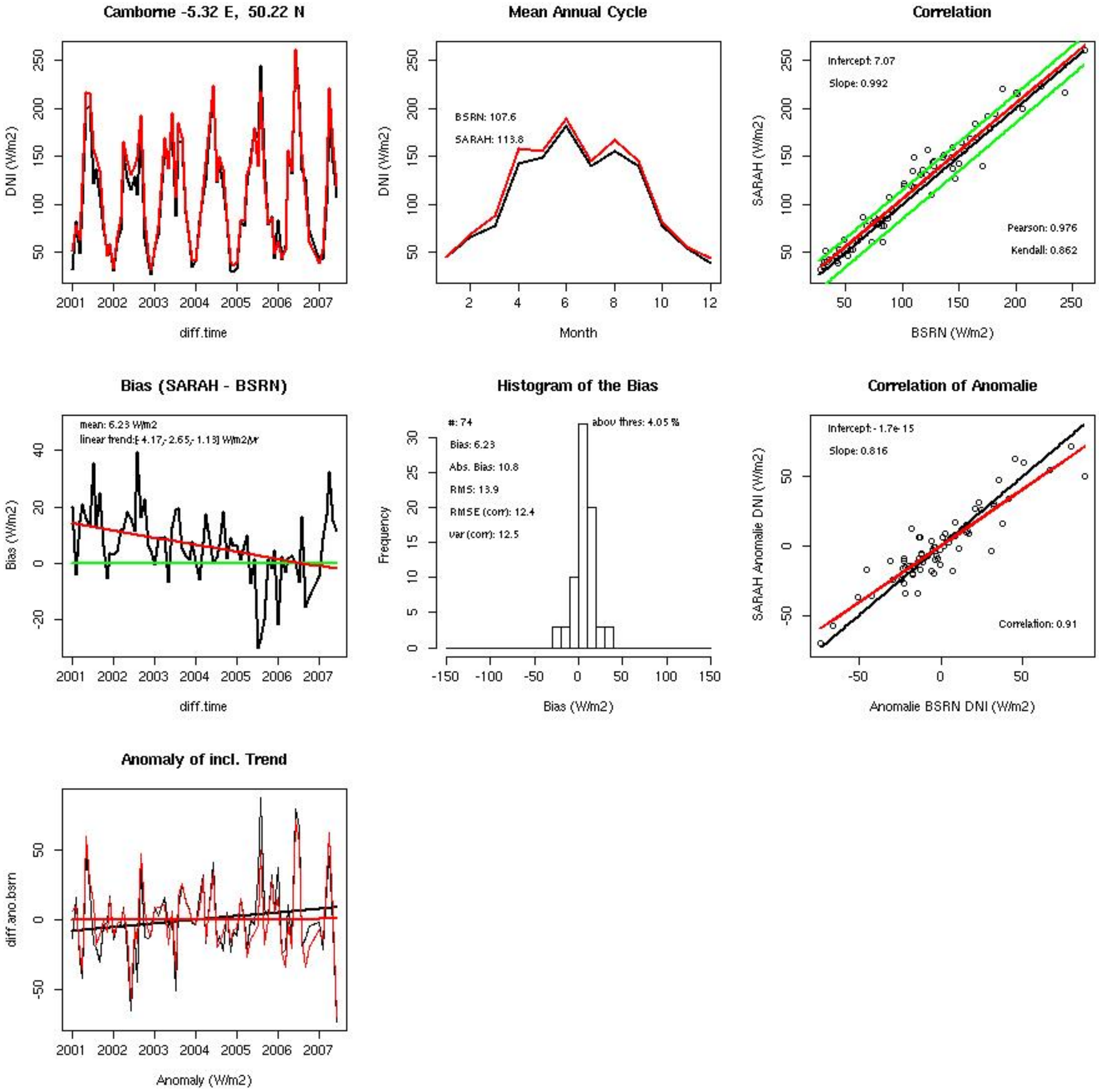
Camborne, SIS, monthly mean



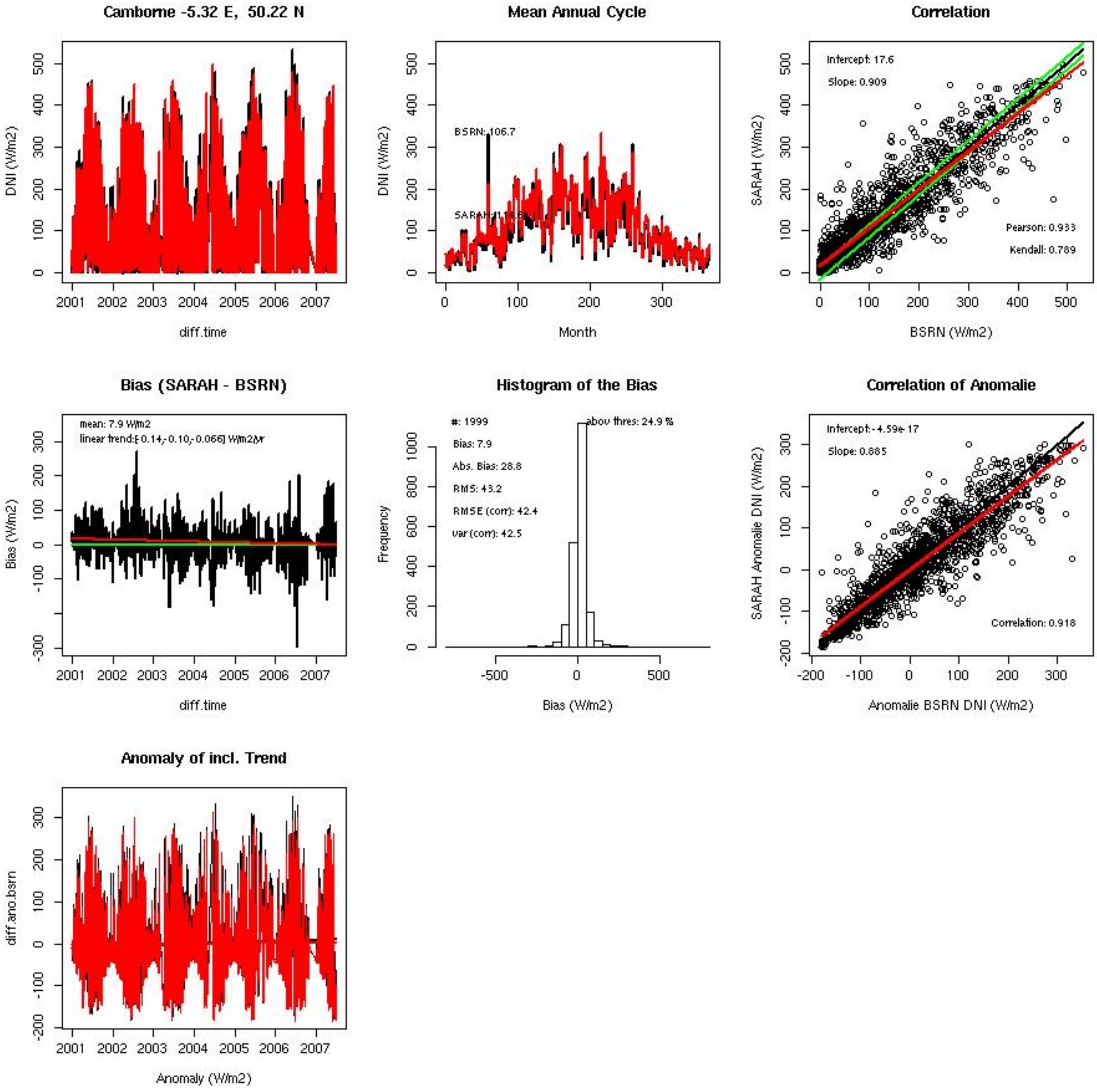
Camborne, SIS, daily mean



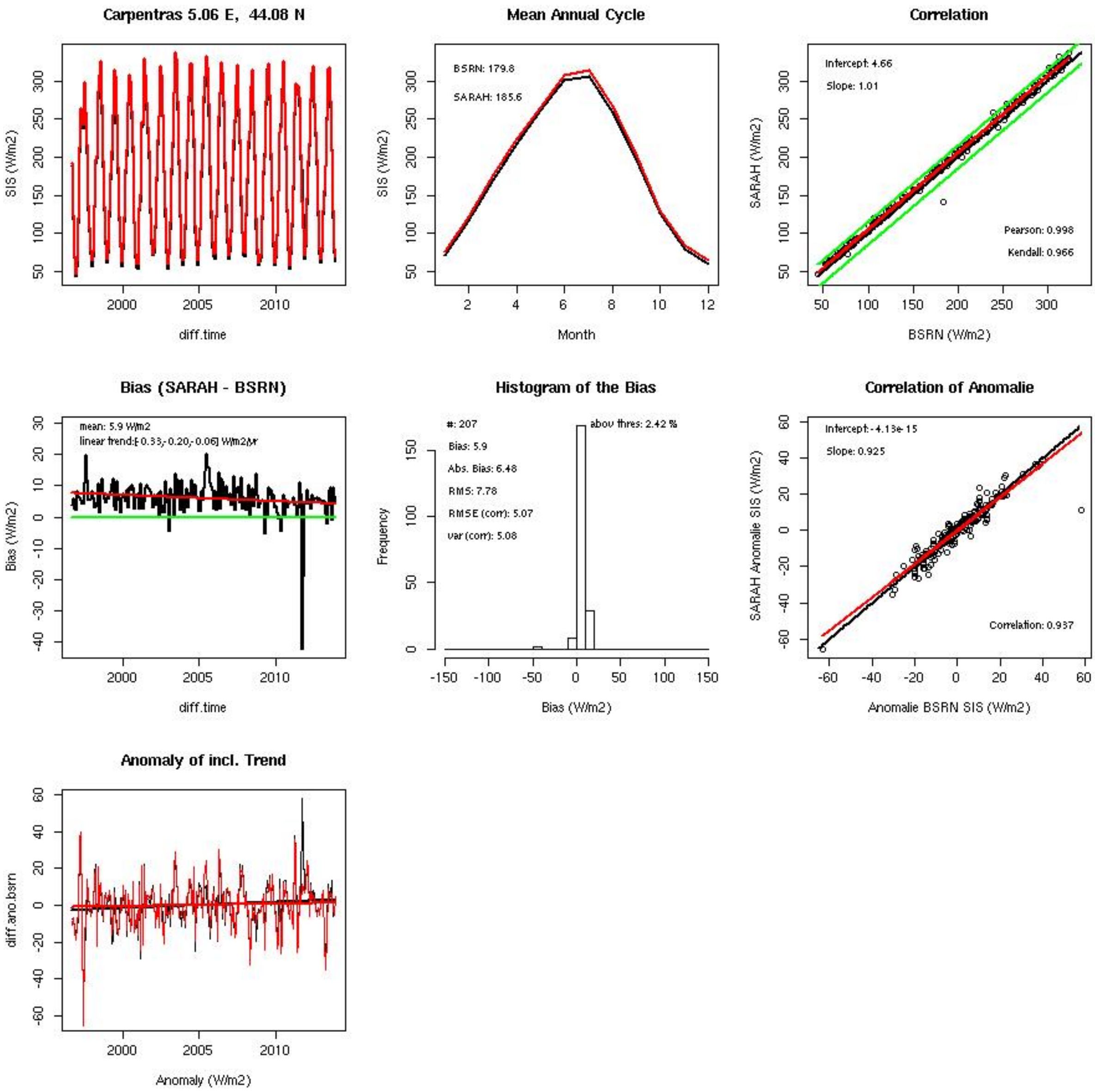
Camborne, DNI, monthly mean



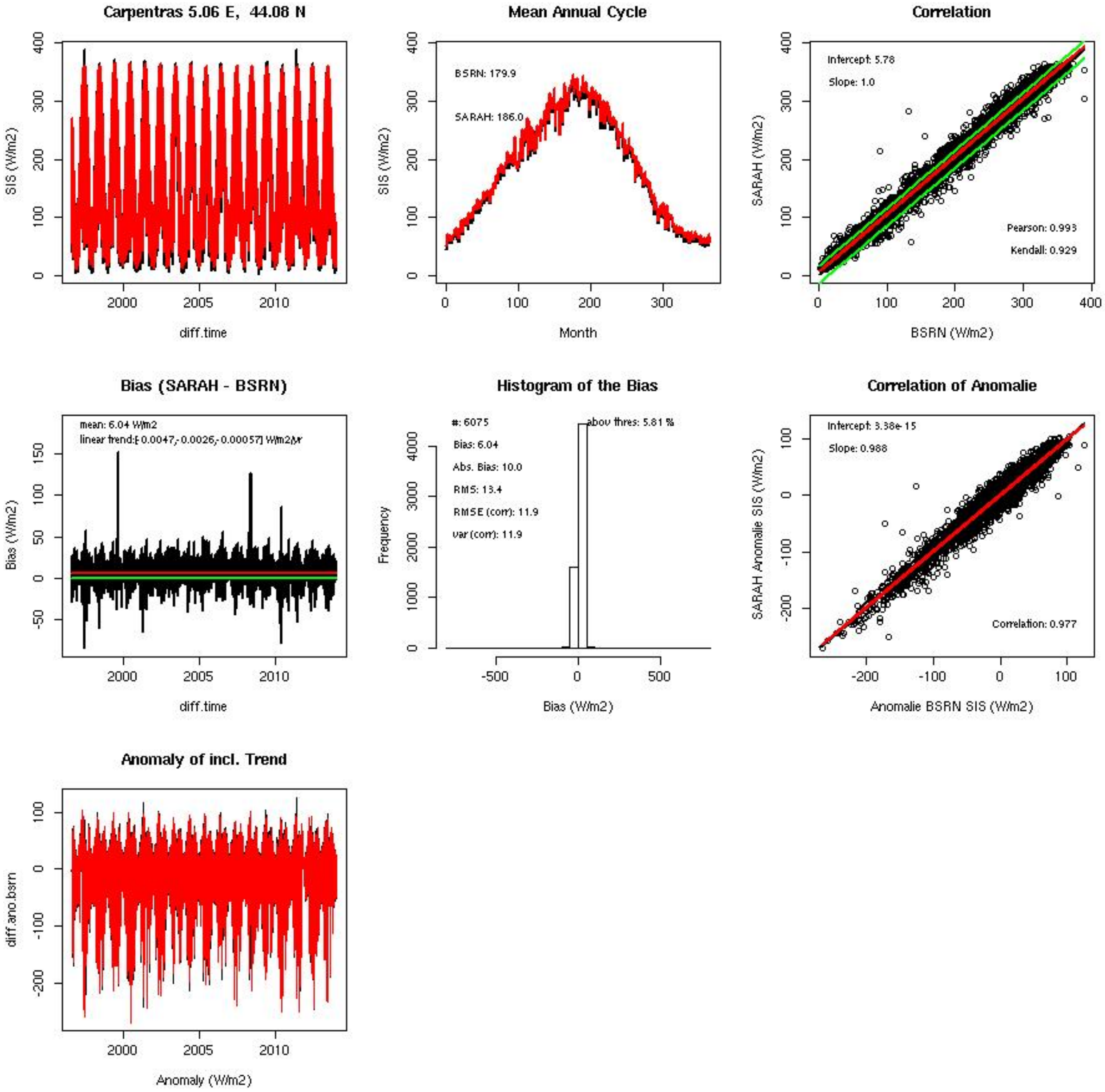
Camborne DNI, daily mean



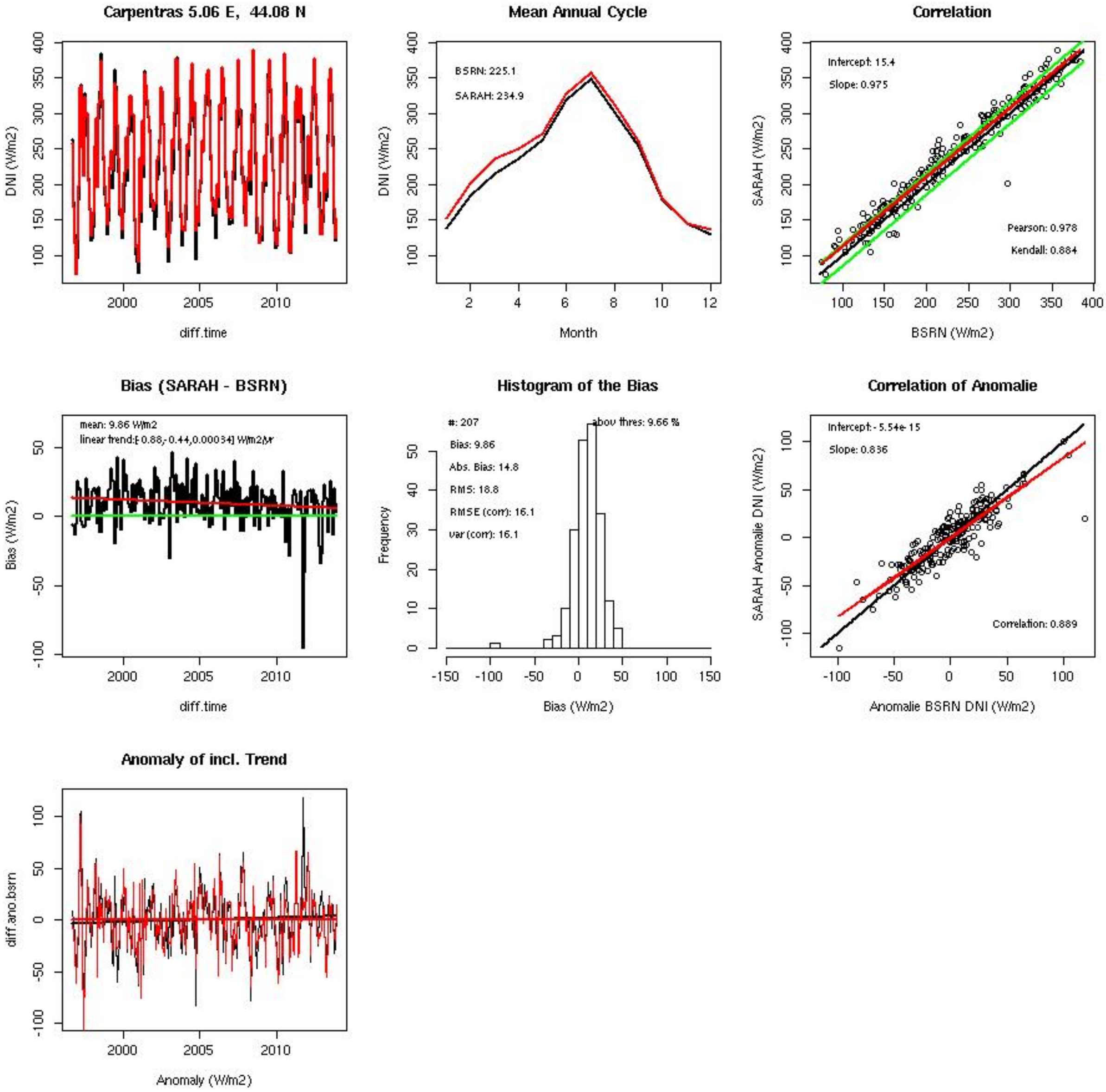
Carpentras, SIS, monthly mean



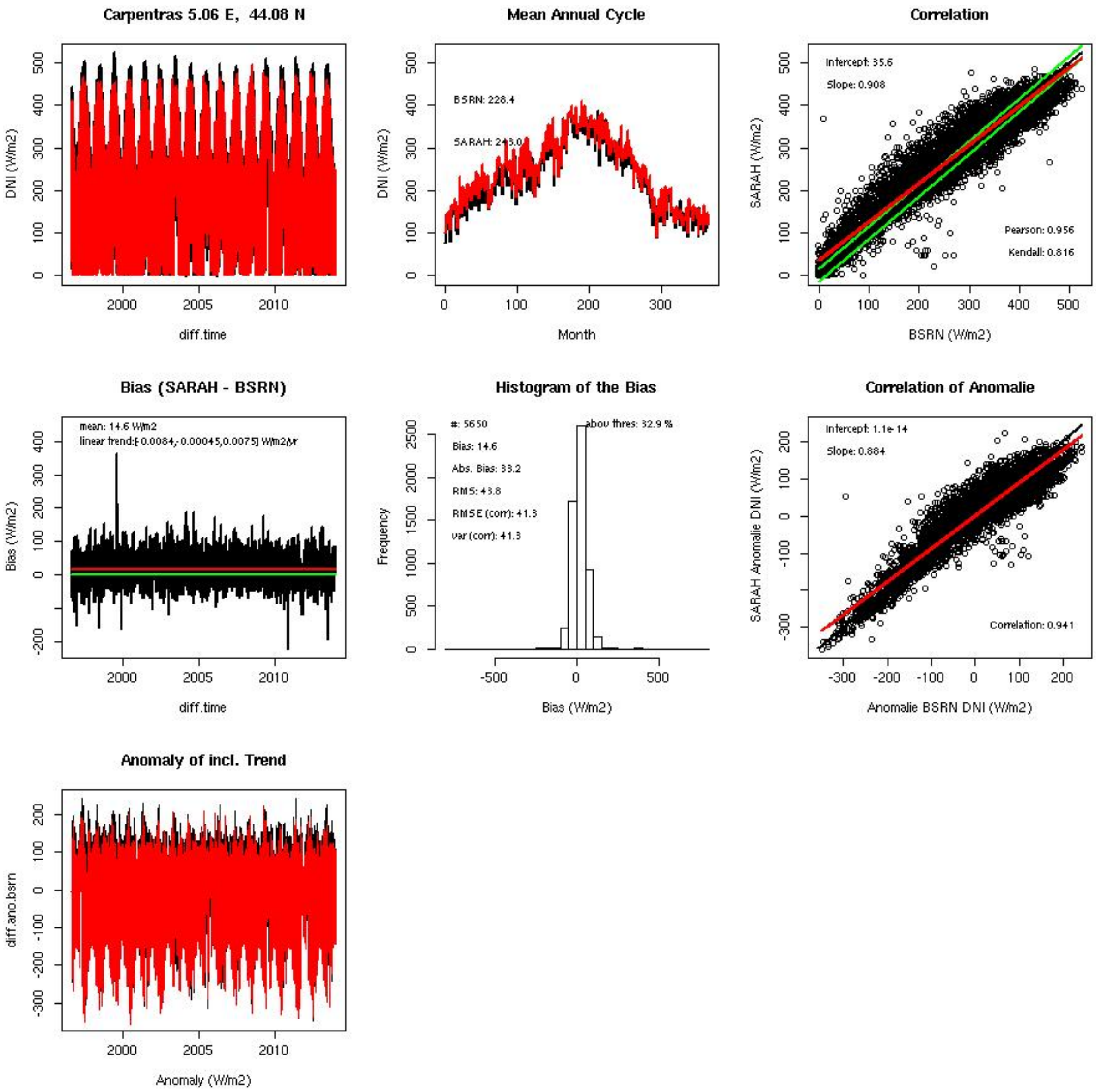
Carpentras, SIS, daily mean



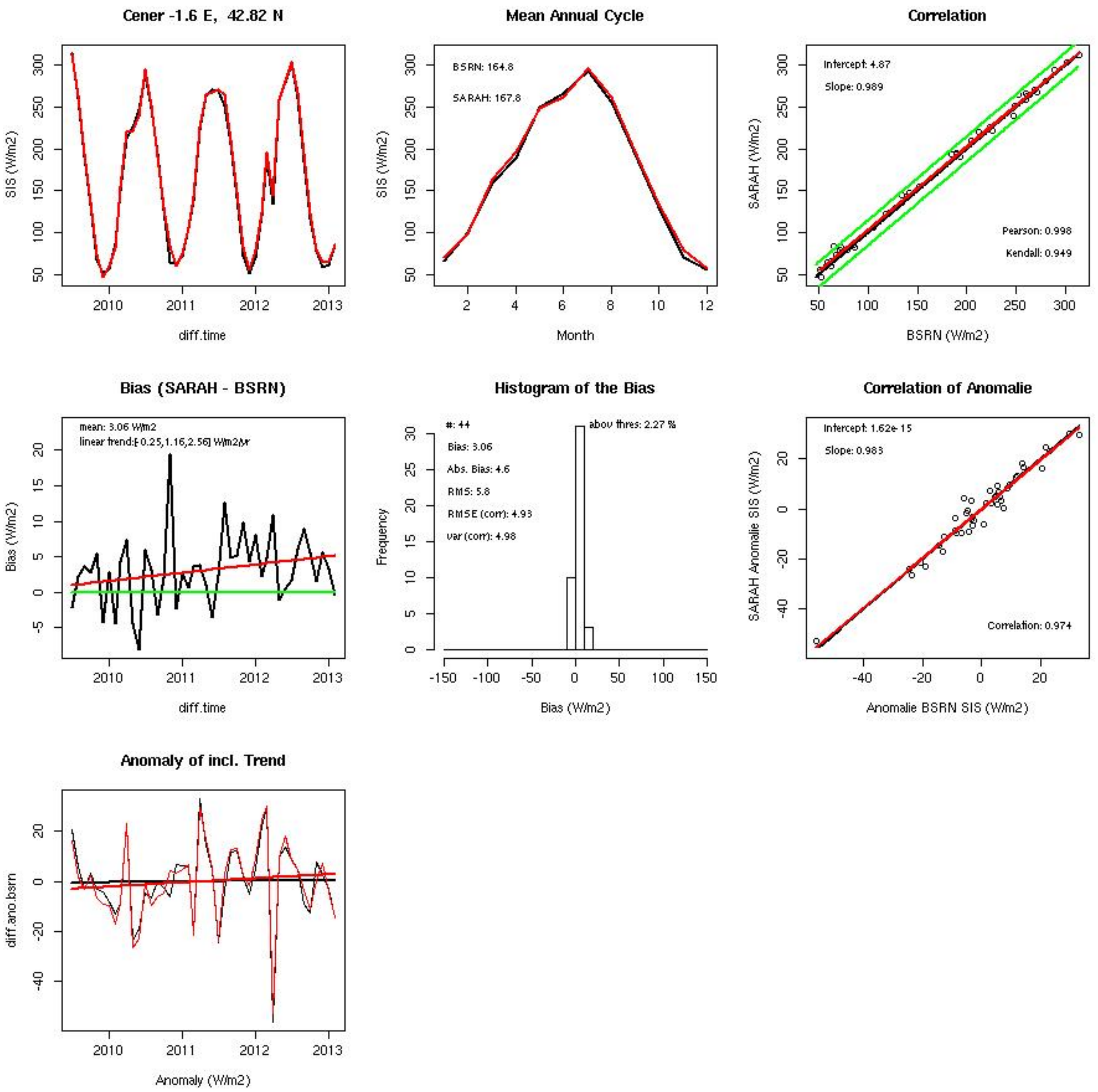
Carpentras, DNI, monthly mean



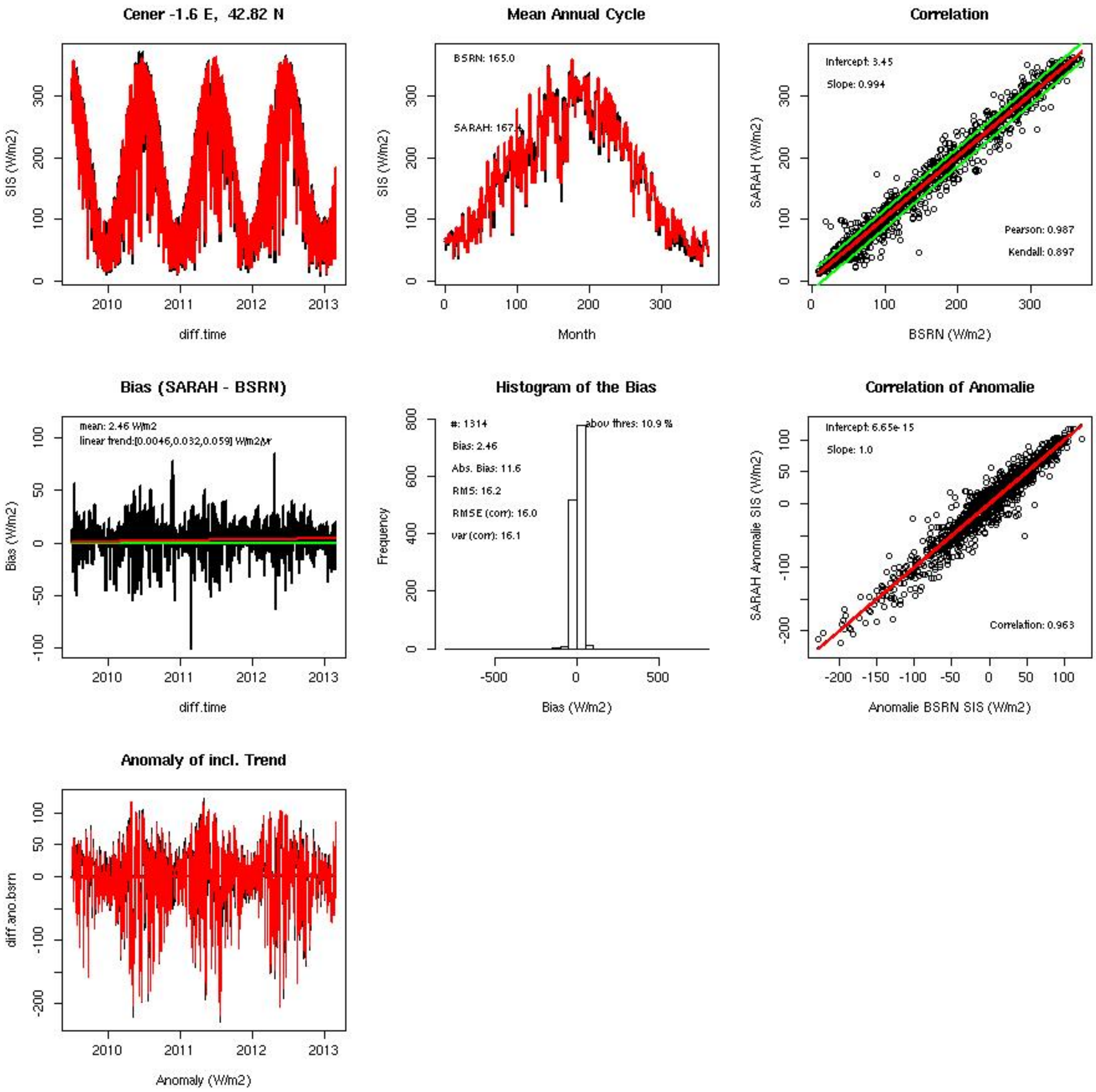
