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Trends and Variability of Surface Solar Radiation in Europe based on Surface- and Satellite-based Data Records

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Abstract.

The incoming solar radiation is the essential climate variable that determines the Earth's energy cycle and climate. As long-term high-quality surface measurements of solar radiation are rare, satellite data are used to derive more information on its spatial pattern and its temporal variability. Recently, the EUMETSAT Satellite Application on Climate Monitoring (CM SAF) has published two new satellite-based climate data records: Surface Solar Radiation Dataset - Heliosat, Edition 2 (SARAH-2) and Clouds and Radiation Dataset based on AVHRR Satellite Measurements, Edition 2 (CLARA-A2). Both data records provide estimates of surface solar radiation. In this study, these new climate data records are compared to surface measurements in Europe during the period 1983-2015. SARAH-2 and CLARA-A2 show a high accuracy compared to ground-based observations (mean absolute deviations of 6.9 and 7.3 W/m^2 respectively) highlighting a good agreement considering the temporal behavior and the spatial distribution. The results show an overall brightening period since the 1980's onwards (comprised between 1.9 and 2.4 $W/m^2/decade$), with substantial decadal and spatial variability. The strongest brightening is found in Easter Europe in spring. An exception is found for Northern and Southern Europe, where the trends shown by the station data are not completely reproduced by satellite data, especially in summer in Southern Europe. We conclude that the major part of the observed trends in surface solar radiation in Europe is caused by changes in clouds and that remaining differences between the satellite- and the station-based

data might be connected to changes in the direct aerosol effect and in snow cover.

1. Introduction

Solar radiation is an essential climate variable ECV and the main energy source for the Earth-Atmosphere system [*Wild et al.*, 2015; *Ohmura and Gilgen*, 1993; *Ramanathan et al.*, 2001]. High-quality and long term measurements of the solar radiation are of major importance for our understanding of the climate system [*Hartmann et al.*, 1986]. Further, surface solar radiation (SSR) is a main constitute for the surface radiation budget [*Wild et al.*, 2017] that e.g. determines the temperatures of the troposphere. Moreover the SSR is of high importance not only for climate studies but also for many other applications e.g. solar energy production [*Wild et al.*, 2015; *Huld et al.*, 2017; *Miglietta et al.*, 2017], agriculture [*Stanhill and Cohen*, 2001] and vegetations dynamics [e.g. *Mercado et al.*, 2009].

Available studies document a widespread reduction ($3-9\,W/m^2$) of SSR from the 1950s to the 1980s called "global dimming" [*Stanhill and Cohen*, 2001] and a subsequent increase ($1-4\,W/m^2$) since the 1980s called "brightening" [*Wild et al.*, 2005; *Gilgen et al.*, 2009; *Wild*, 2009]. These variations are mostly due to changes in the transparency of the atmosphere due to variations in cloudiness and/or changes in anthropogenic aerosol emissions [*Liepert et al.*, 1994; *Stanhill and Cohen*, 2001; *Wild*, 2009; *Wild et al.*, 2016]. However, the full understanding of the mechanisms and the contributions of both phenomena to the observed chnages are still have some uncertain due to for example the lack of long-term SSR data, especially over ocean, remote land areas (e.g., Africa and Siberia) and areas characterized by complex orography (e.g. the Alpine region) [*Wild*, 2009, 2012; *Sanchez-Lorenzo et al.*, 2015]. Here, data from satellite observations (e.g., those provided by the EUMETSAT Satellite Application Facility on Climate Monitoring - CM SAF) provide valuable additional information [*Schulz et al.*, 2009], as they deliver an unique spatial coverage since the 1980s for both land and oceans [*Hinkelmann et al.*, 2009; *Zhang et al.*, 2015; *Raschke et al.*, 2016; *Karlsson et al.*, 2017b].