Carpentras, DNI, daily mean



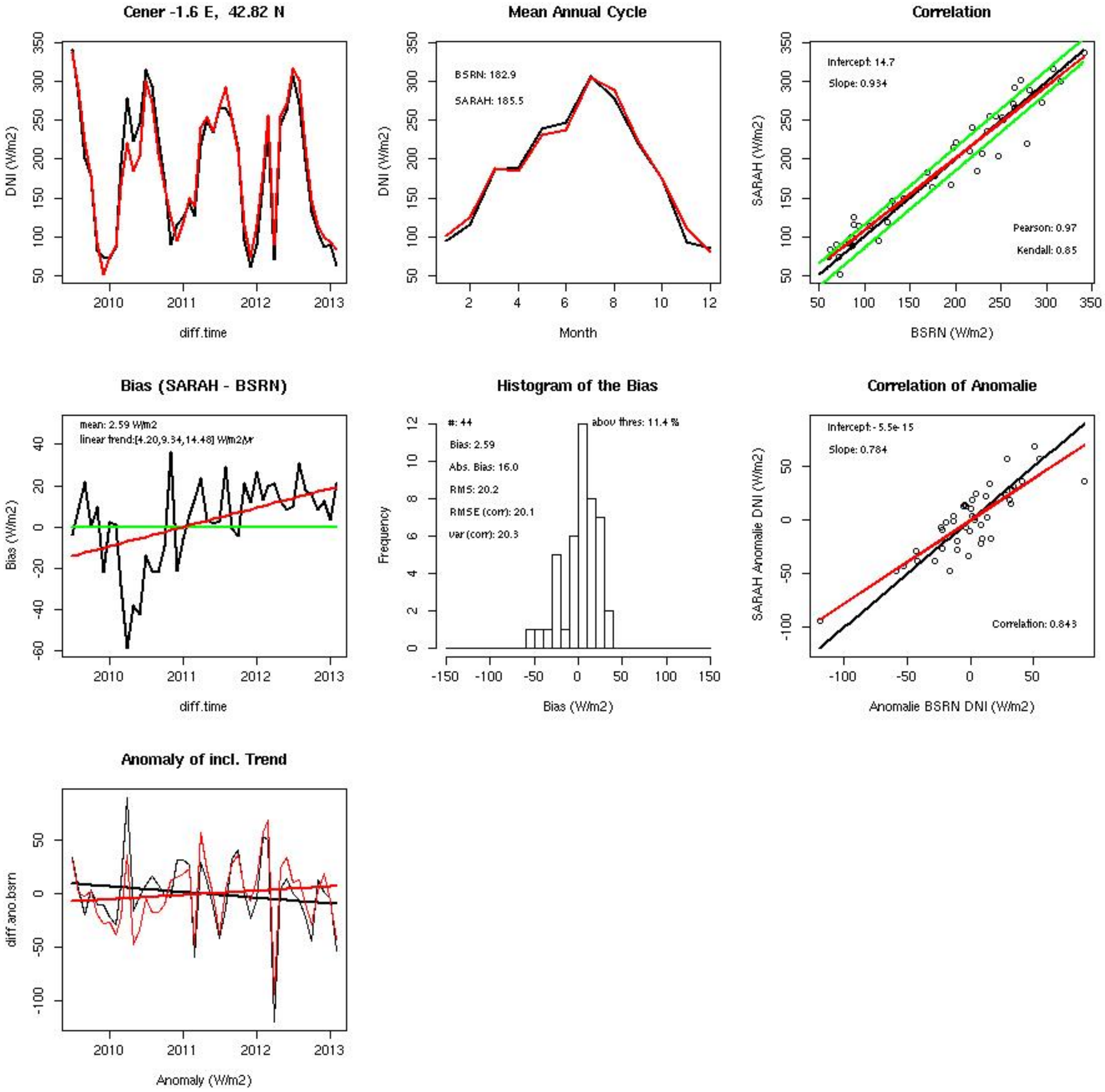
Cener, SIS, monthly mean



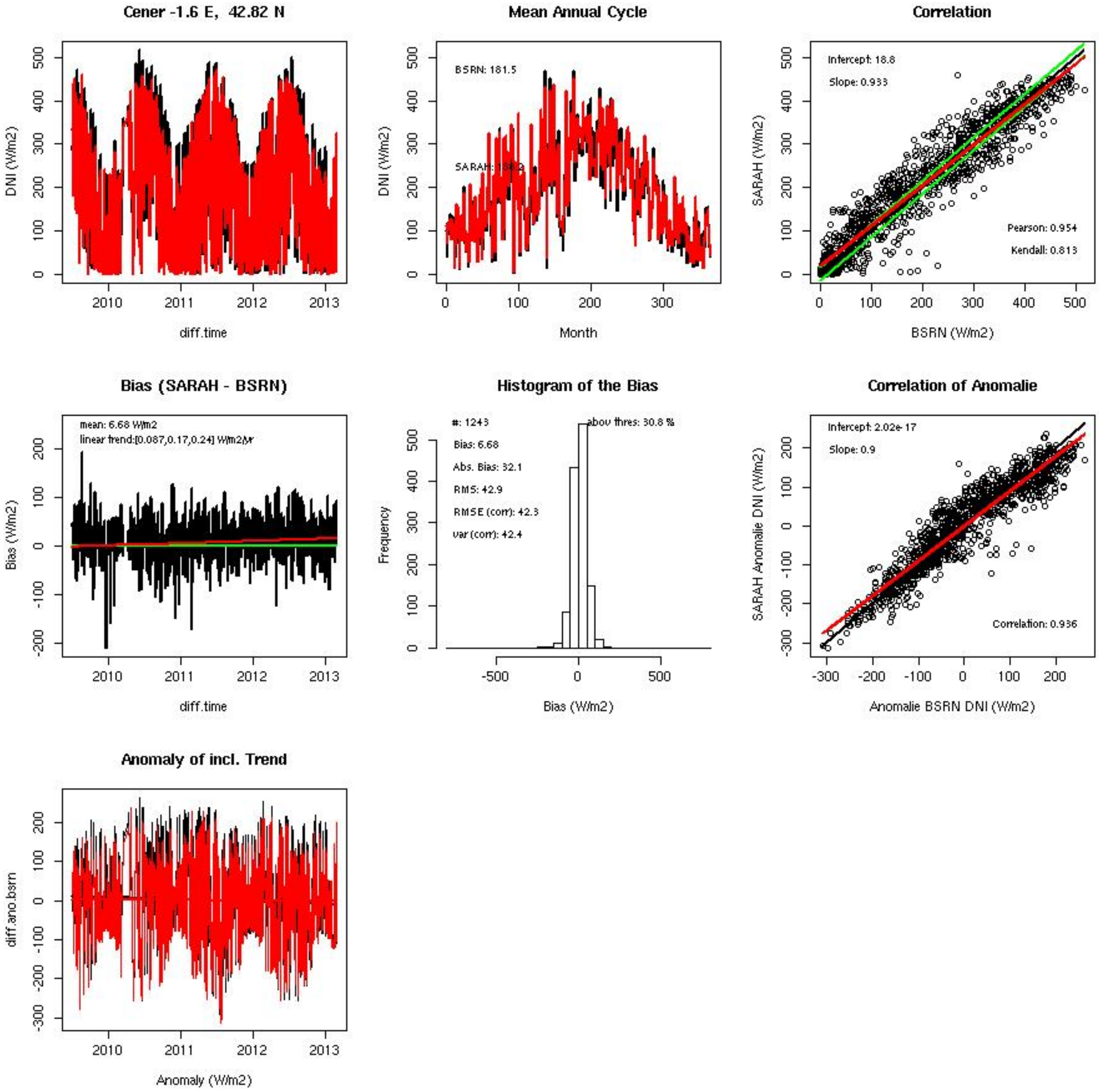
Cener, SIS, daily mean



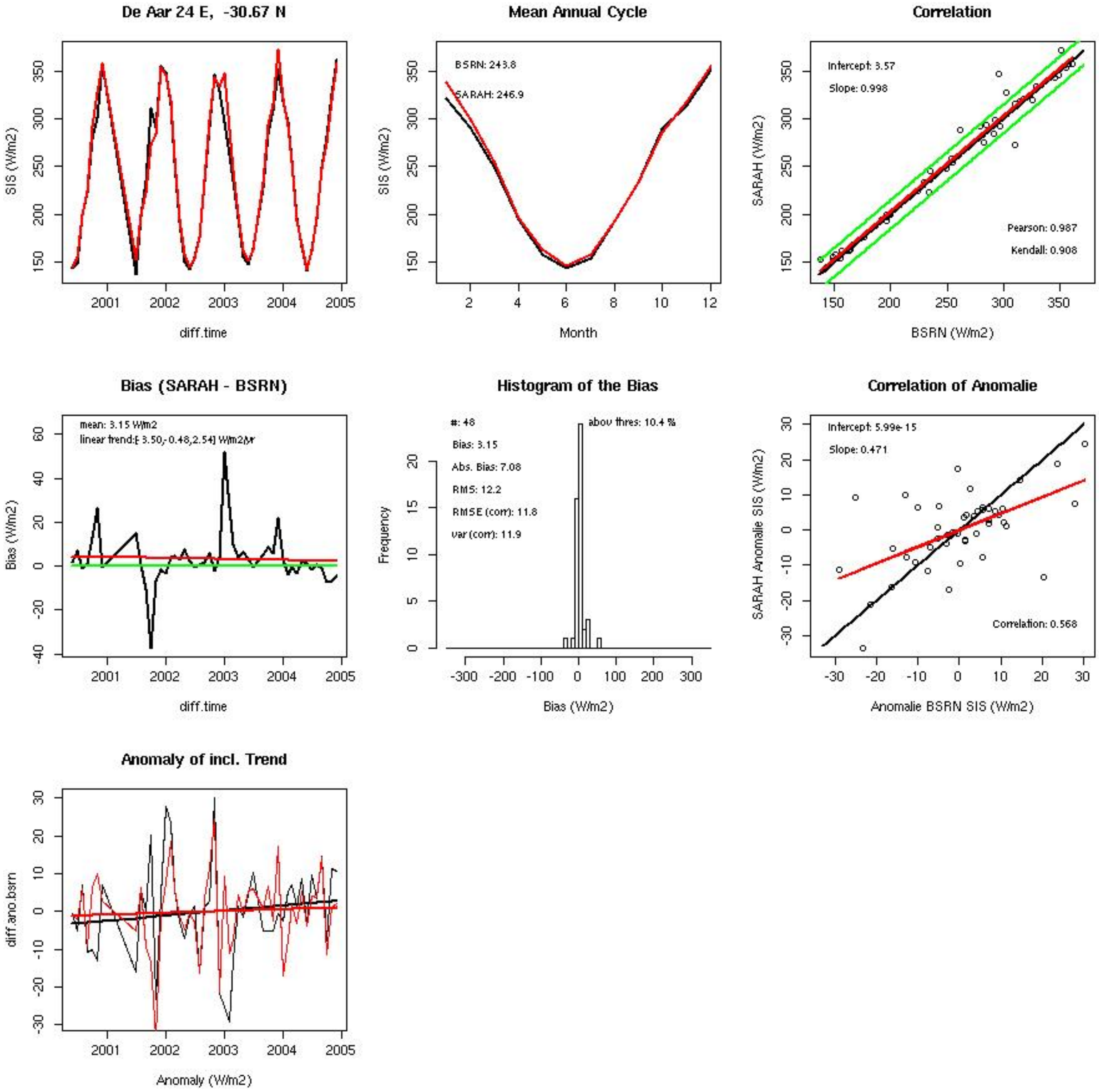
Cener, DNI, monthly mean



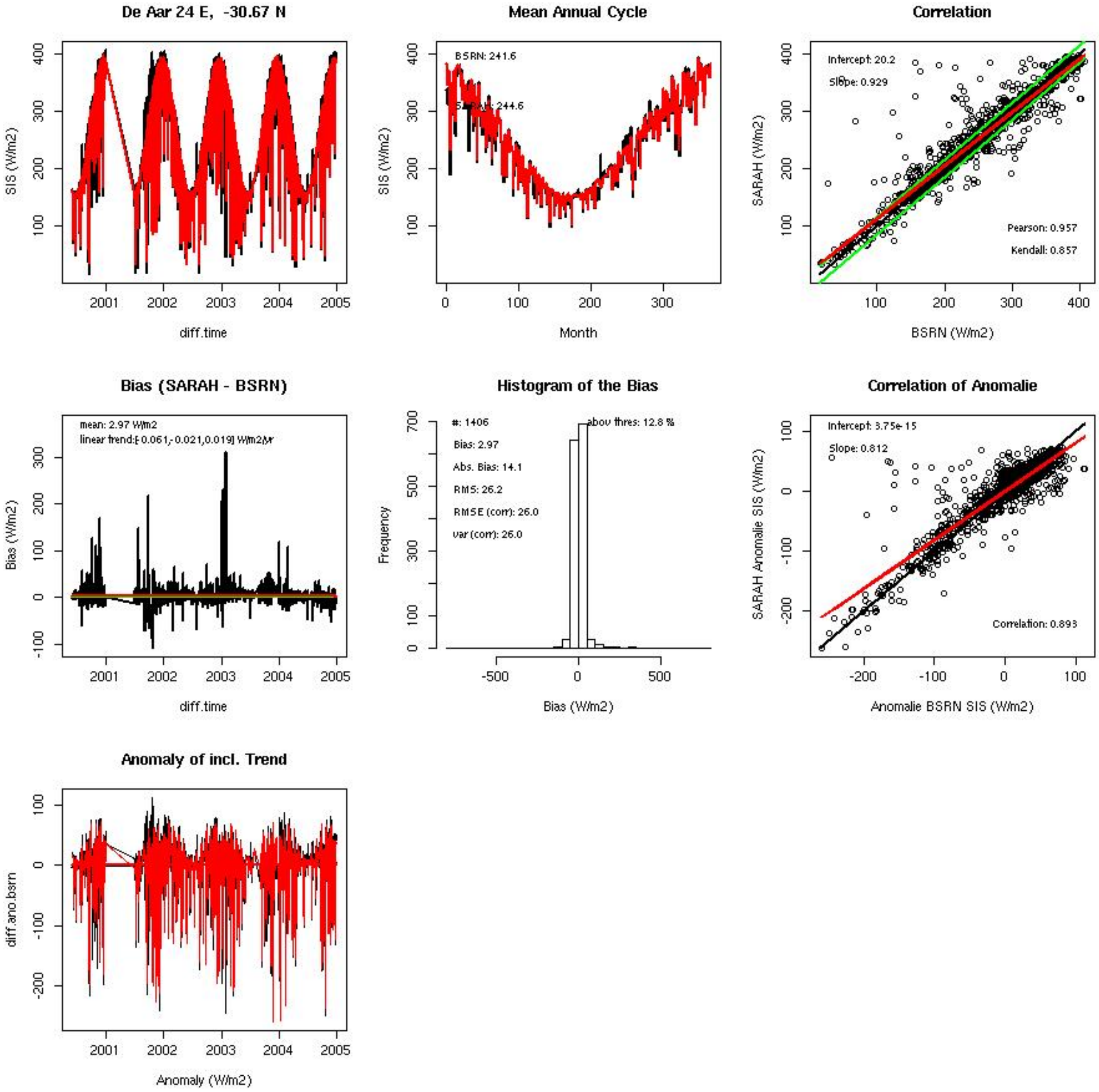
Cener, DNI, daily mean



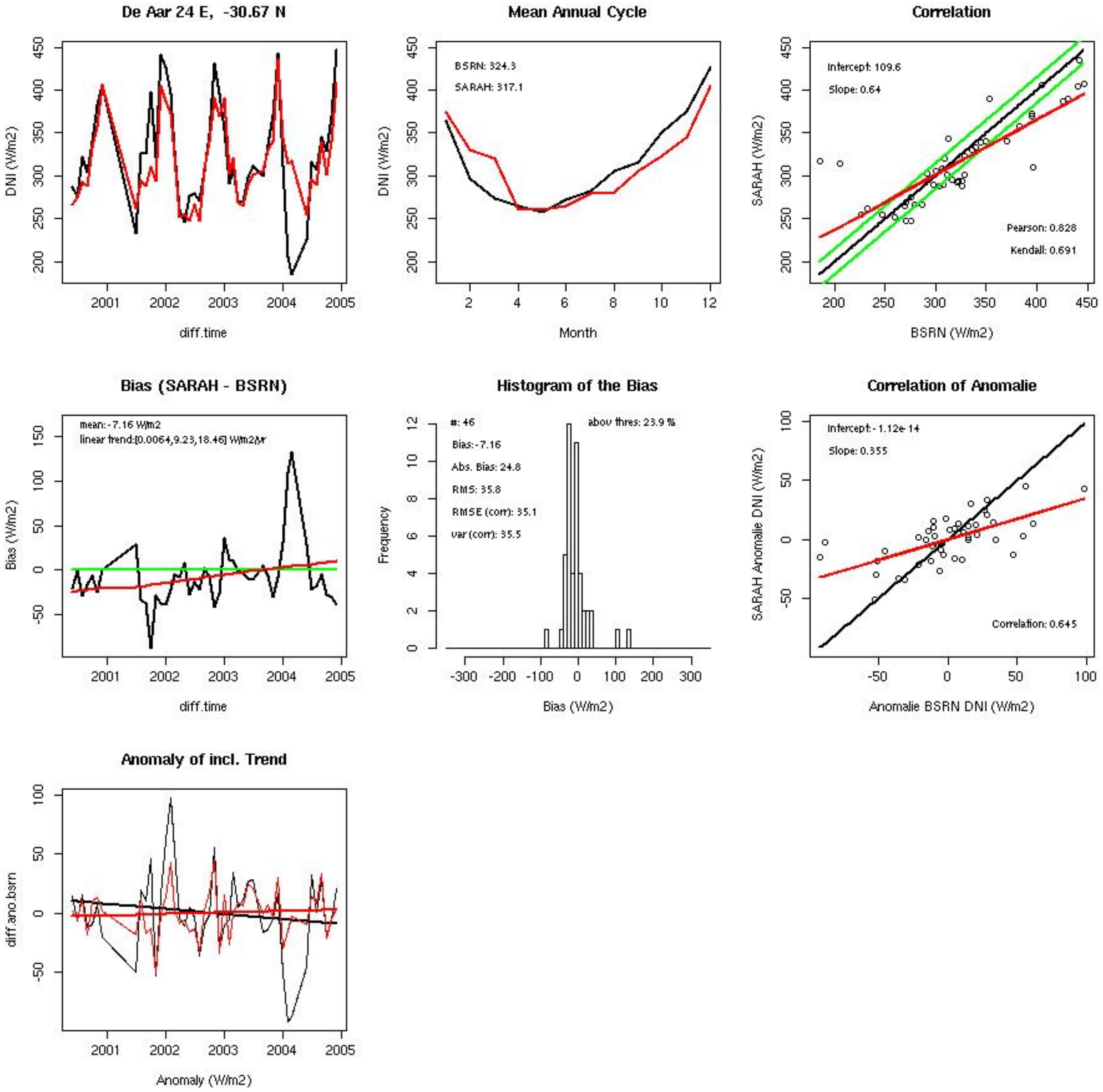
De Aar, SIS, monthly mean



De Aar, SIS, daily mean



De Aar, DNI, monthly mean



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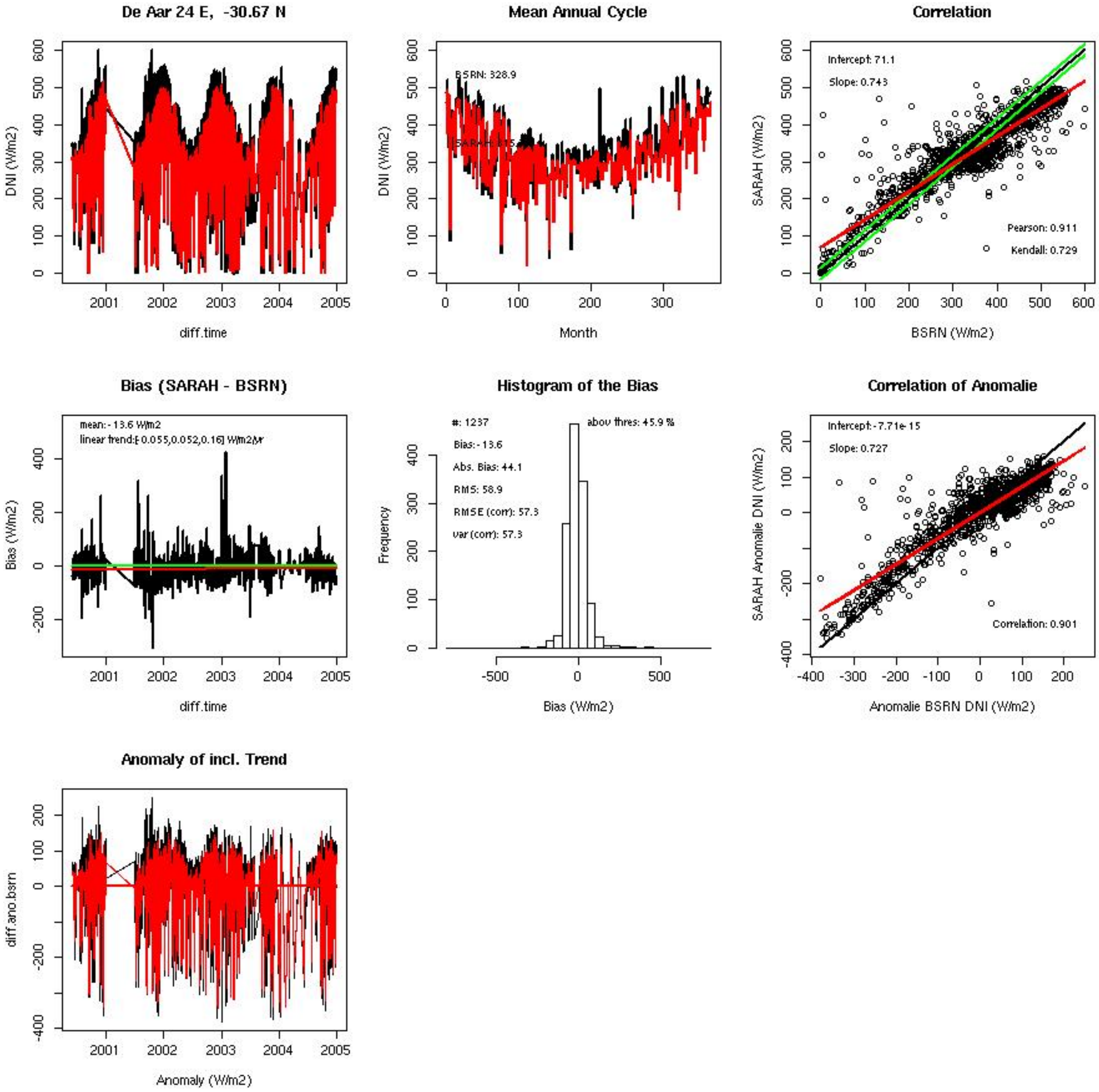

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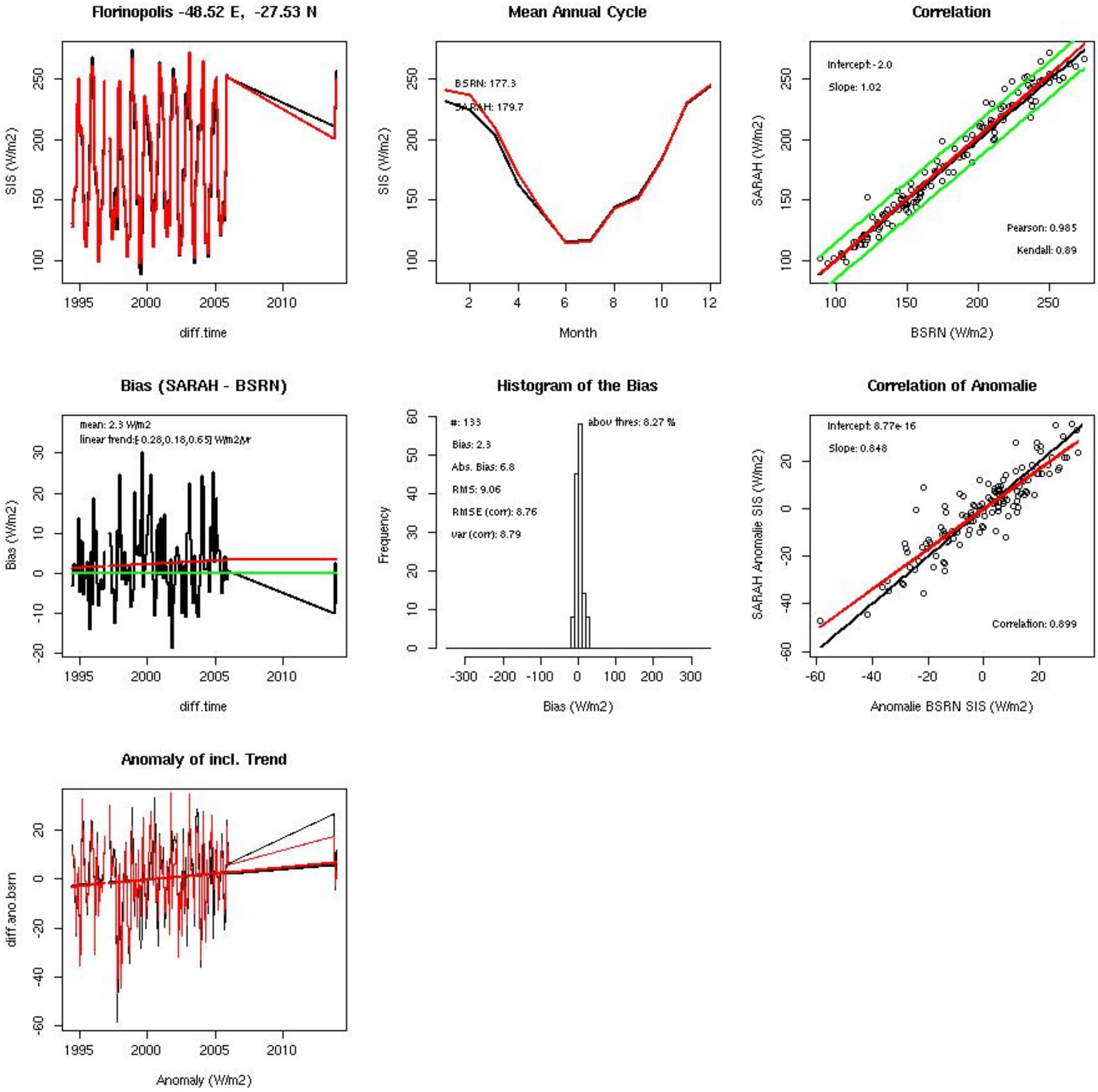

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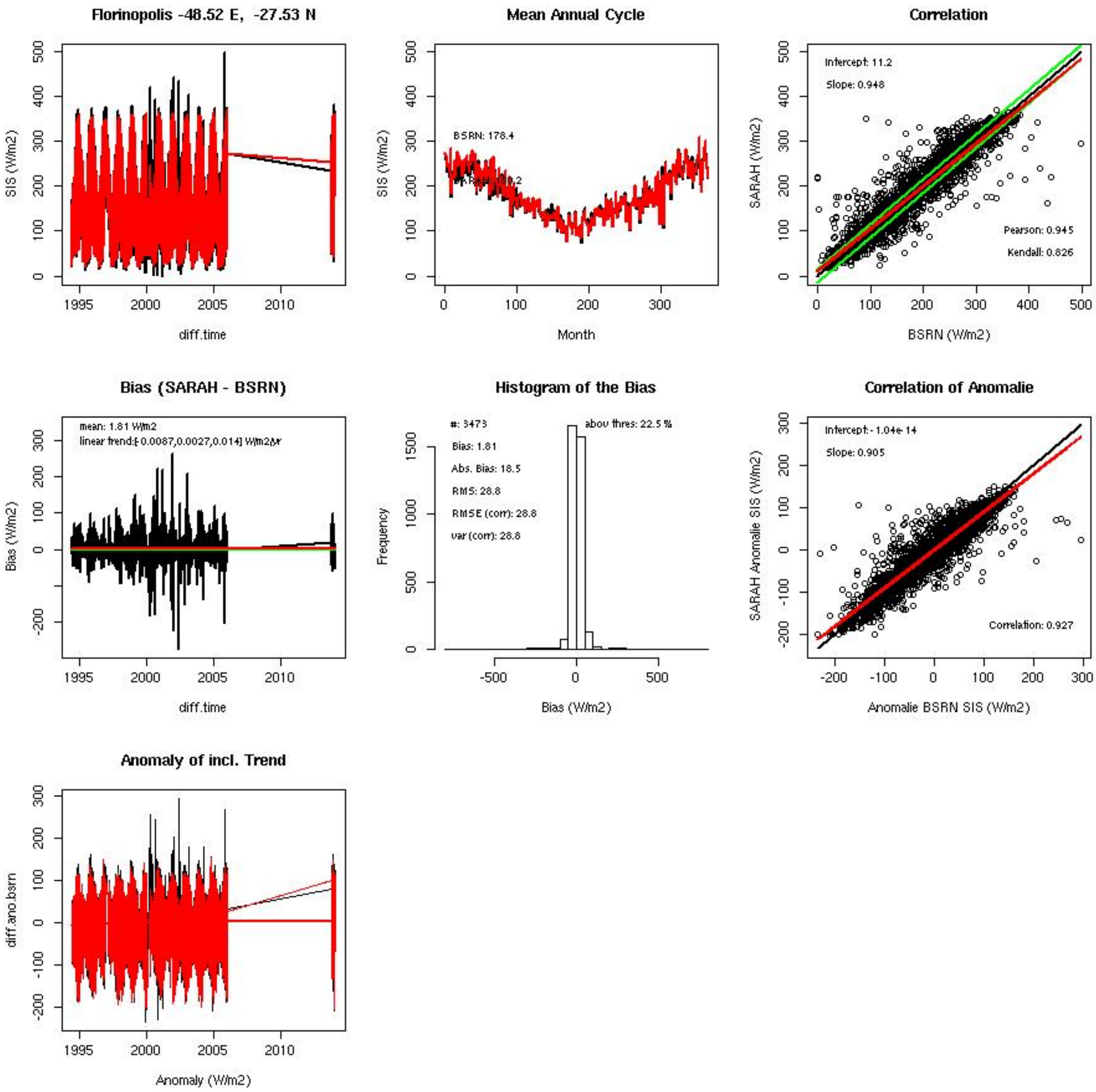

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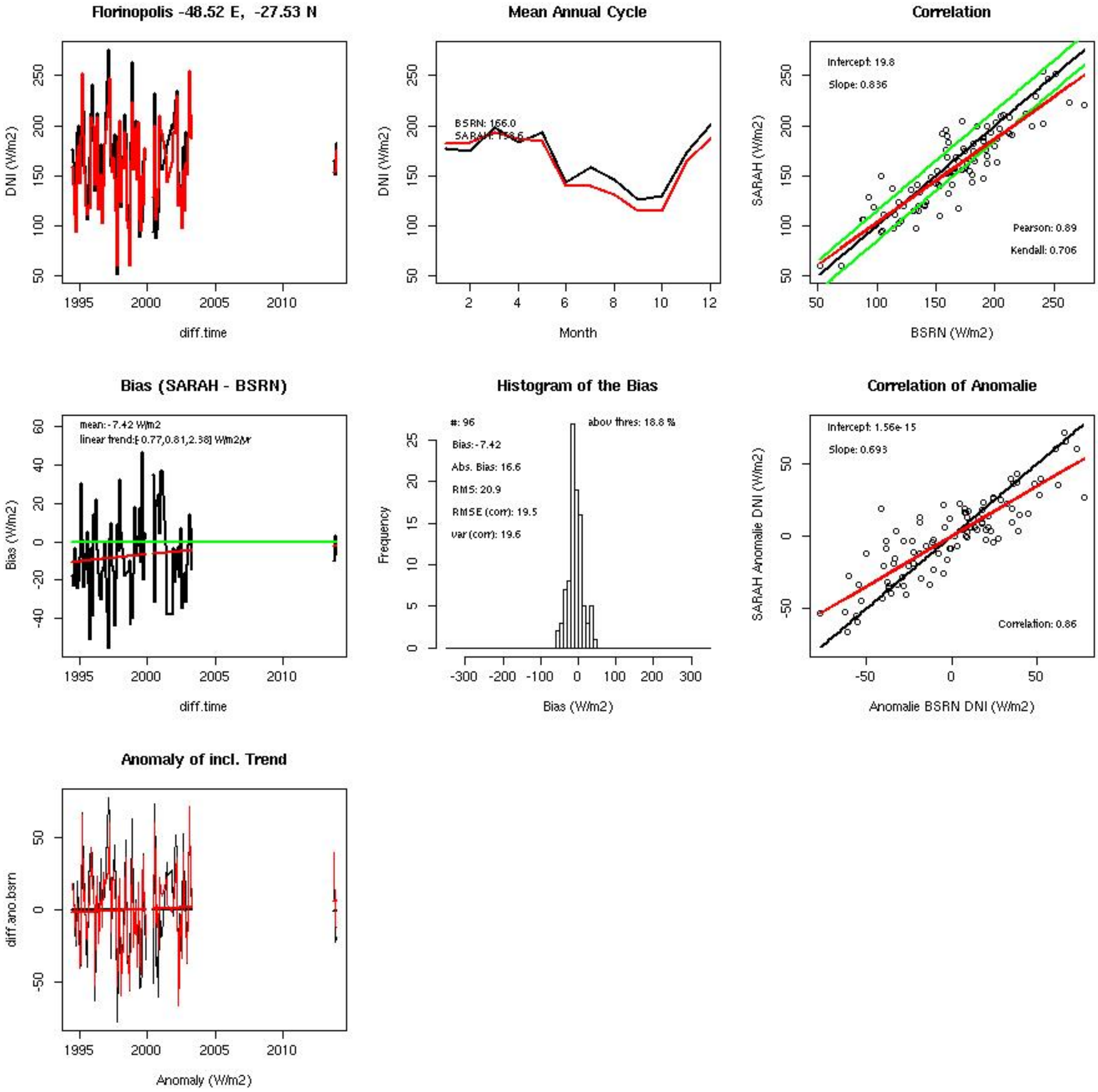

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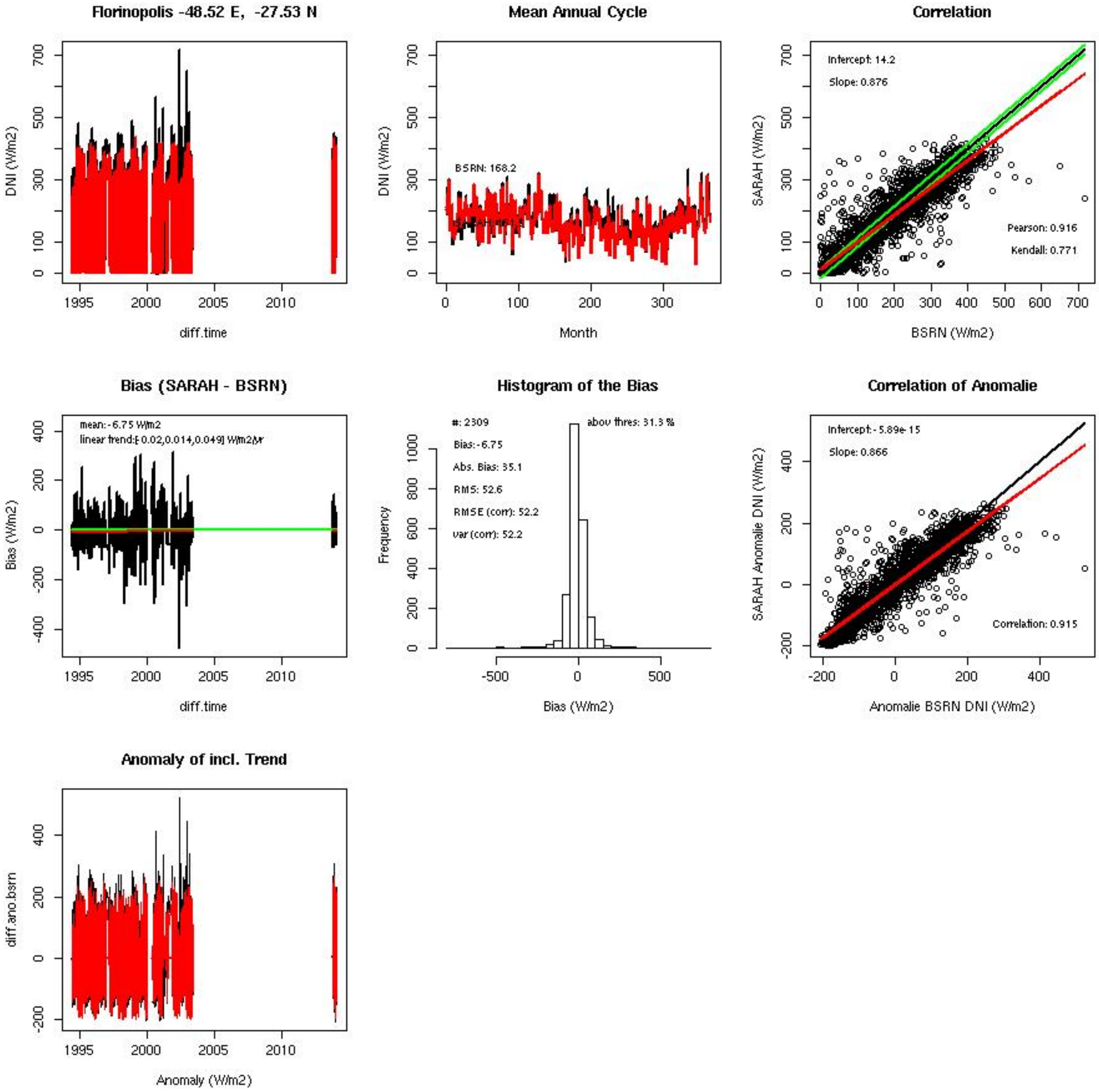

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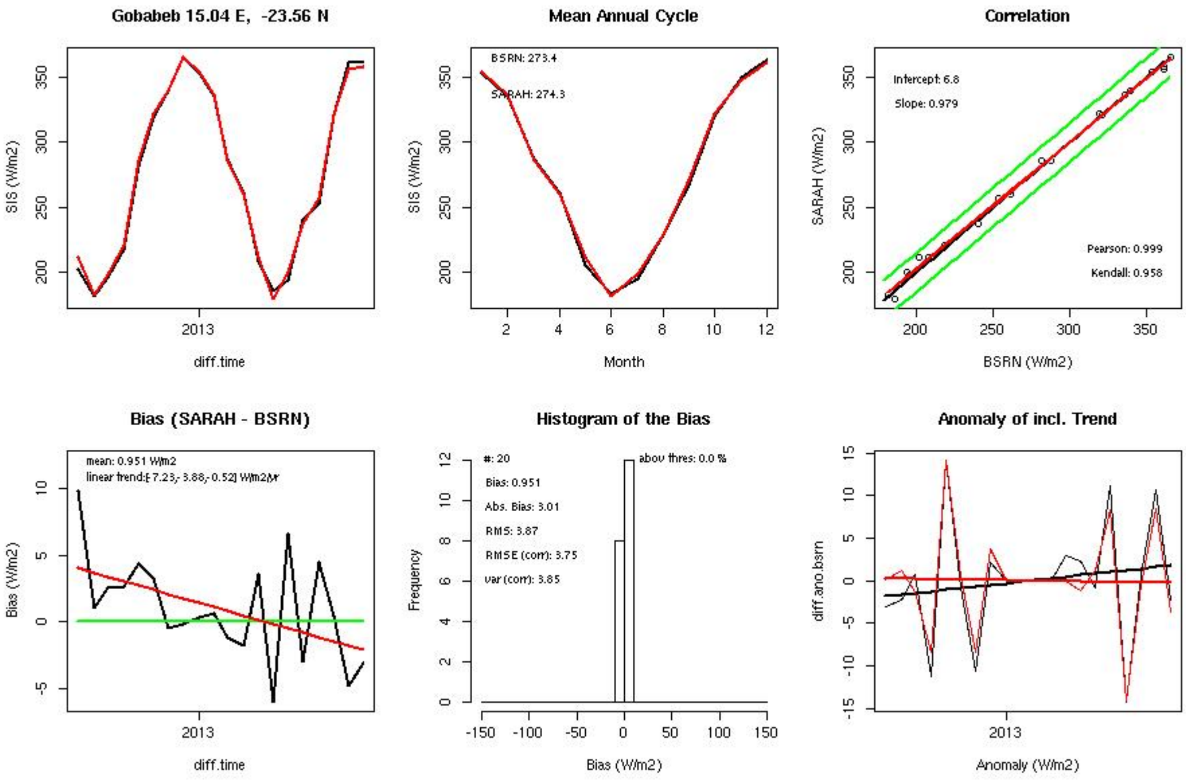

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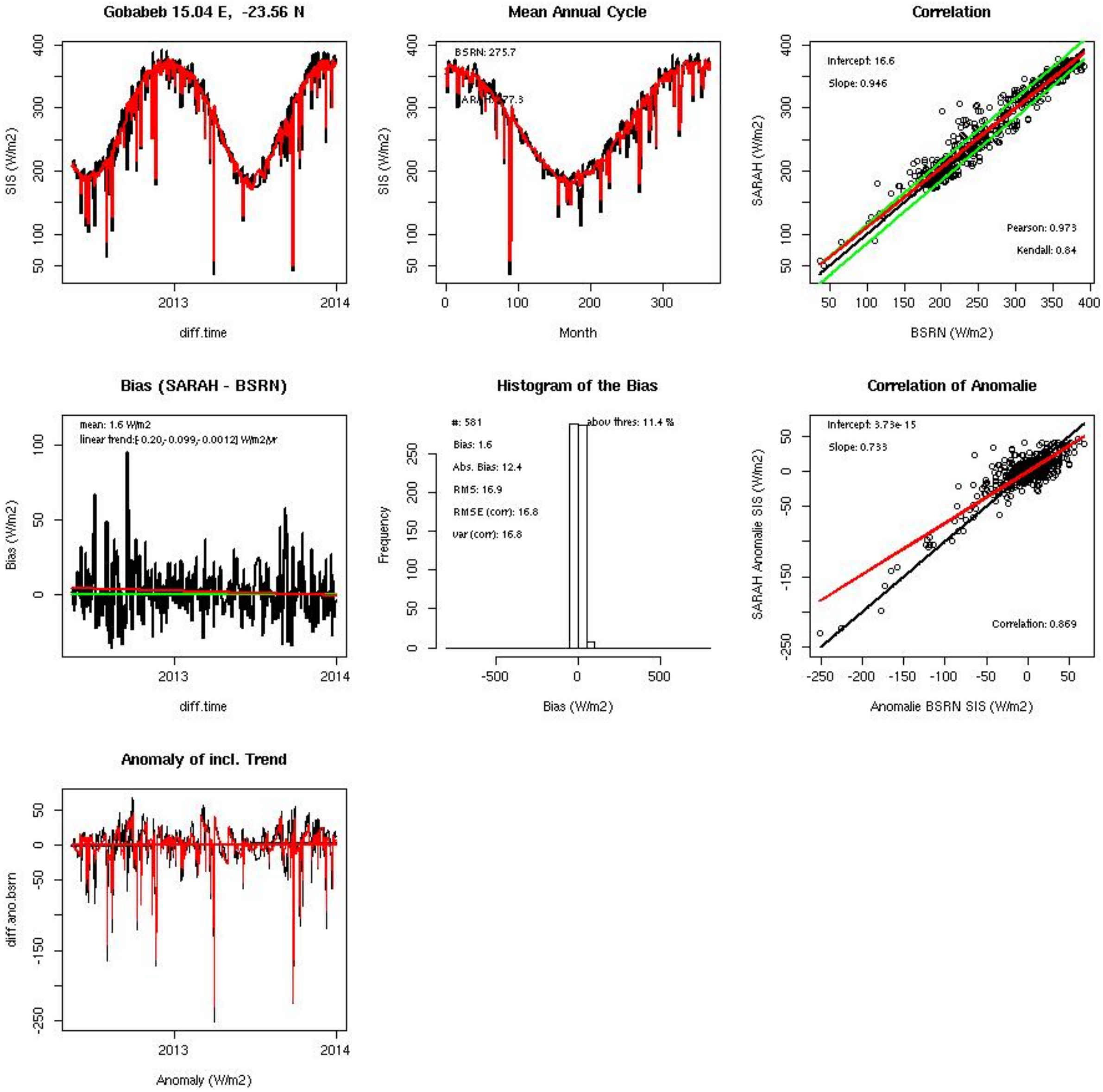

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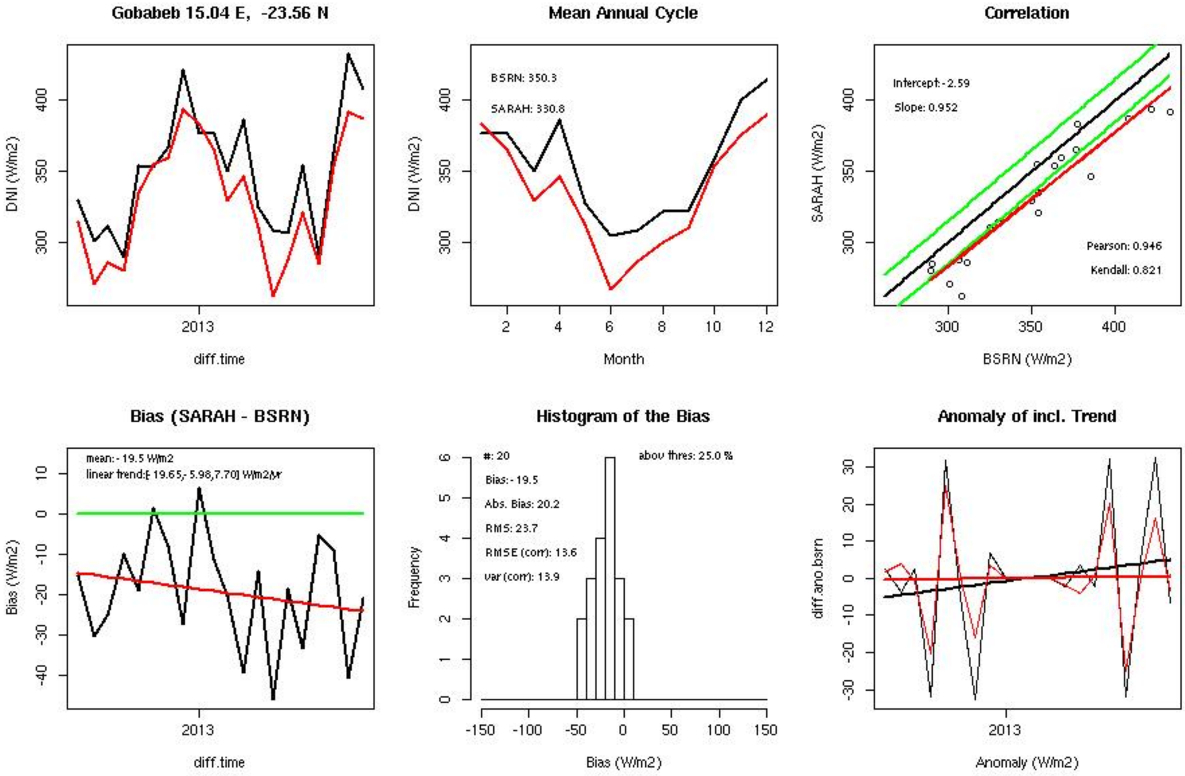

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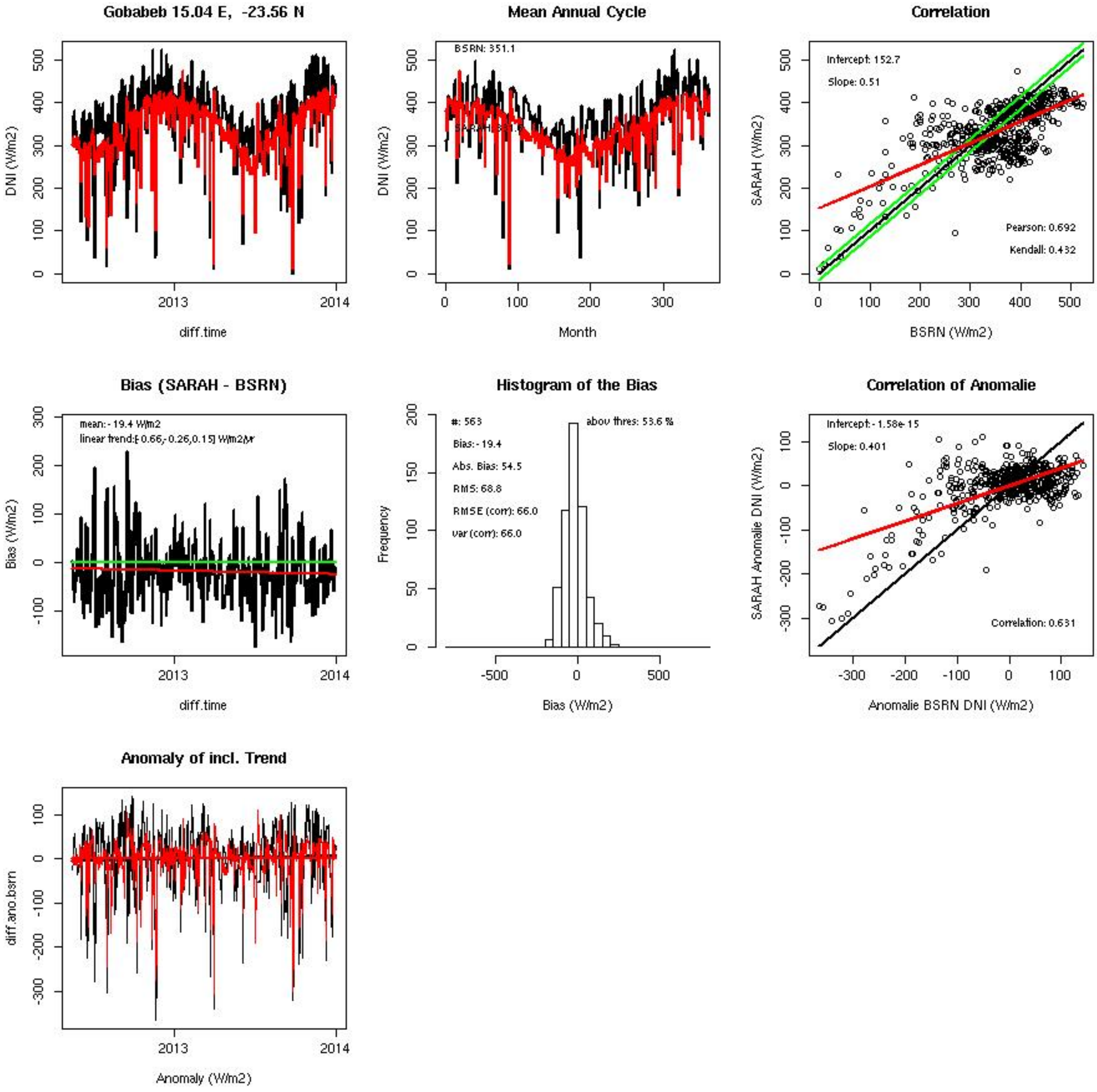

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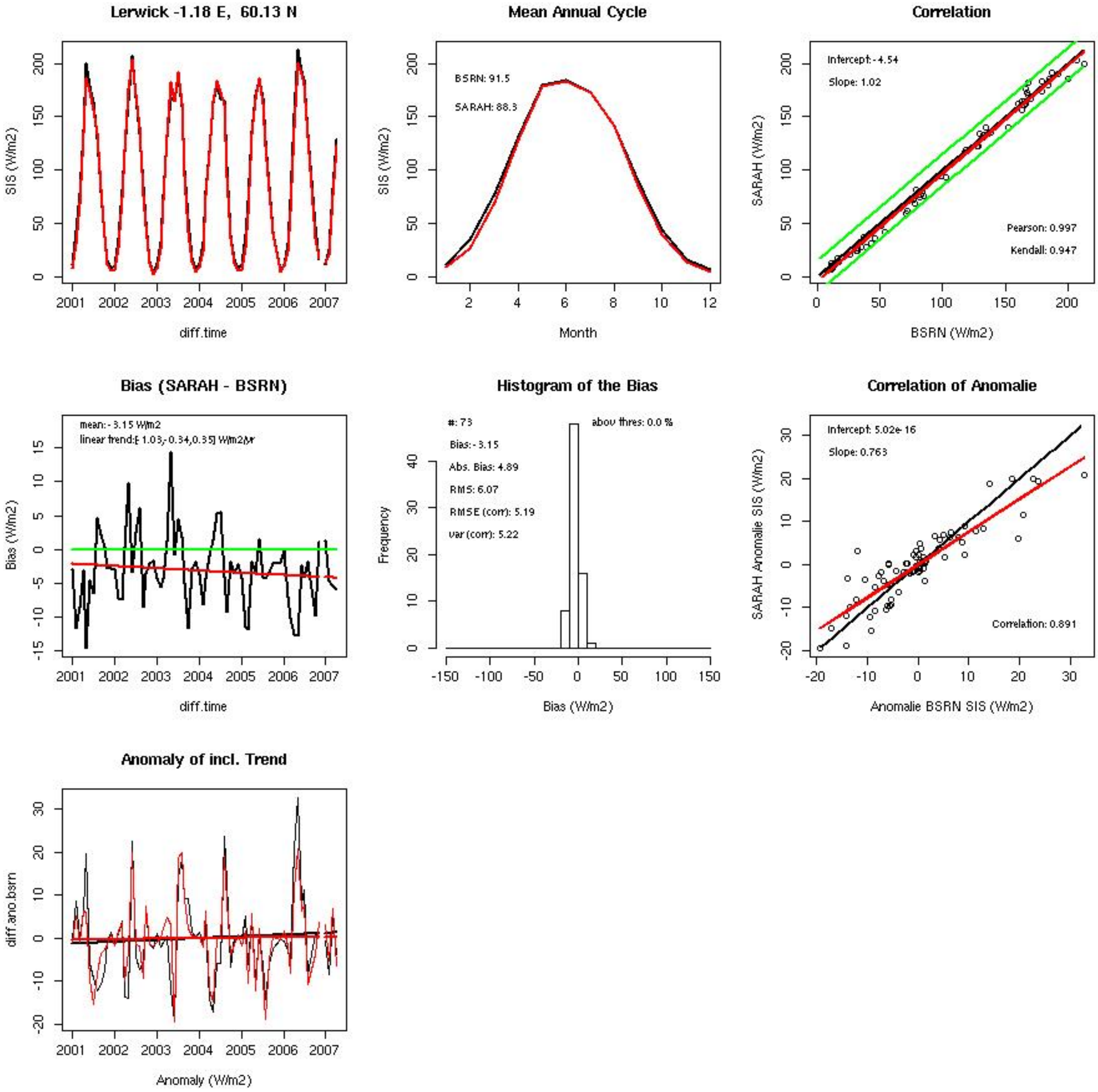

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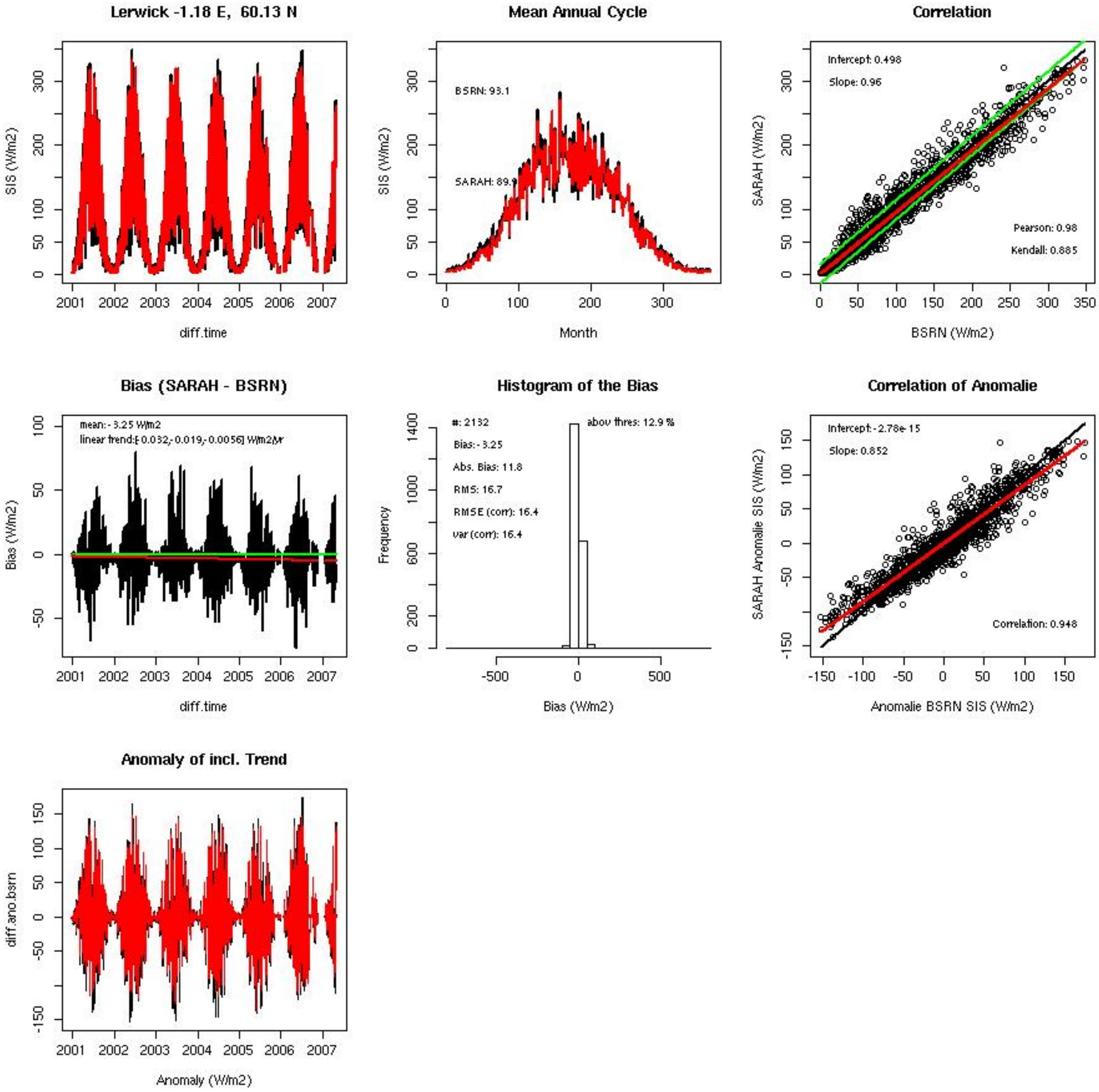

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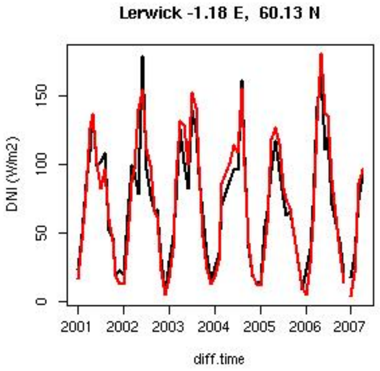

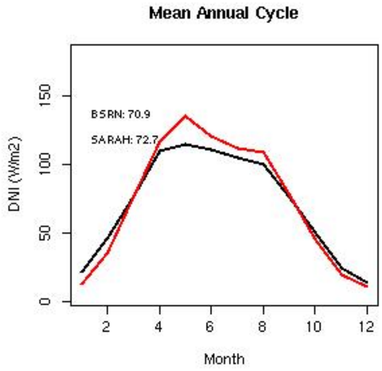

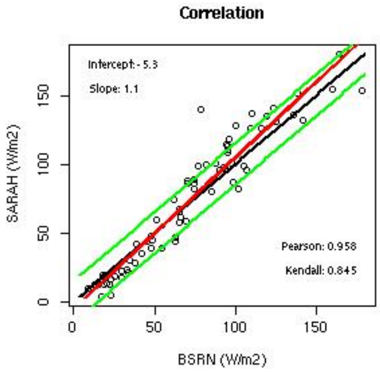

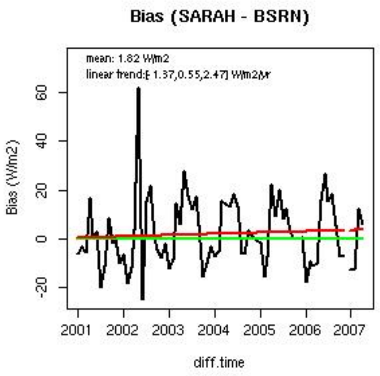

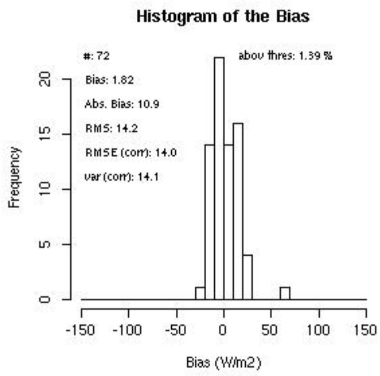

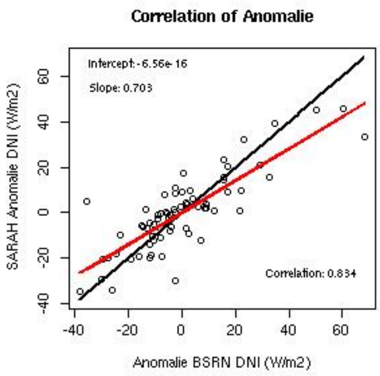

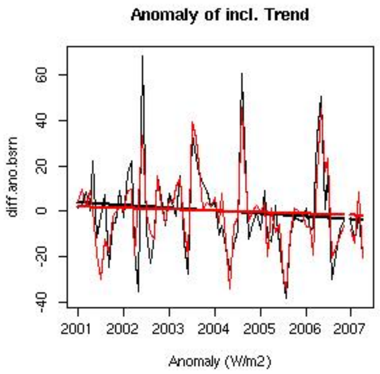

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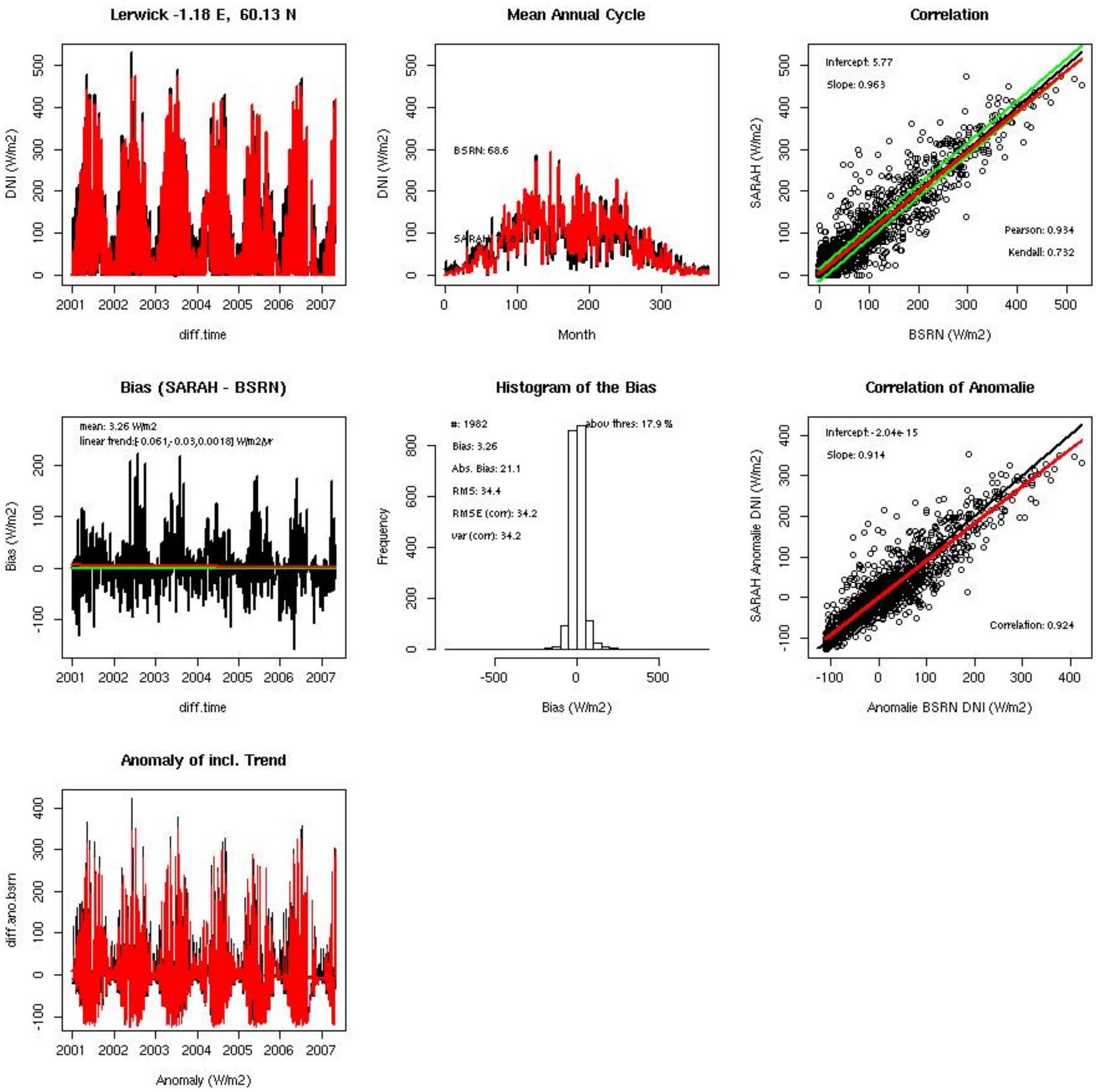

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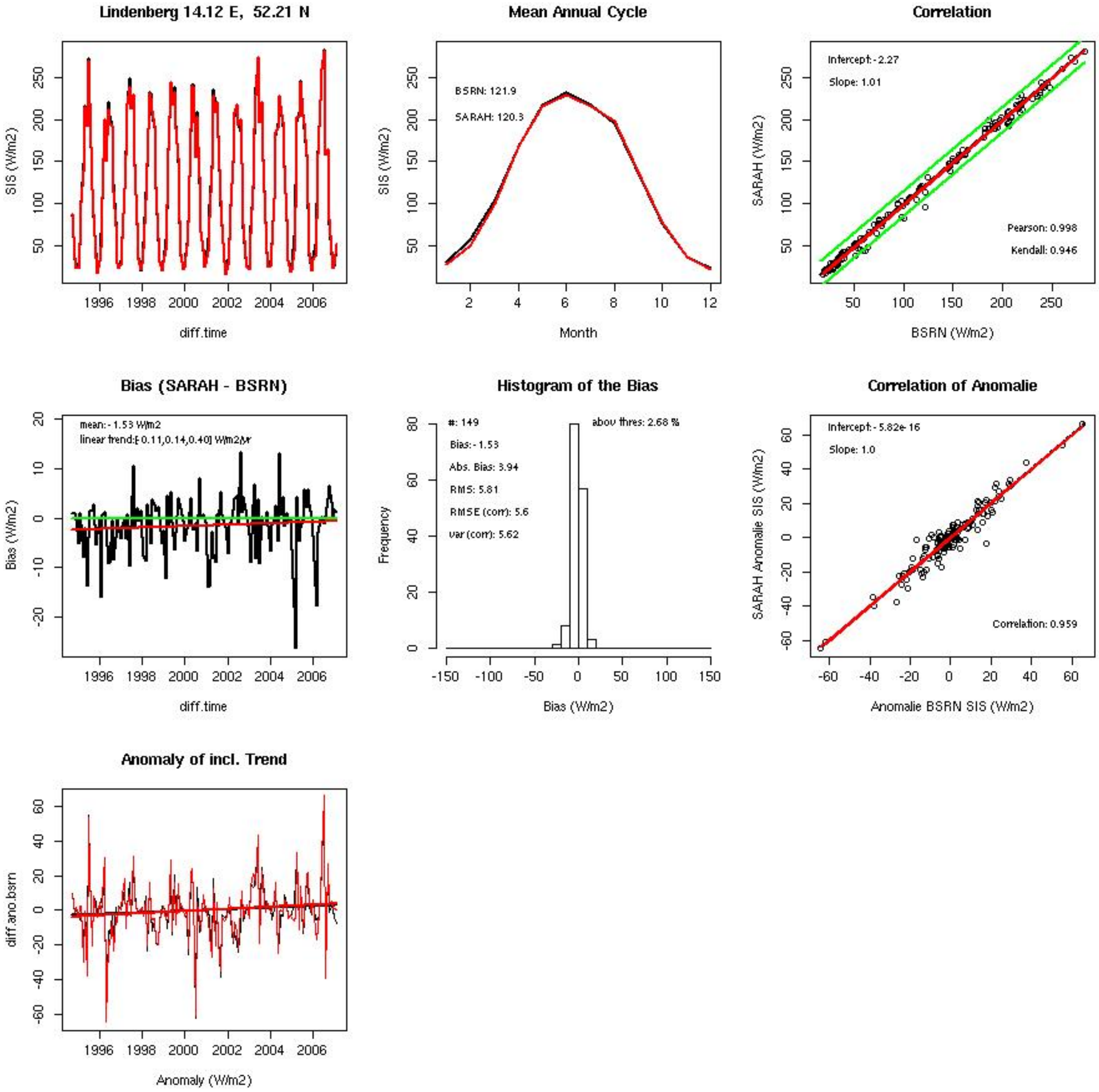

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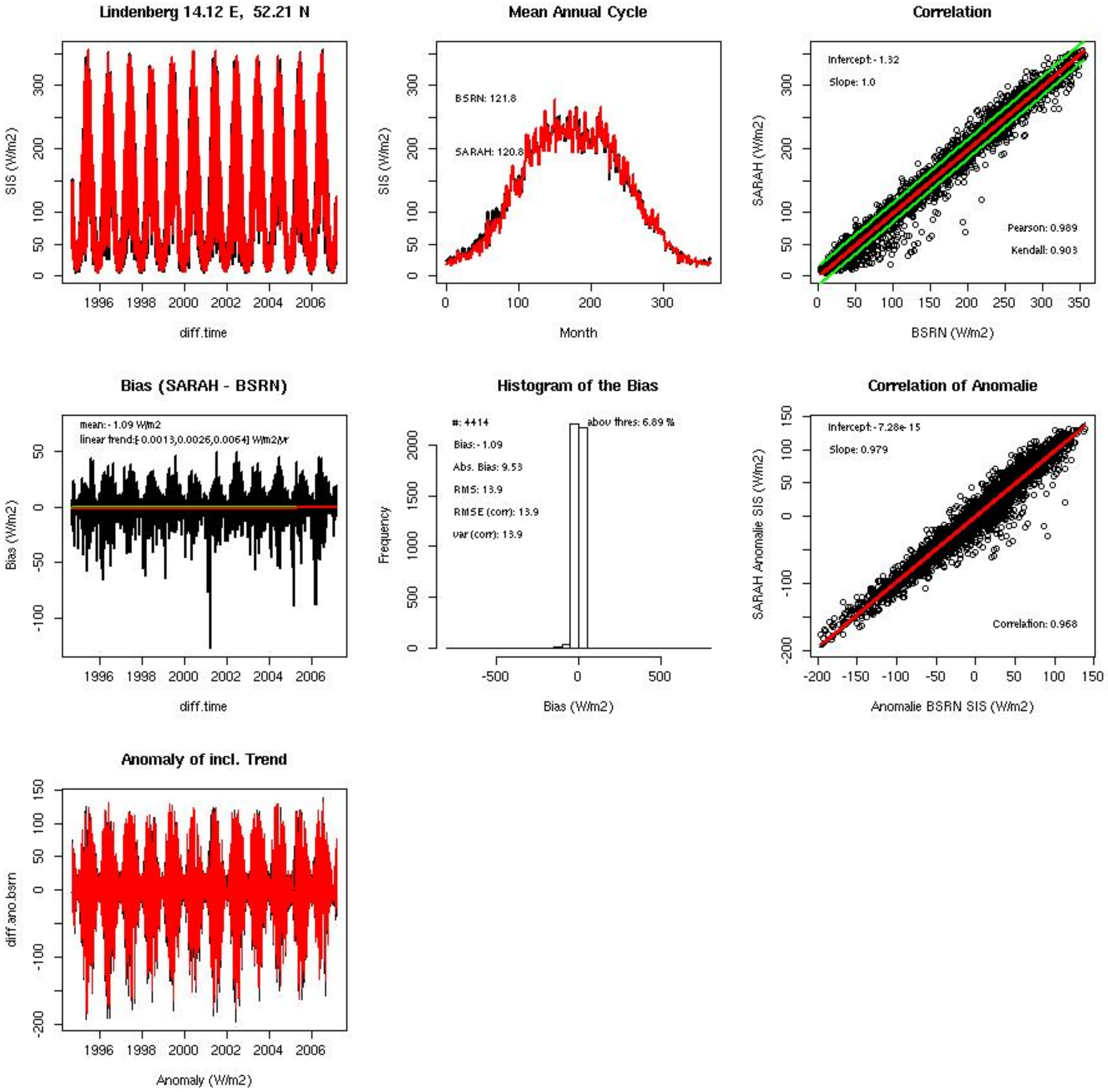

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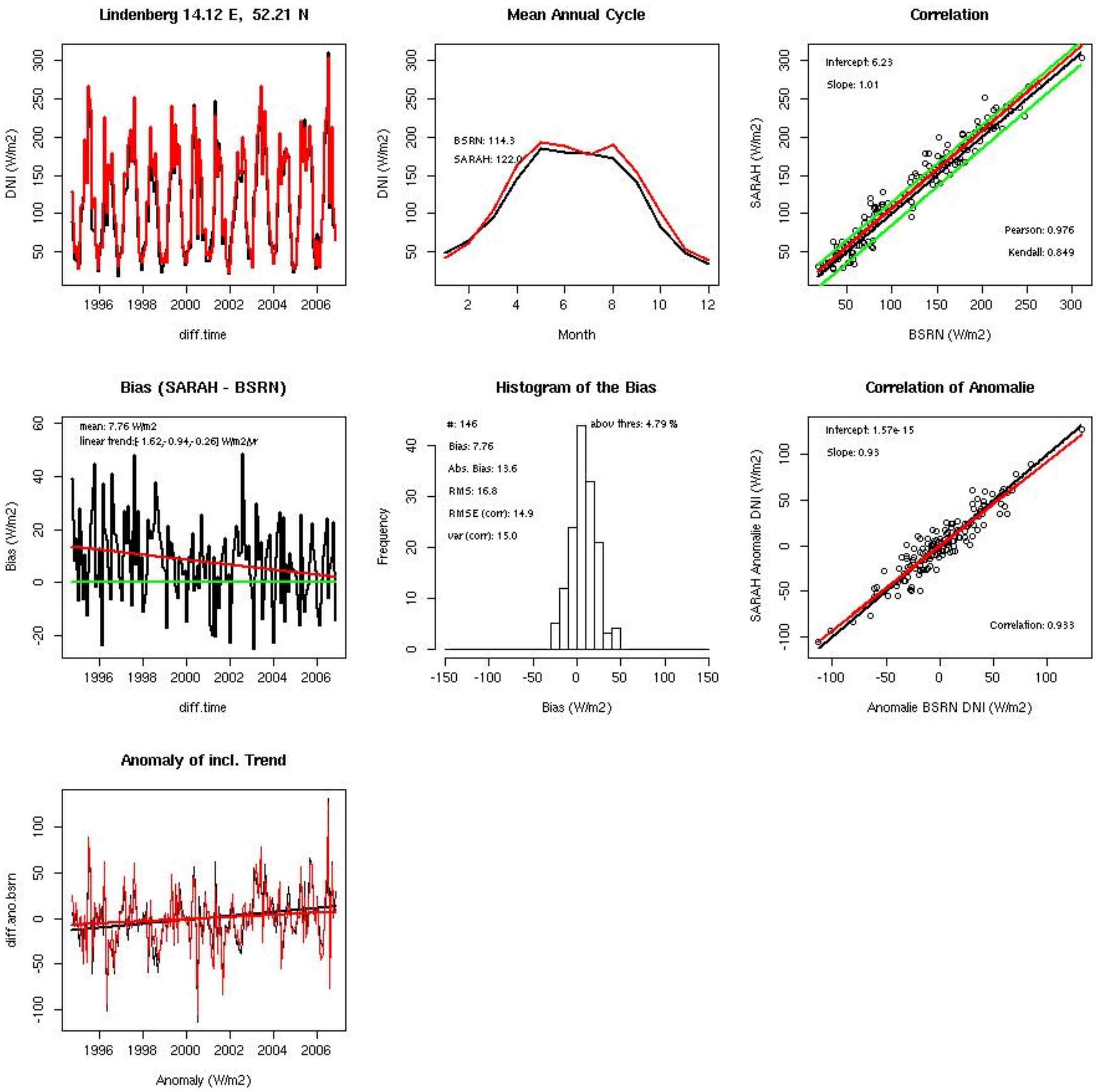

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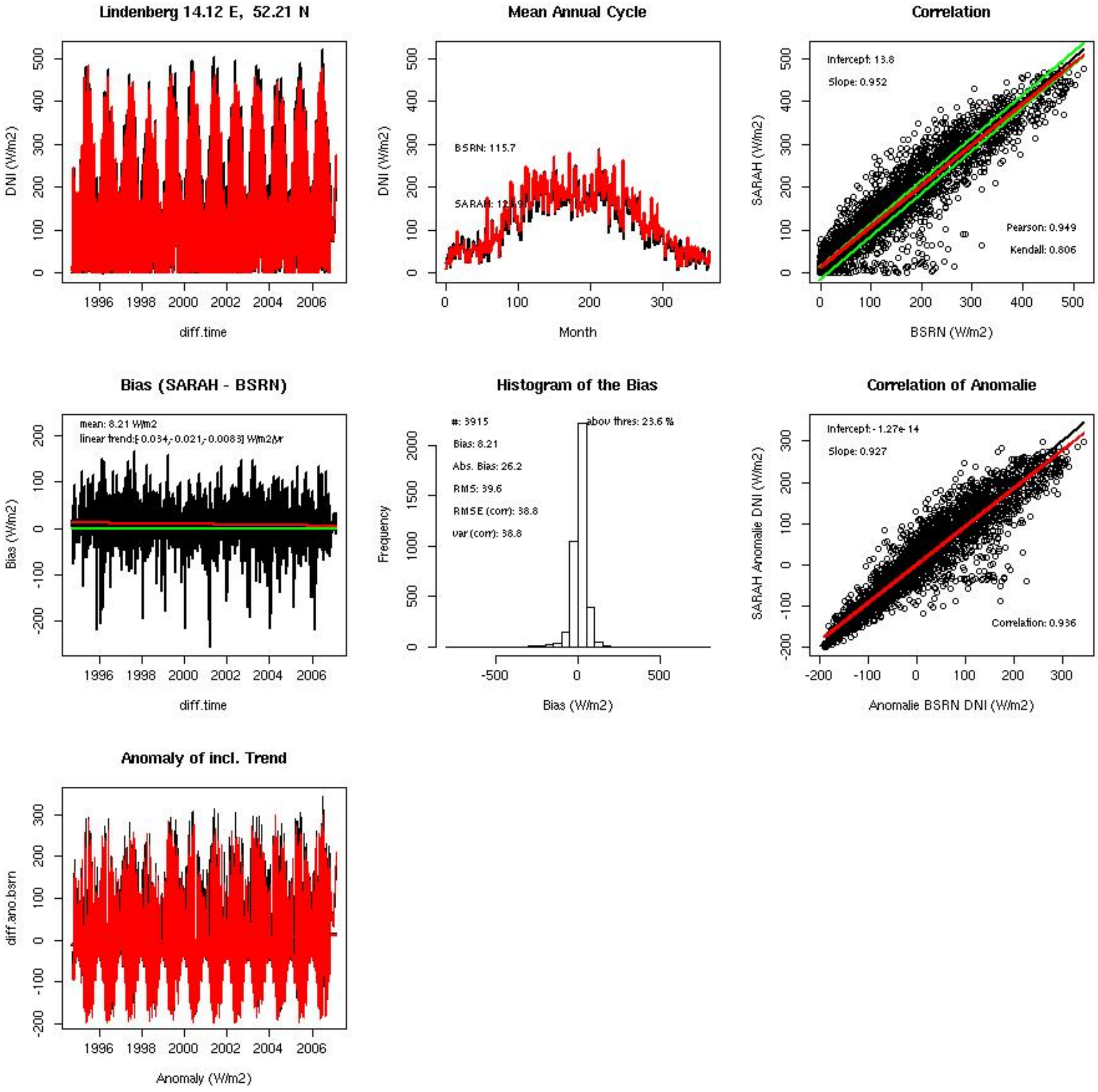

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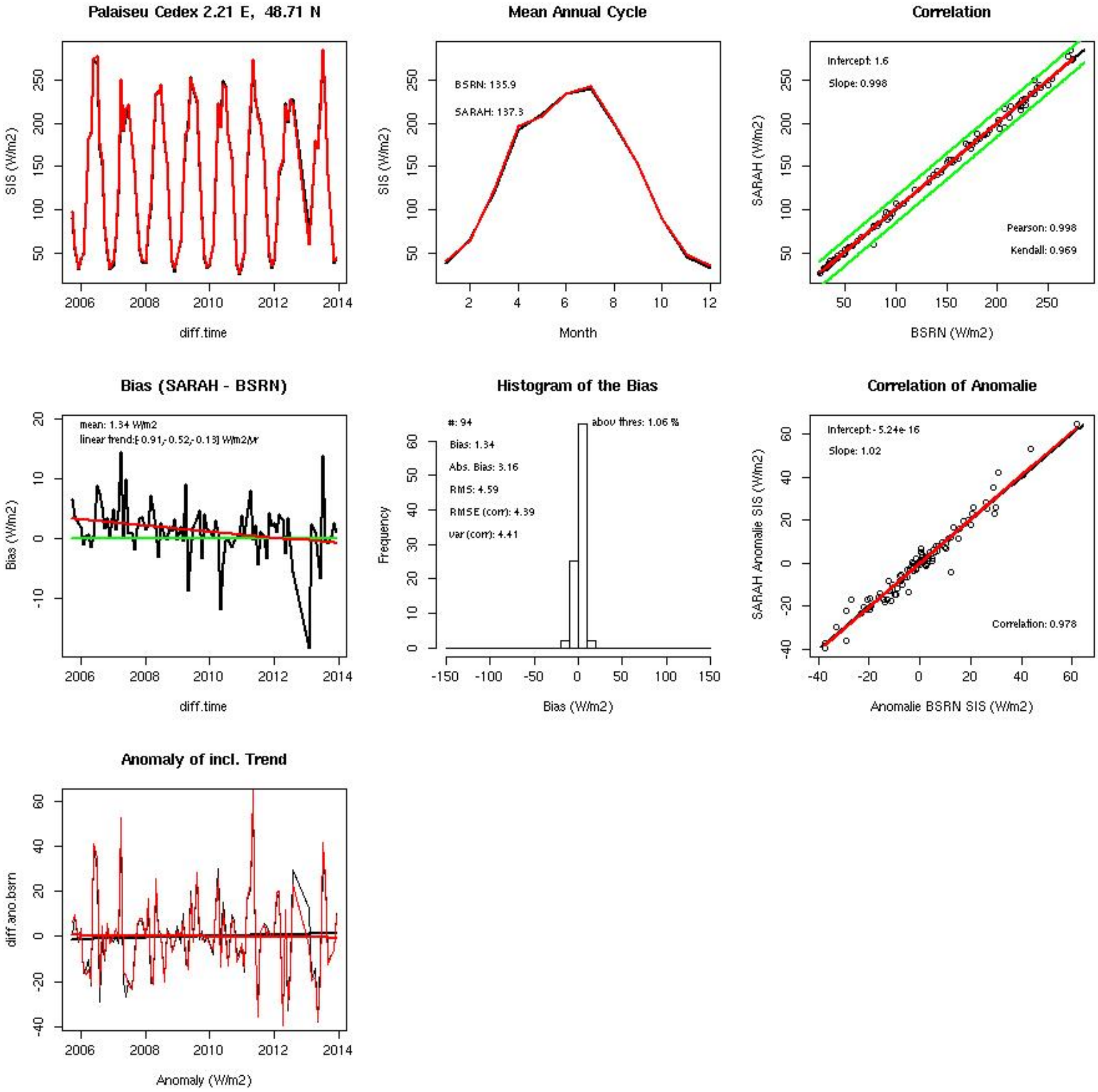

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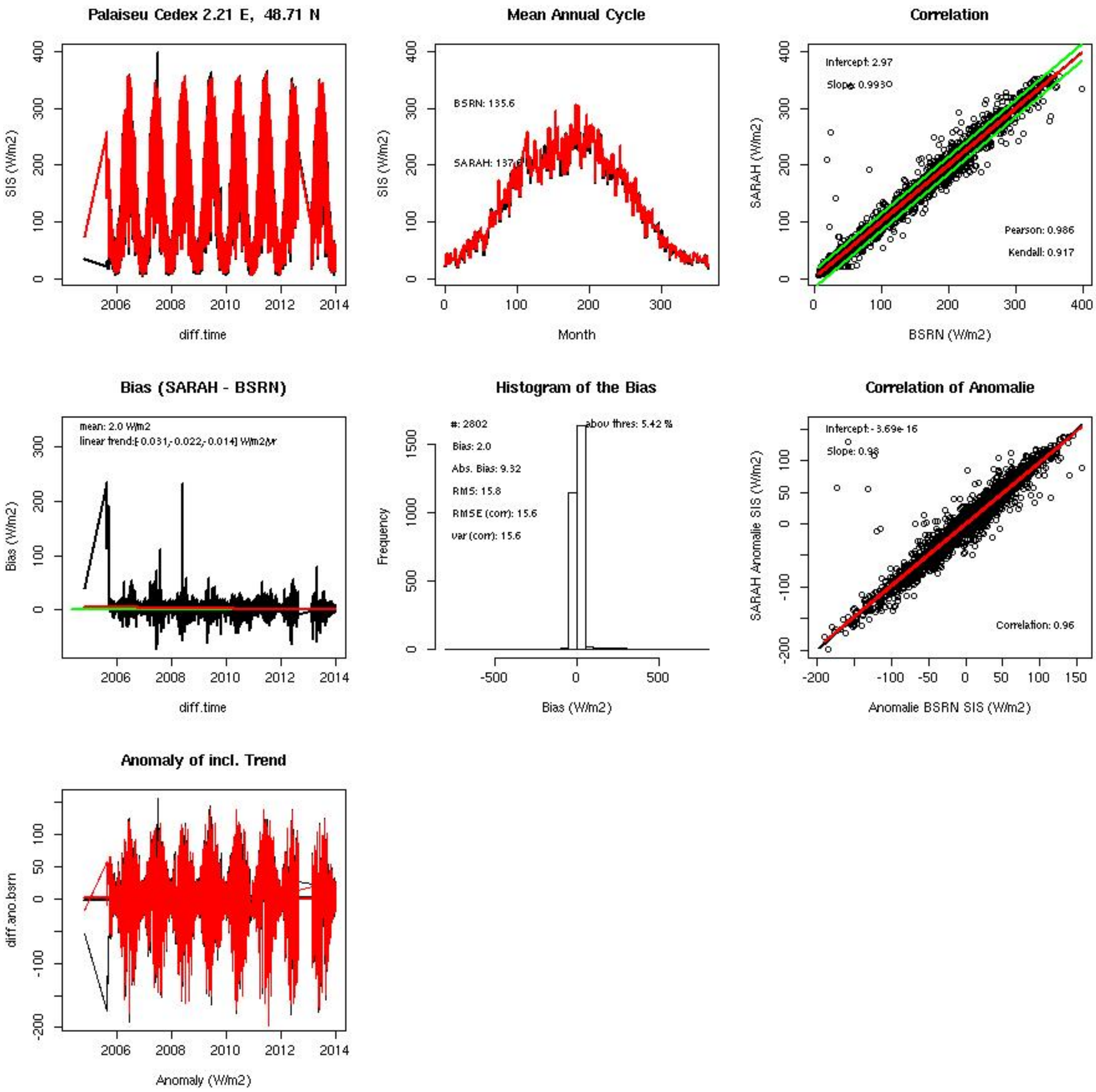

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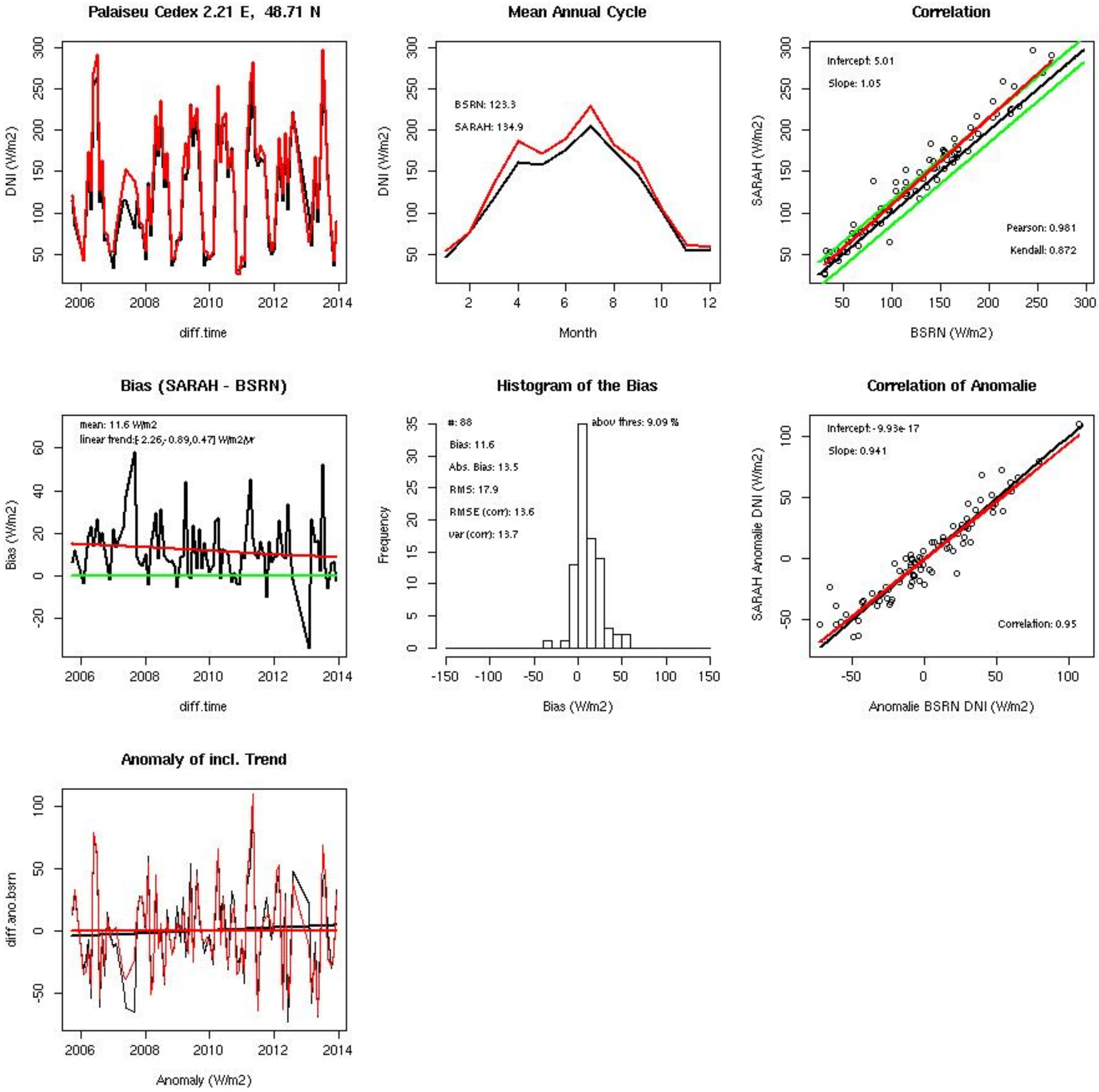

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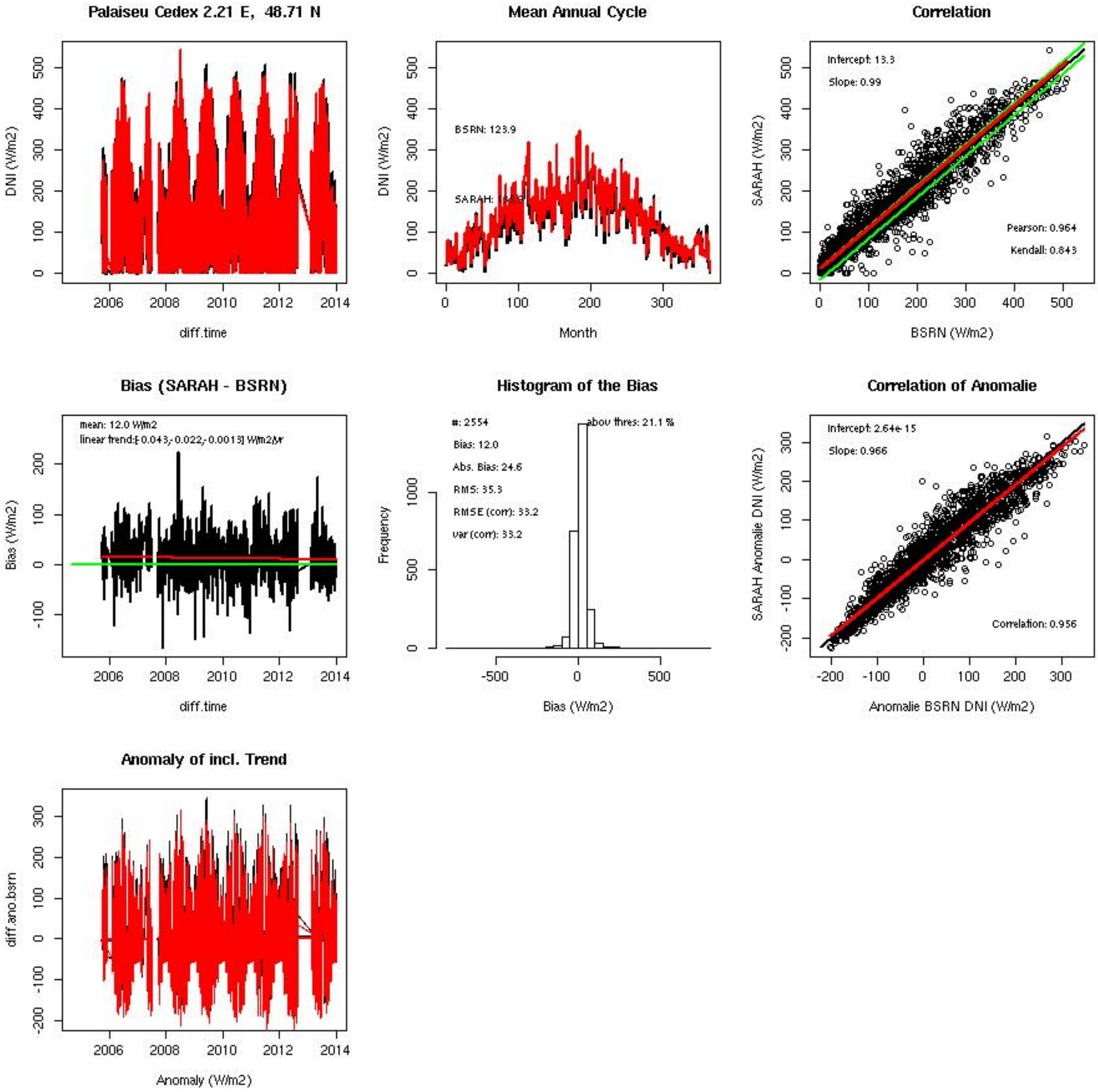

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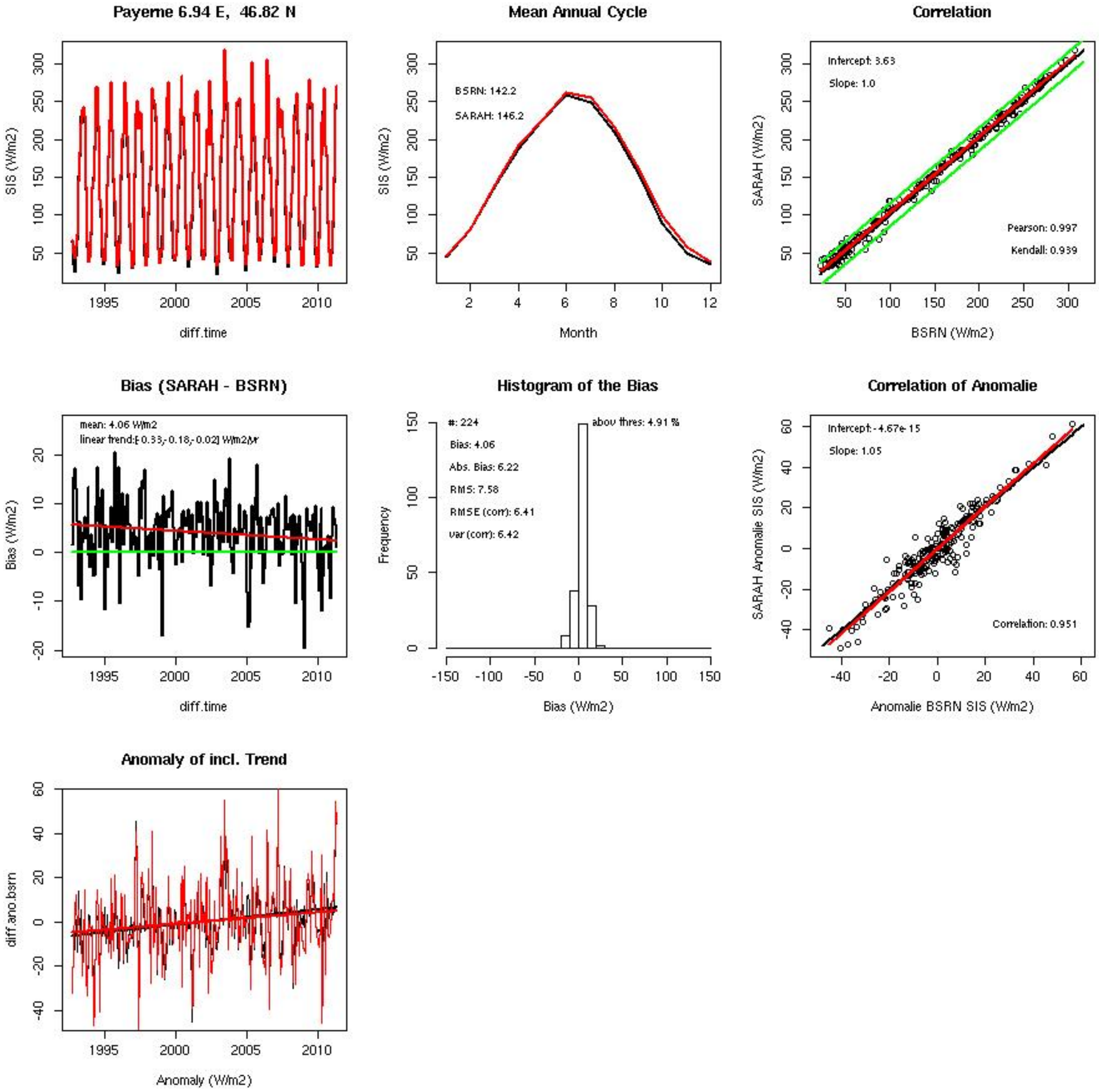

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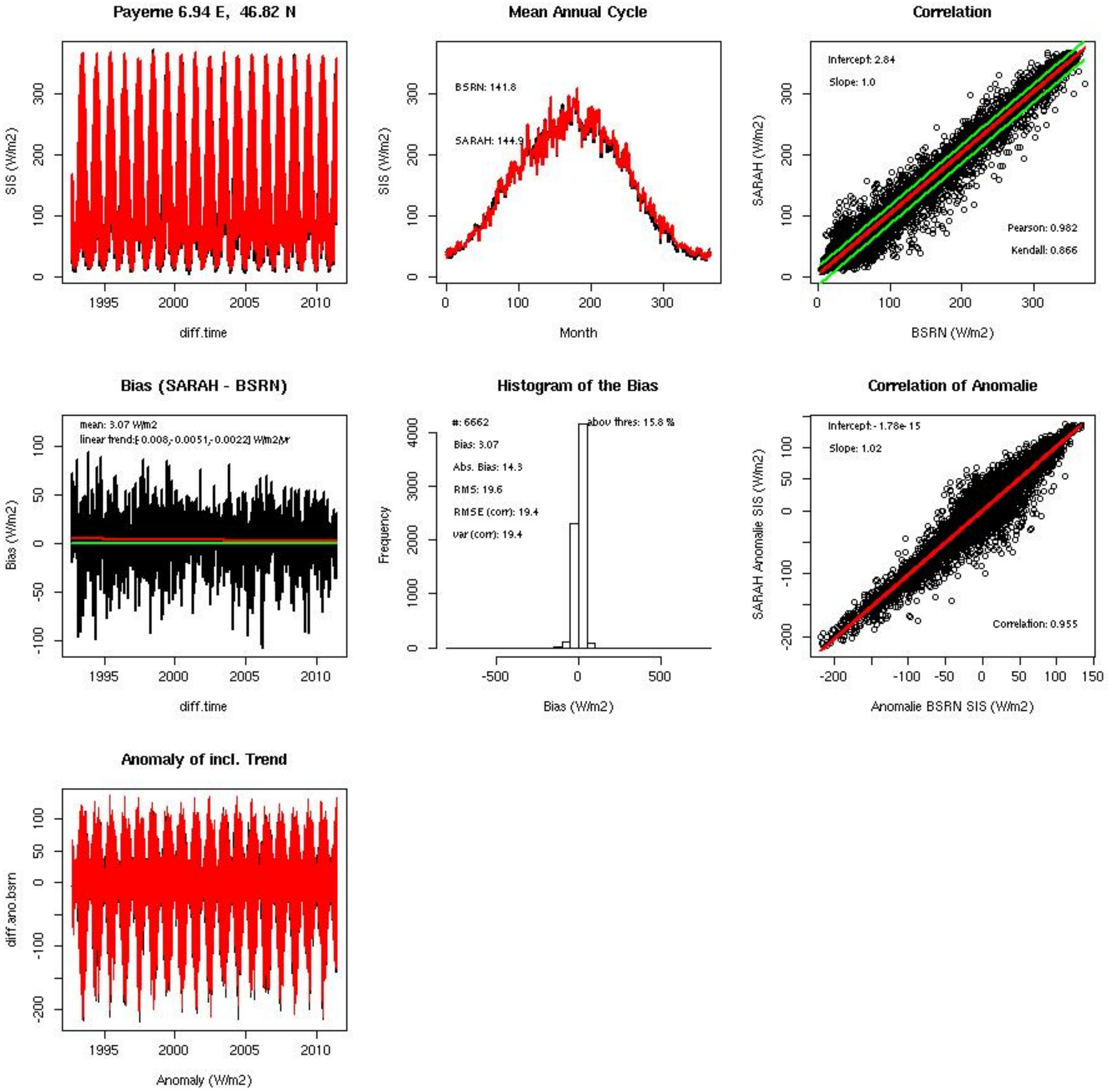

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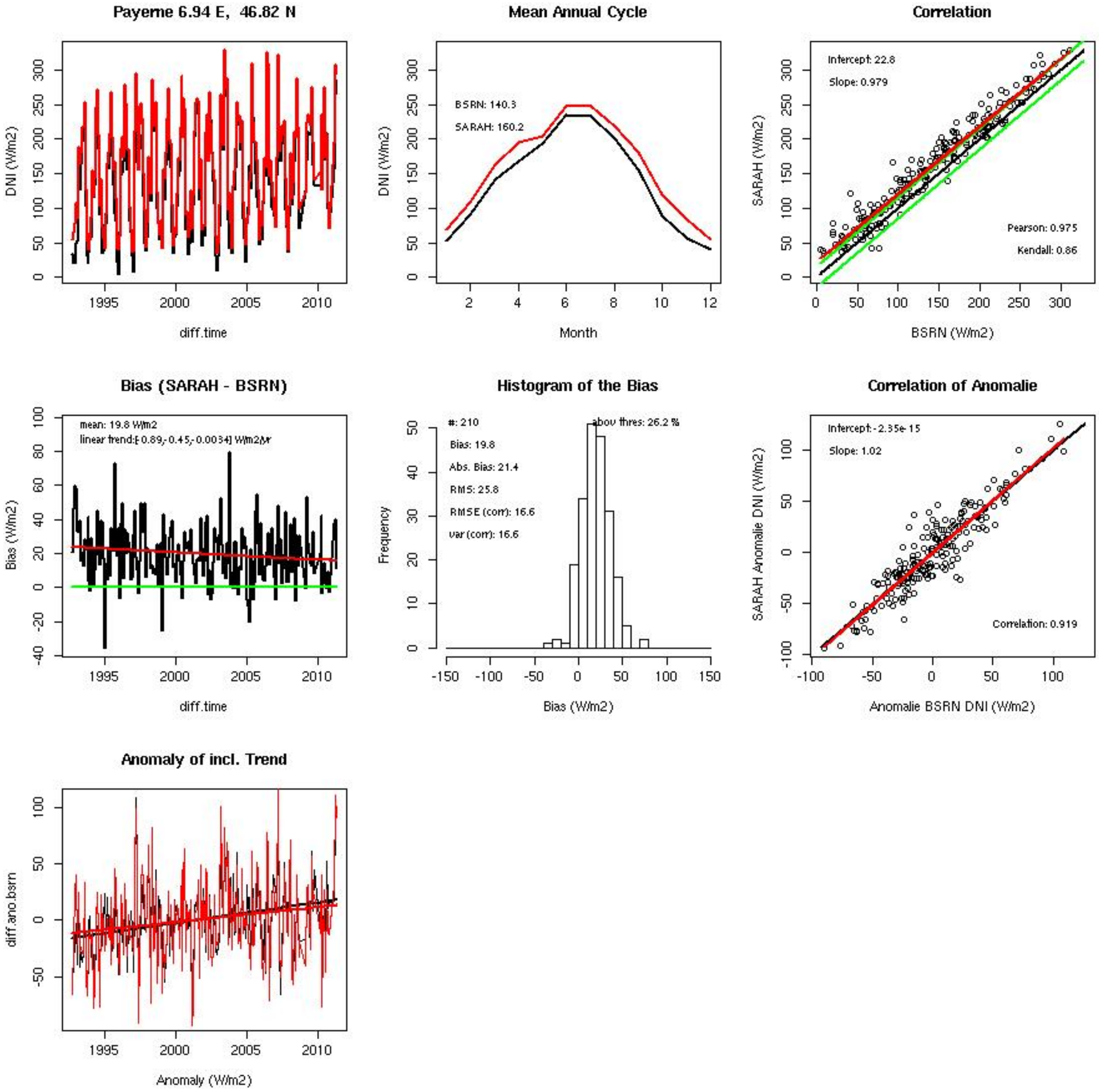

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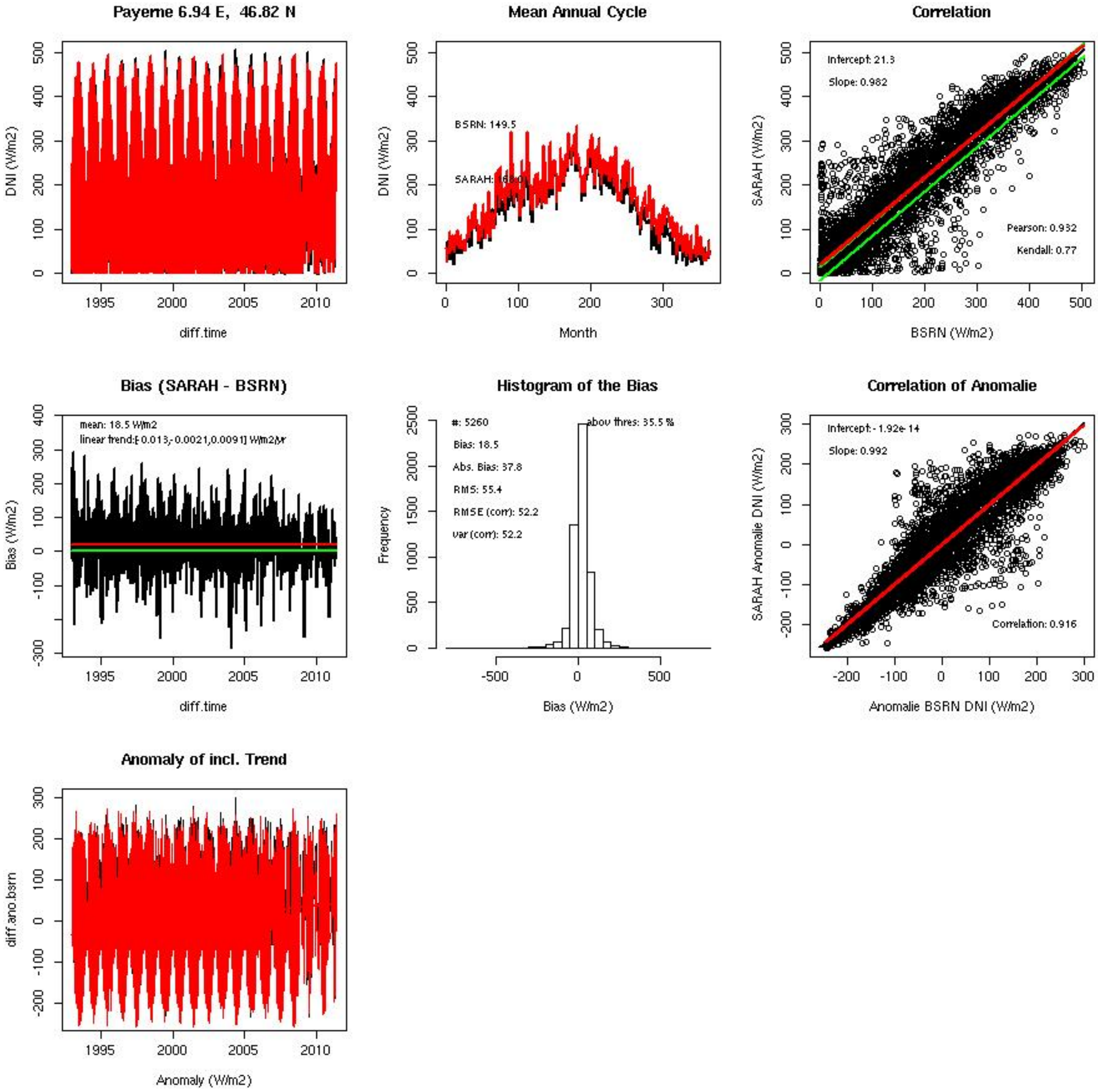

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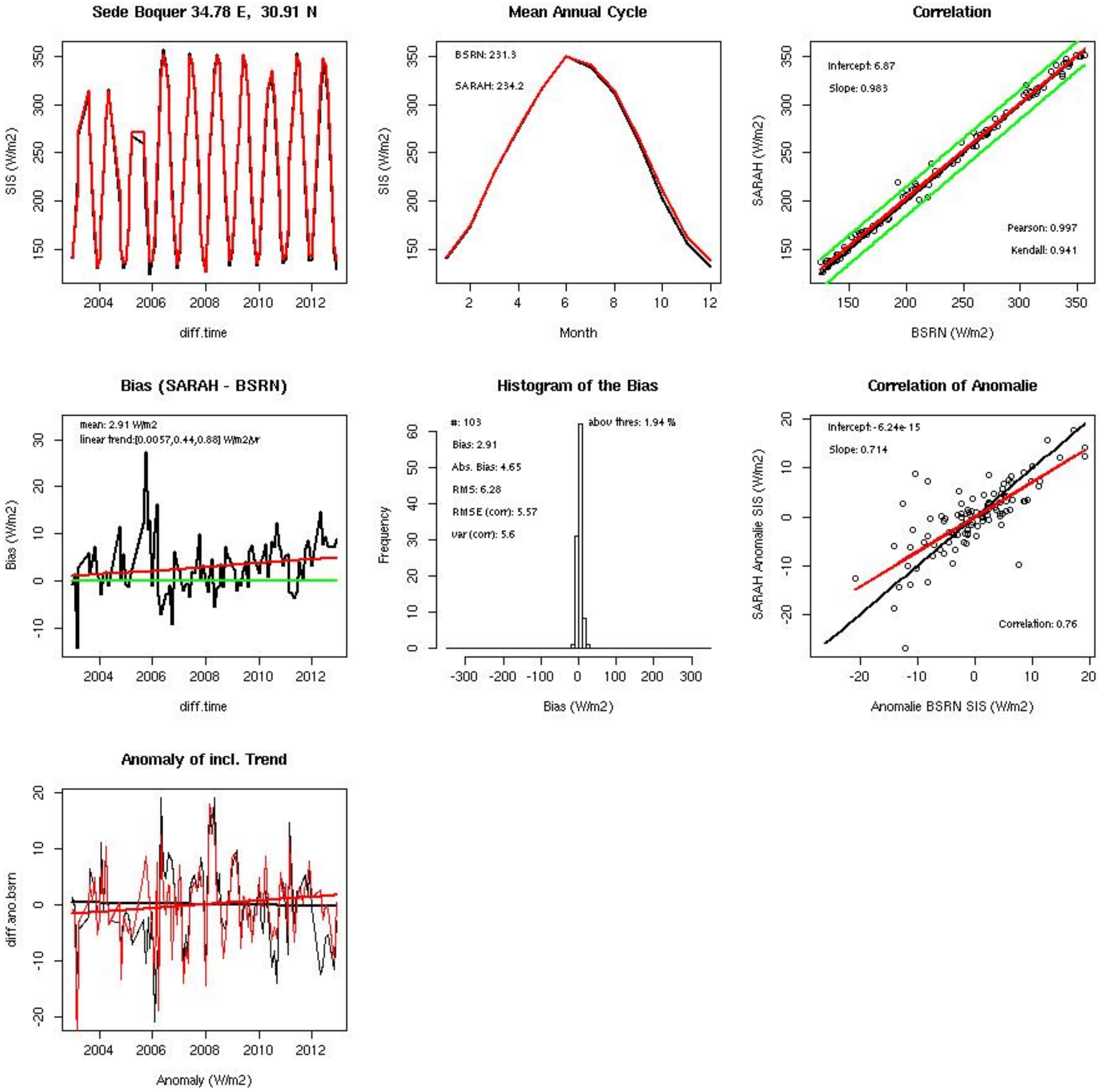

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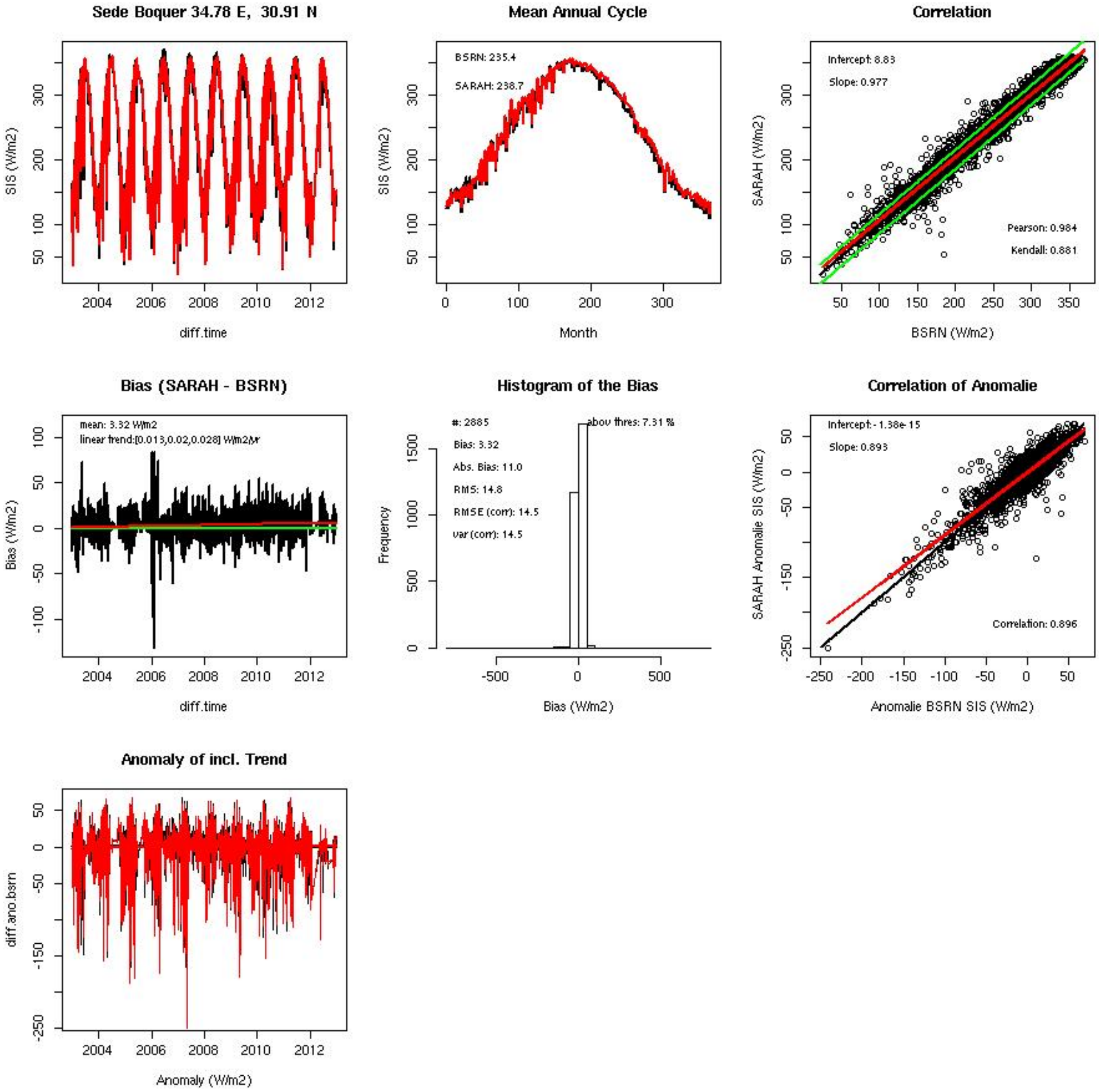

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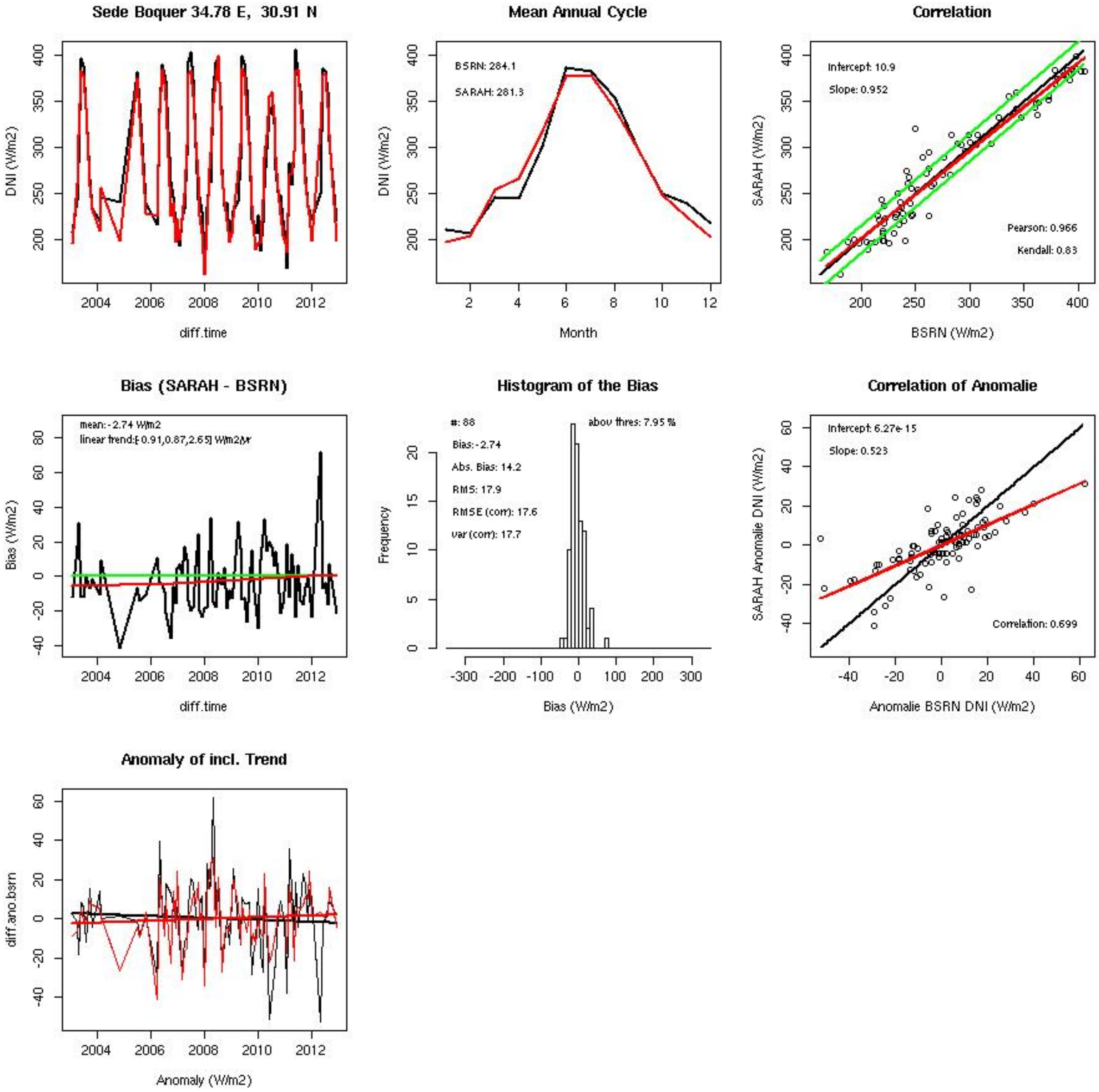

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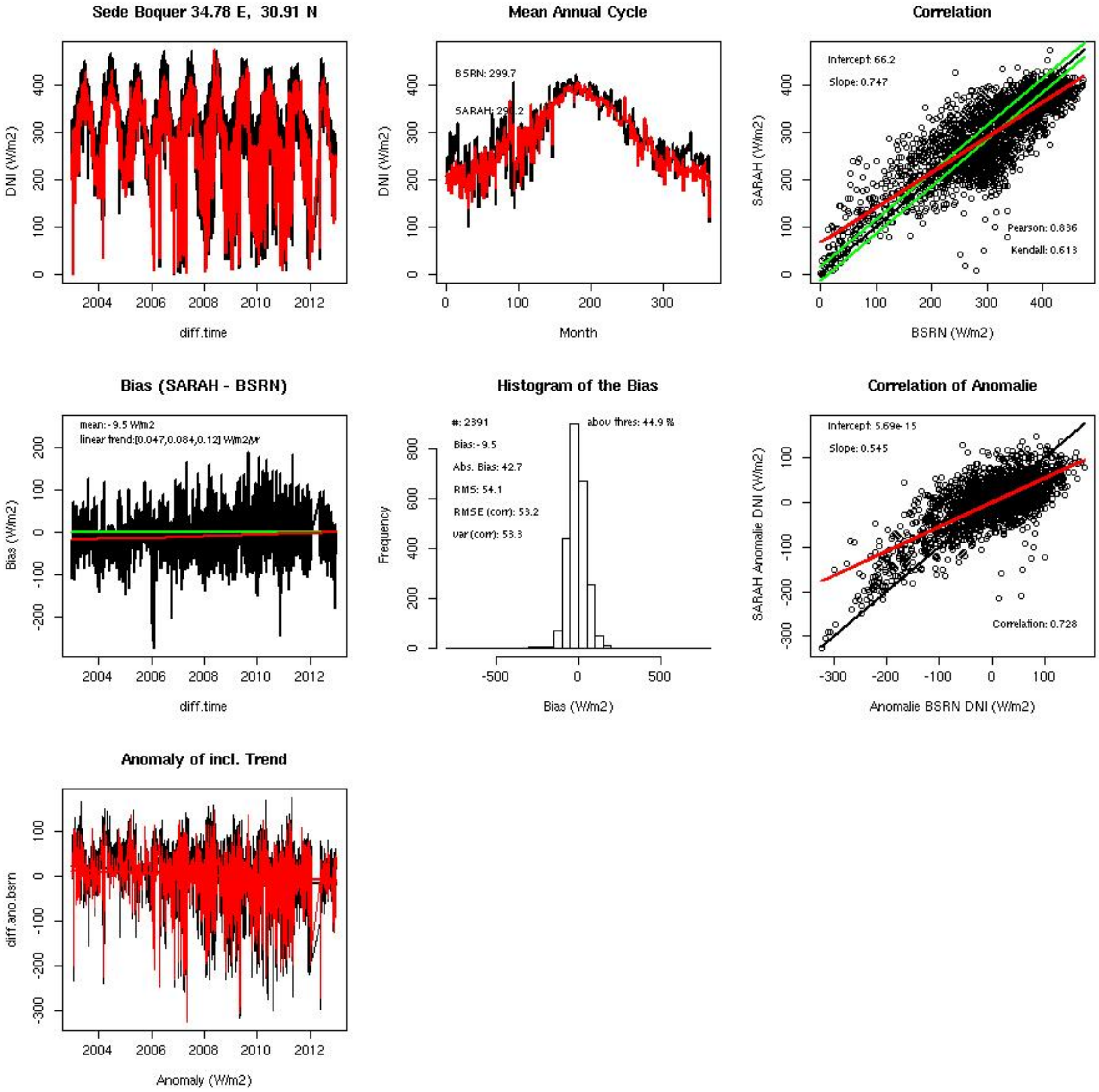

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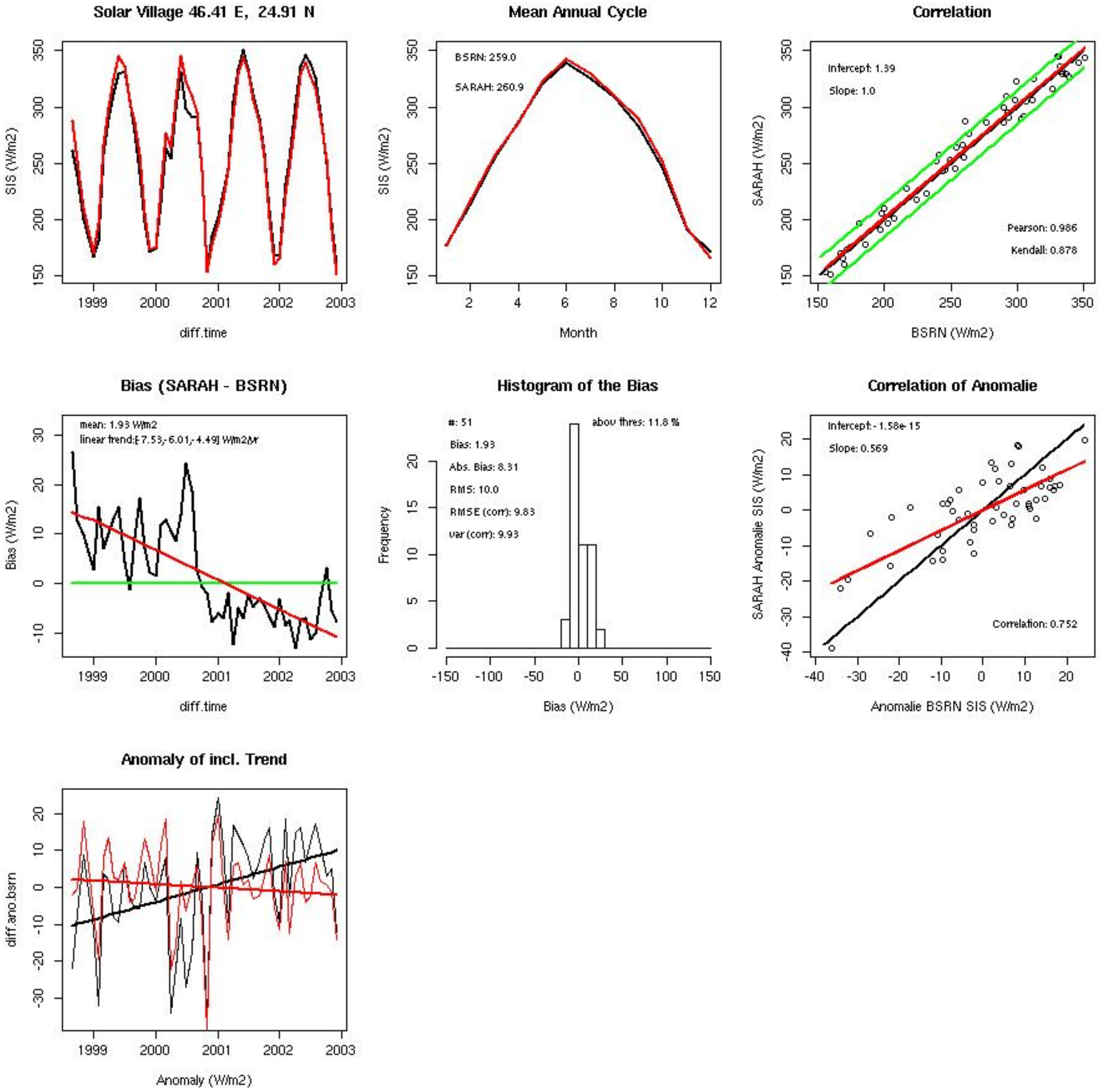

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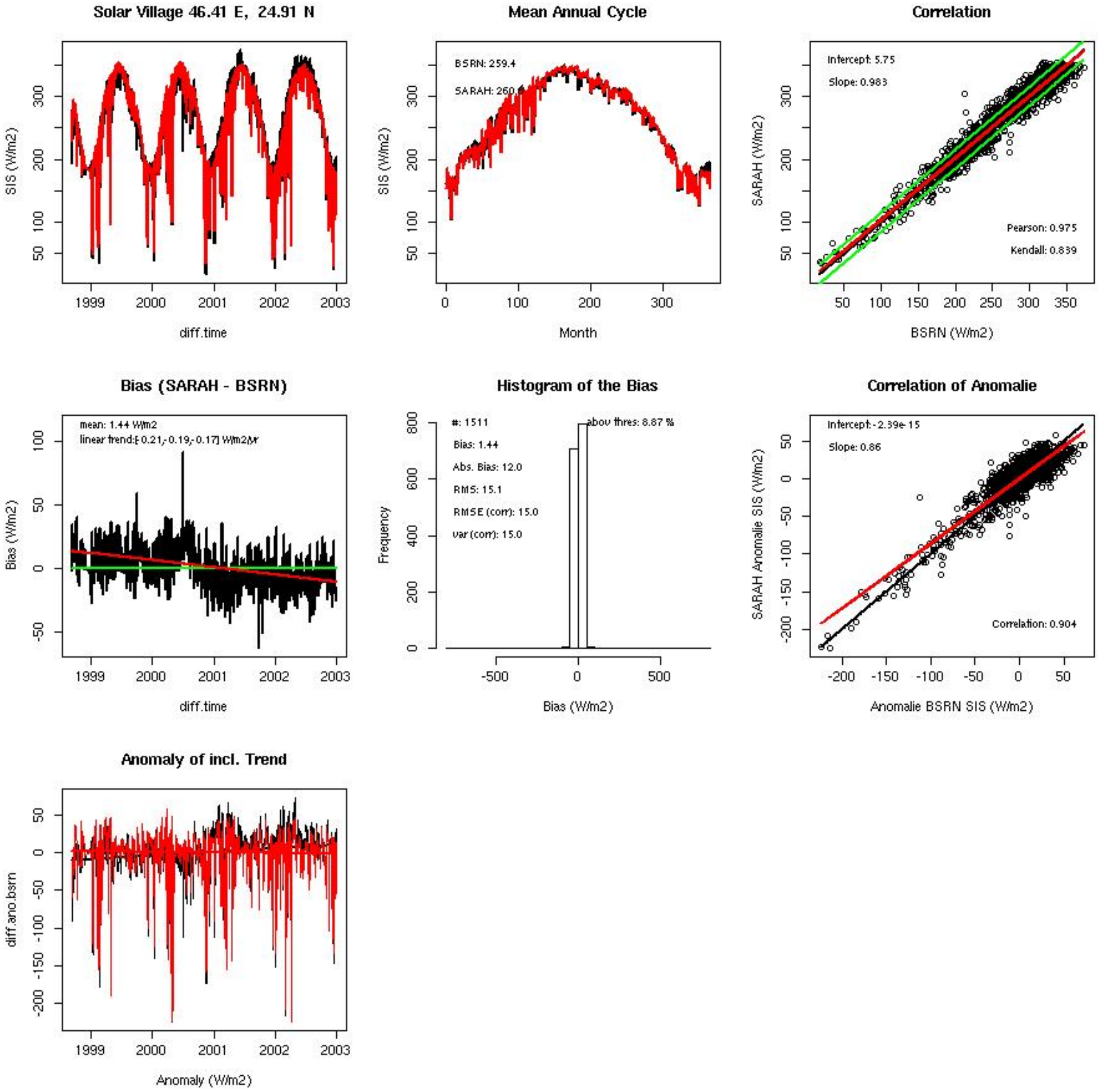

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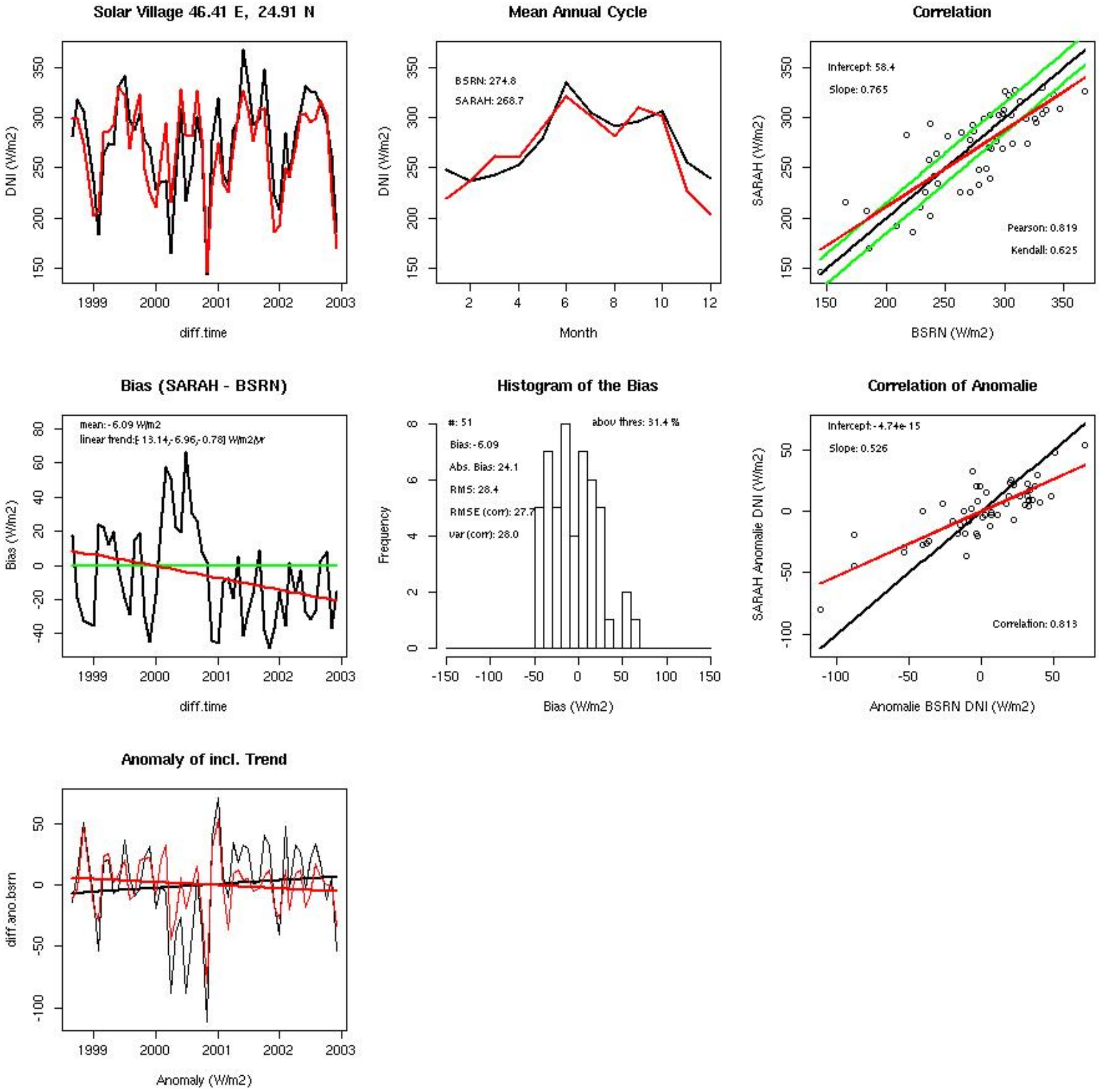

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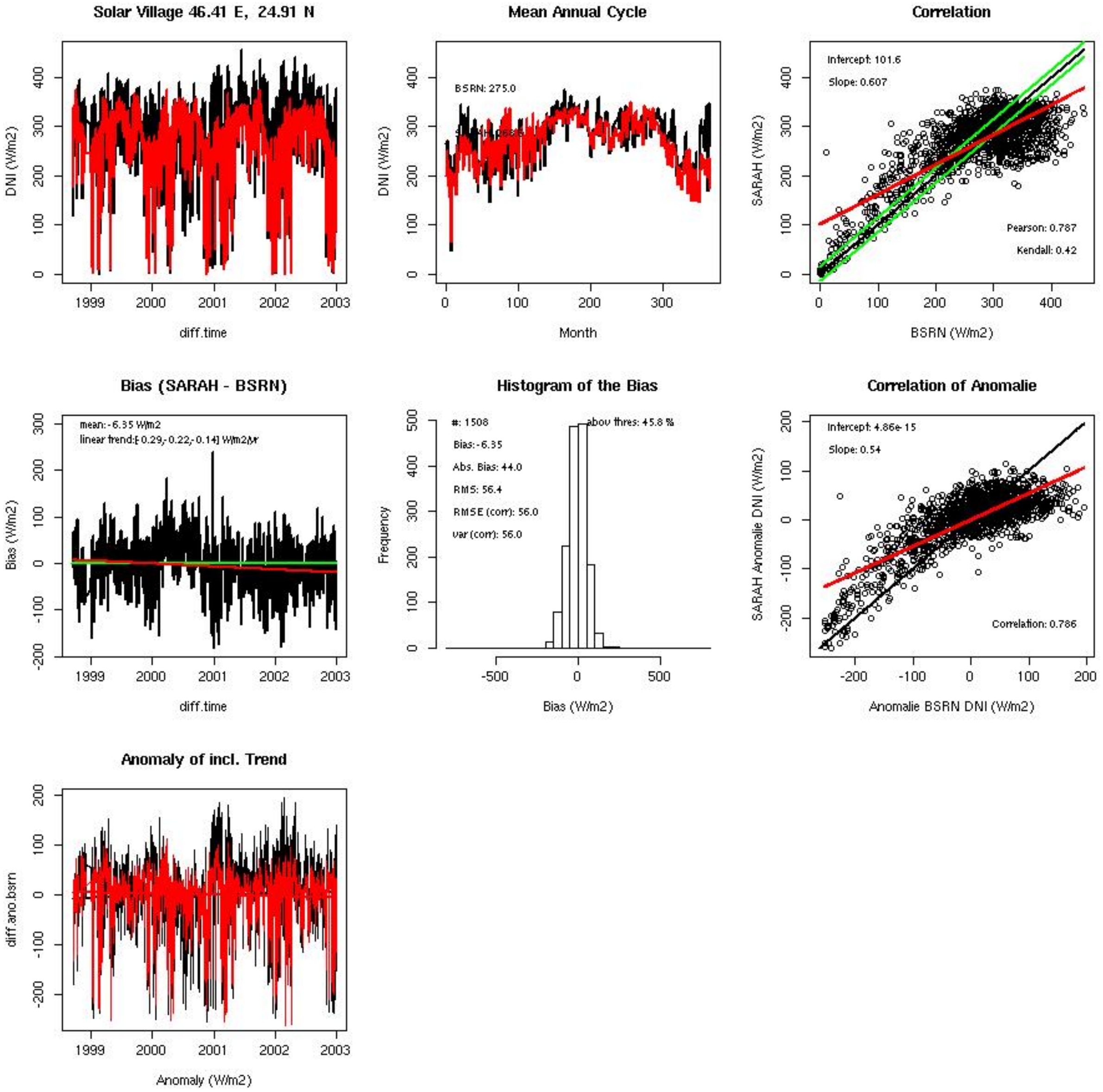

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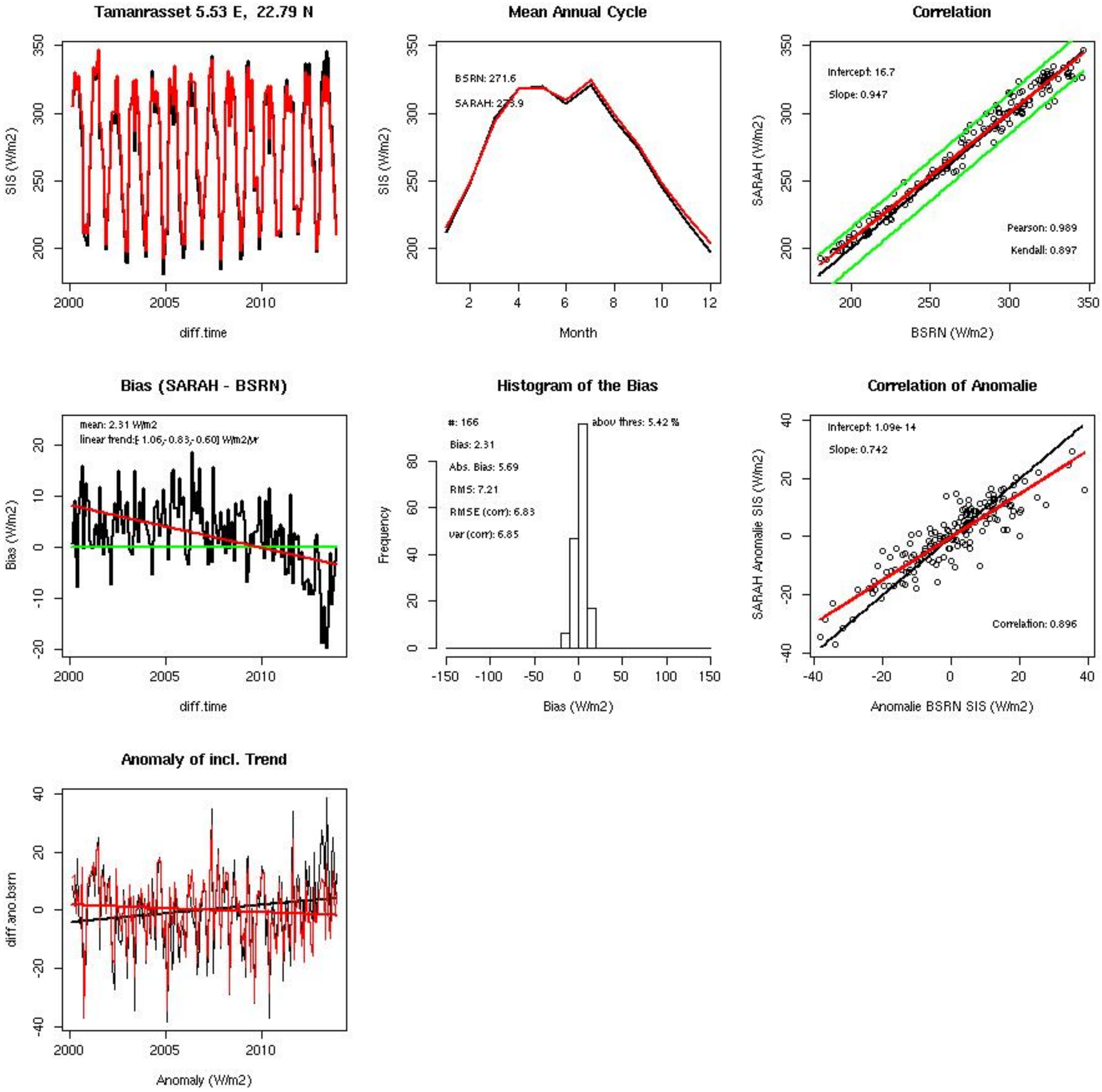

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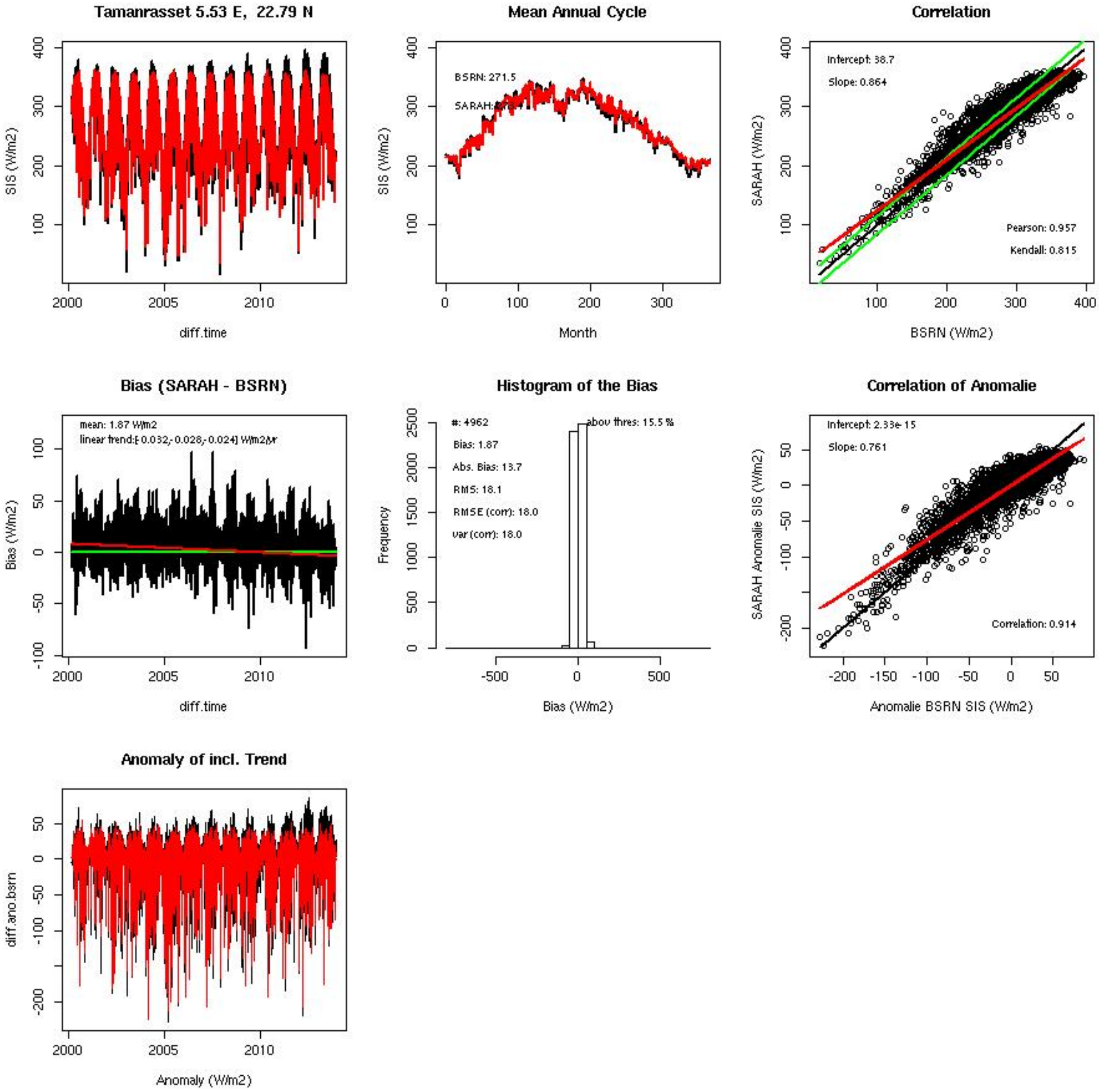

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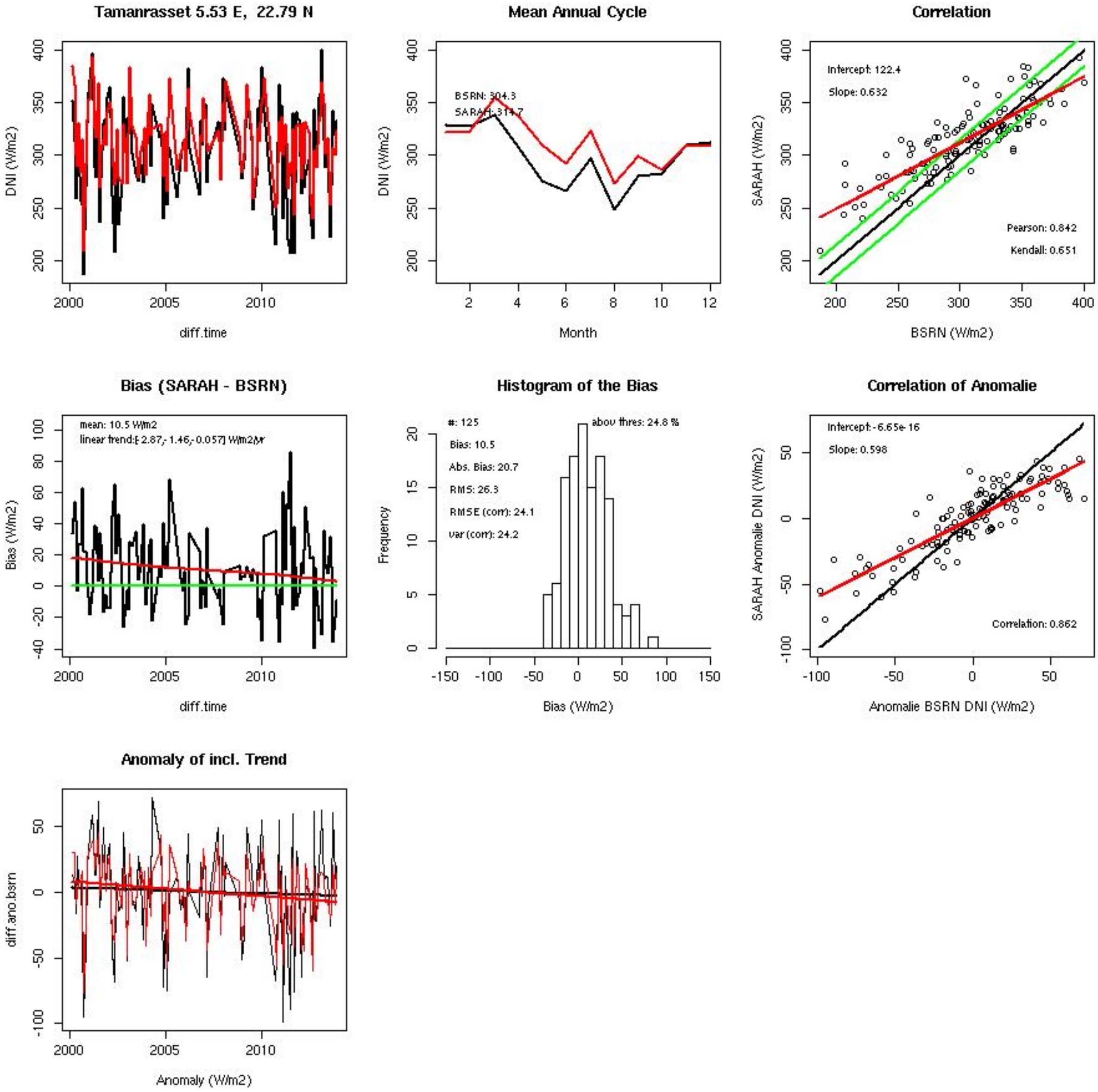

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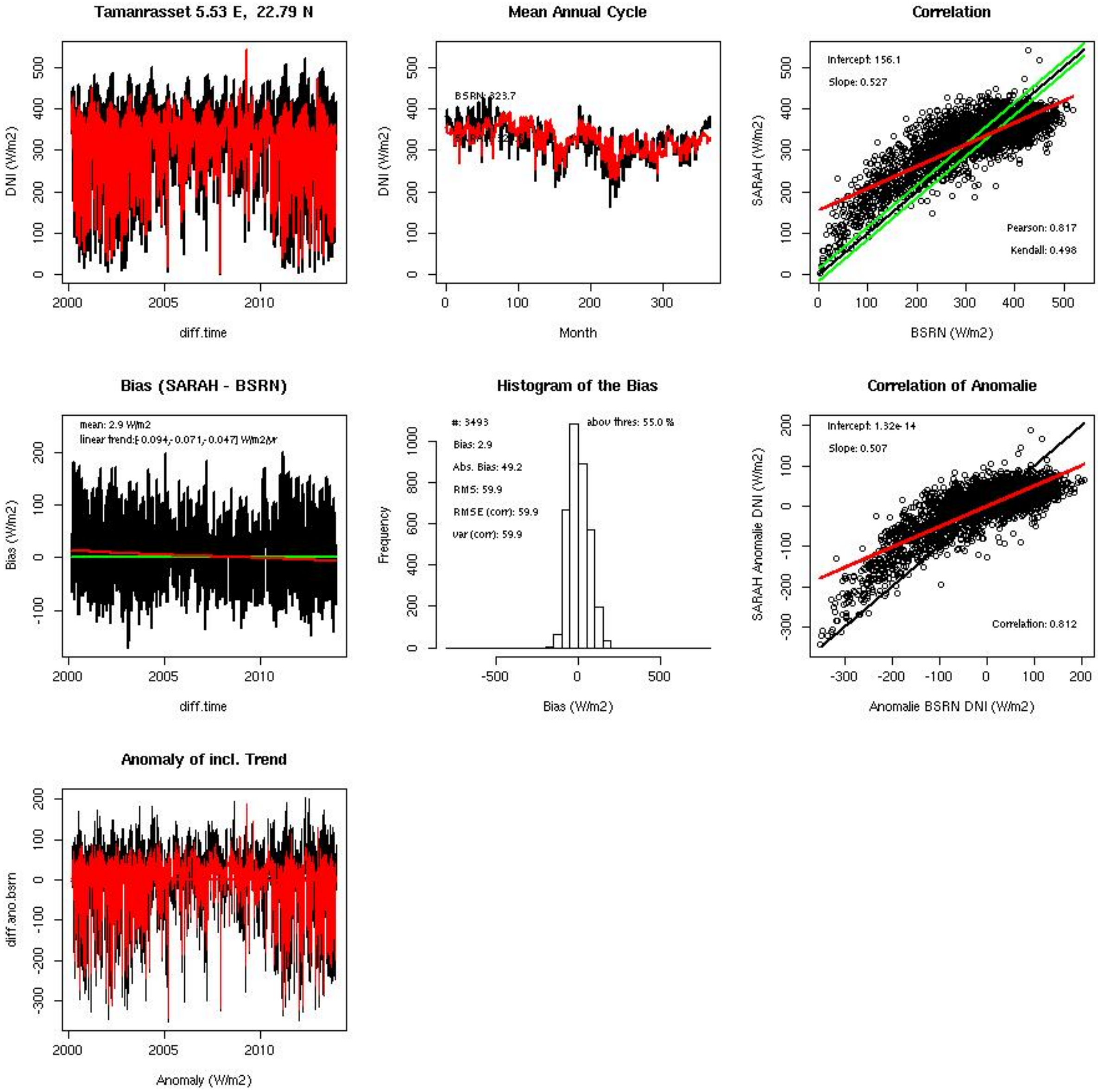

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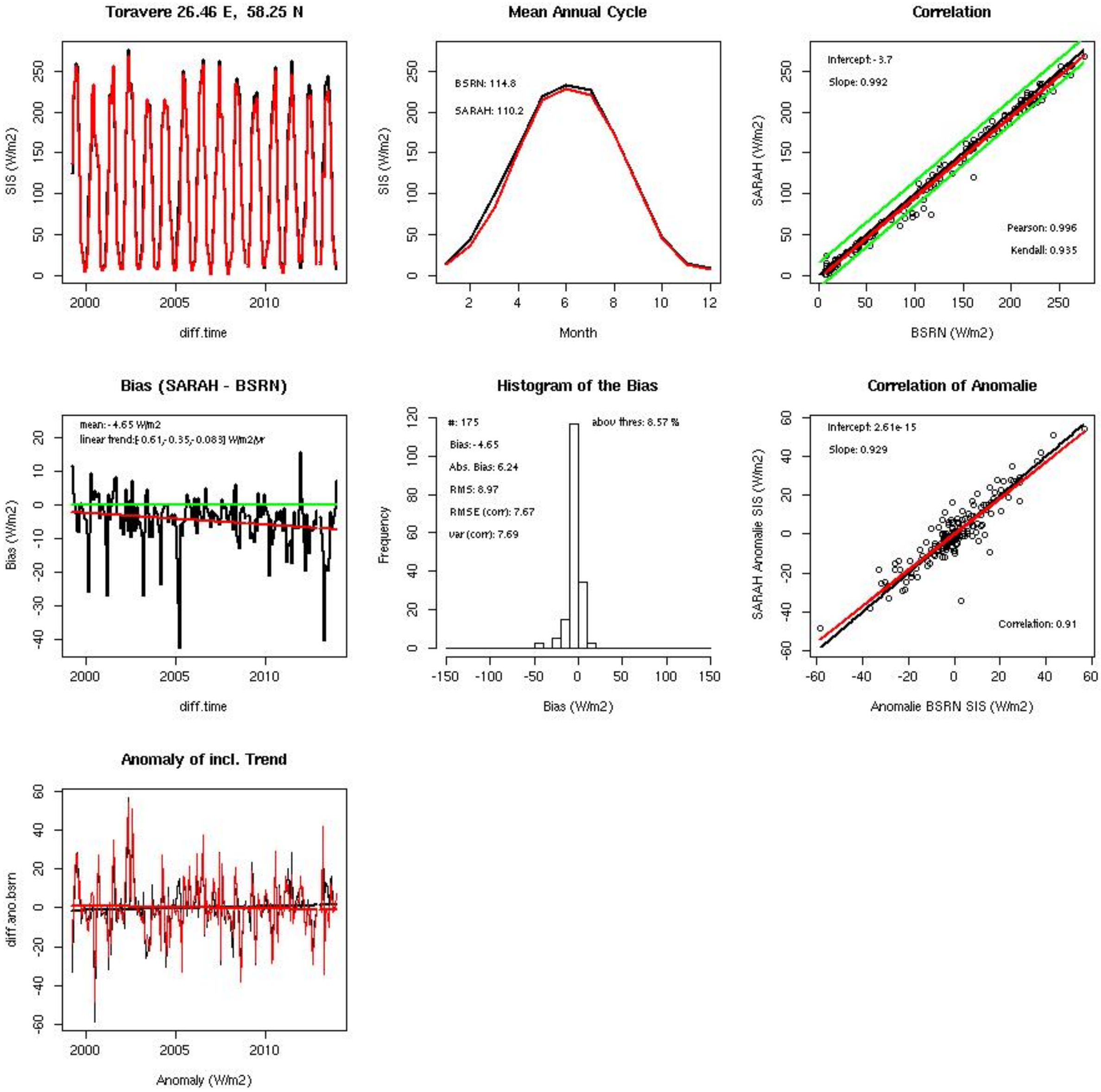

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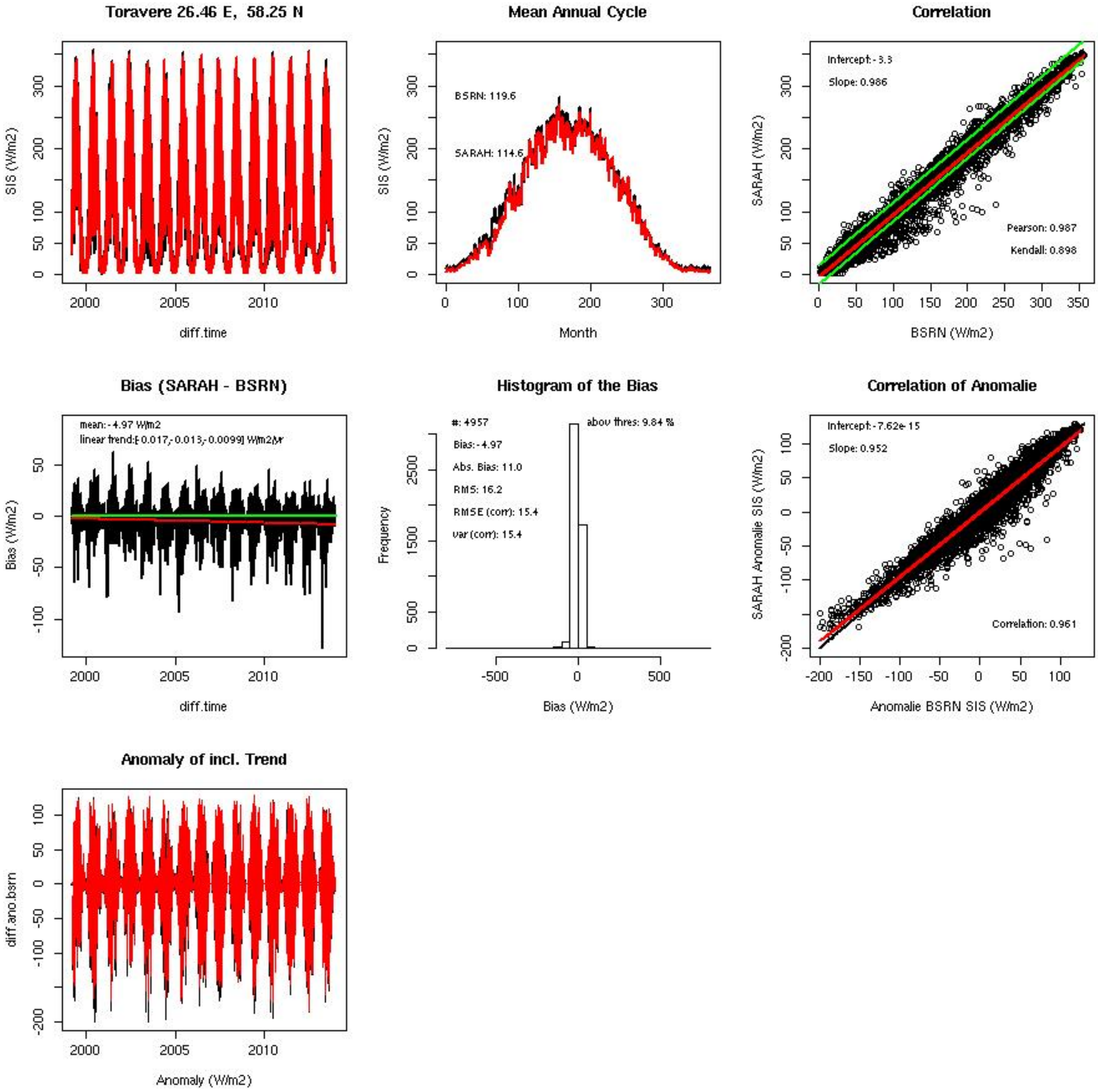

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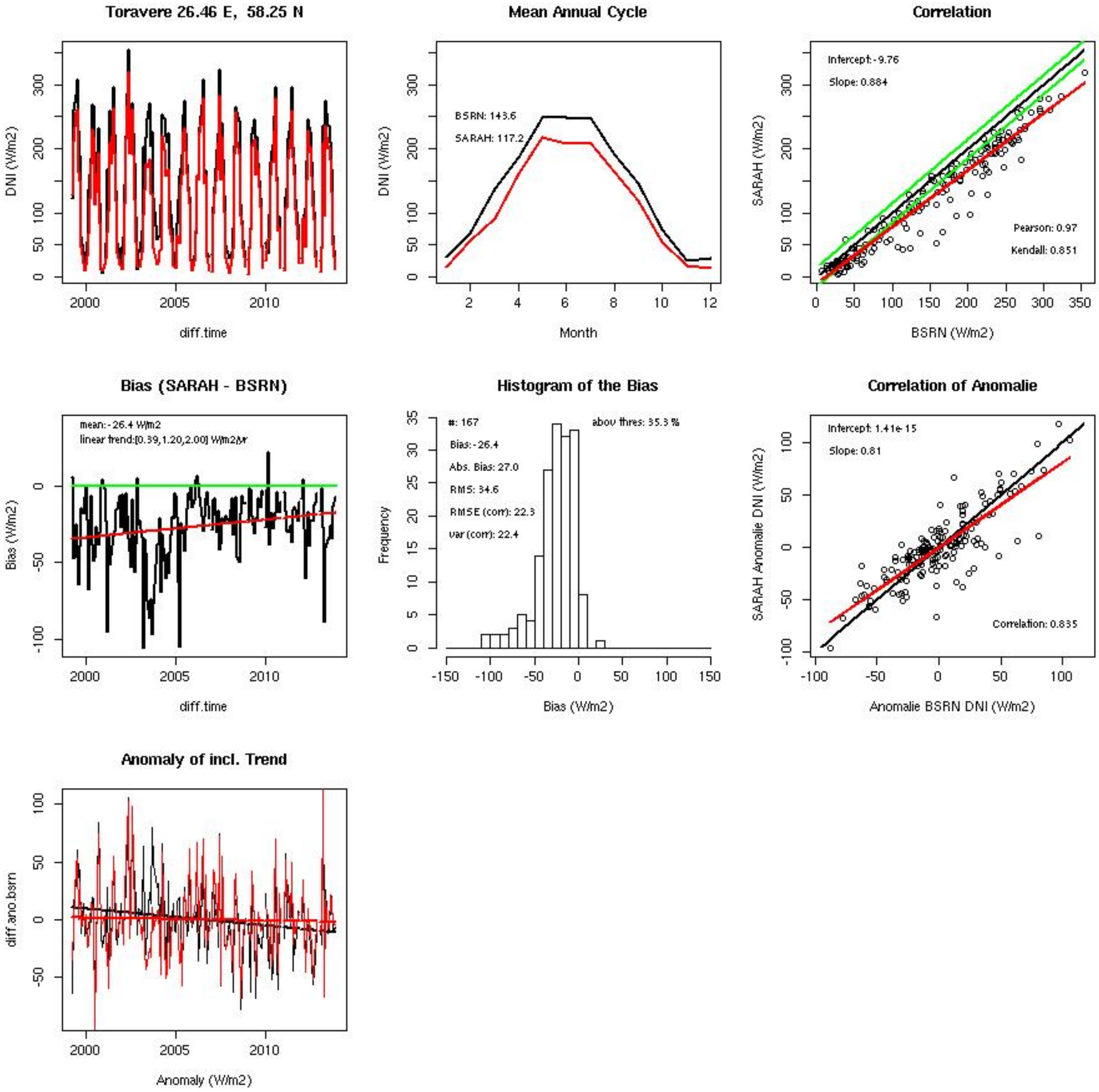

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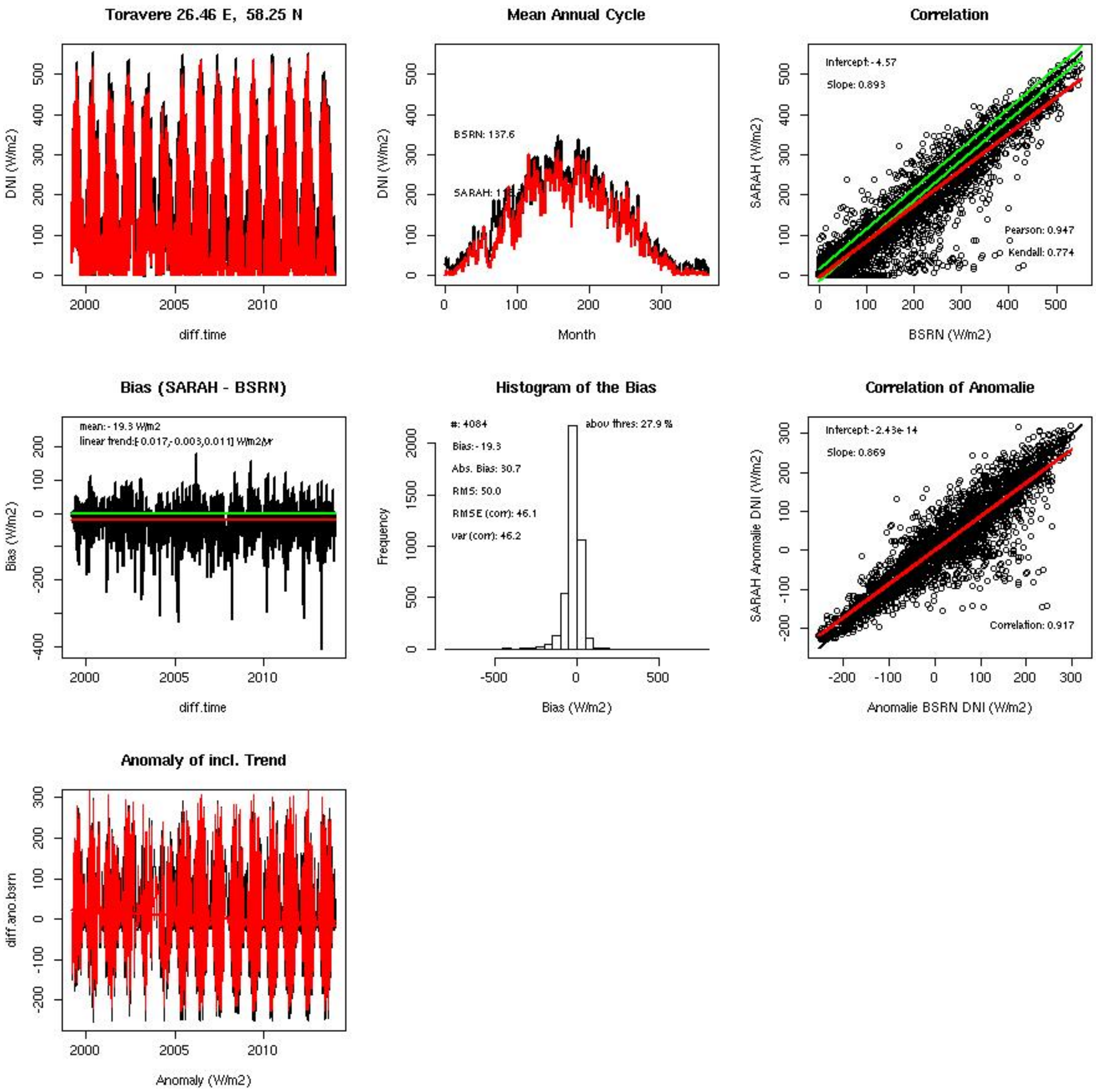

8 Appendix B: Glossary

Abbreviation	Explanation
AC	Anomaly correlation
BSRN	Baseline Surface Radiation Network
CDOP	Continuous Development and Operational Phase
CDR	Climate Data Record
CM SAF	Satellite Application Facility on Climate Monitoring
DNI	Direct Normal Irradiance
DWD	Deutscher Wetterdienst
ECV	Essential Climate Variable
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FD	Flux dataset (ISCCP)
FRAC	Fraction of days larger than the target value
GCOS	Global Climate Observing System
GEWEX	Global Energy and Water Cycle Experiment
ISCCP	International Satellite Cloud Climatology Project
MAD	Mean absolute deviation for the monthly, daily or hourly means
SD	Standard deviation
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