The highest quality of ground-based measurements of SSR are collected in the Baseline Surface Radiation Network (BSRN) Archive [*Ohmura et al.*, 1998]. Unfortunately, globally there are only about 50 BSRN stations available and their temporal coverage starts on in 1992. Therefore, BSRN cannot be used to evaluate variability and trends given by the satellite records on climatological scale. For Europe, several long-term station measurements are available and have been used already for the analysis of trends and changes, the Global Energy Budget Archive - GEBA [*Wild et al.*, 2017; *Sanchez-Lorenzo et al.*, 2017], the World Radiation Data Center - WRDC and measurements provided and managed by inidvidual countries [e.g. *Sanchez-Lorenzo et al.*, 2013; *Manara et al.*, 2016]).

Satellite-based data of SSR from the CM SAF has been validated by *Urraca et al.* [2017] in Europe using station measurements from national and international databases. It was found that the CM SAF satellite-based SSR data is of a high quality. *Sanchez-Lorenzo et al.* [2017] used European station data and a former version of the CM SAF satellite data of SSR to validate trends in Europe during the time period 1983-2010. They found overall positive Trends of SSR in Europe, and largest trends in spring.

In this study, two satellite-based climate data records of SSR provided by the CM SAF are evaluated with surface measurement in Europe for the time period 1983-2015 to assess their accuracy and their ability to capture temporal and spatial variability of SSR in Europe. The data and methods used in this study are presented in Section 2 and 3, respectively. A basic evaluation is shown in Section 4 and the trend and variability analysis are shown in Section 5. The discussion of results and conclusions are presented in Section 6.

2. Data

The data used in this study are two climate data records generated by the CM SAF, namely the Surface Solar Radiation dataset - Heliosat, Edition 2 (SARAH-2) and the CM SAF Clouds, Albedo and Radiation dataset from AVHRR data - Edition 2 (CLARA-A2). For validation purposes ground-based SSR measurements are used.

2.1. Station data

Long-term measurements of SSR are freely available from the Global Energy Budget Archive (GEBA) [*Sanchez-Lorenzo et al.*, 2015; *Wild et al.*, 2017], maintained by the ETH in Zurich, Switzerland, and from the World Radiation Data Center (WRDC) in St. Petersburg, Russia (`http://wrdc.mgo.rssi.ru/`). Even though all station data have been subject to a quality control and homogenization procedure, the data used in this study has been additionally checked. Additional measurements from Spain [*Sanchez-Lorenzo et al.*, 2013] and Italy [*Manara et al.*, 2016] are used in this study. Overall, 53 stations of monthly SSR measurements over Europe, providing data in the 1983-2015 period, have been collected. A list of all stations including further site information is shown in Table 1. Figure 1 shows the map of the analyzed area (Europe) including the station locations. The stations are relatively equally distributed (except the South-Eastern part of Europe) and cover different climate zones. The stations were further divided into 5 regions with similar temporal variability (determined by means of a Principal Component

Analysis [*Sanchez-Lorenzo et al.*, 2015]), as indicated in Figure 1. This regionalization of stations allows for a condensed and more robust regional trend analysis.

2.2. Clouds, Albedo and Radiation dataset from AVHRR data - Edition 2

The CM SAF Clouds, Albedo and Radiation dataset from AVHRR data - Edition 2 (CLARA-A2, [*Karlsson et al.*, 2017a]), covers the time period 1982-2015 and provides radiation and cloud parameters as daily and monthly means. The data record is based on the polar orbiting satellite measurements from the Advanced Very High Resolution Radiometer (AVHRR) and is available globally with a spatial resolution of $0.25° \times 0.25°$. More information about the CLARA-A2 satellite retrieval and the available data records is provided by *Karlsson et al.* [2017b].

Beside various cloud information and the surface albedo, the CLARA-A2 climate data record contains up- and downwelling surface longwave radiation as well as SSR. The accuracy of monthly SSR from CLARA-A2 has been assessed by *Karlsson et al.* [2017b]. It is found that the monthly mean CLARA-A2 SSR data has a small negative bias of $-1.6\,W/m^2$ and a mean absolute bias of $8.8\,W/m^2$ with reference to globally distributed station data from BSRN.

A known deficiency influencing the quality of SSR in the CLARA-A2 climate data record is the availability of only a single AVHRR instrument at any given time during the 1st decade of the data record (1982-1991). Therefore the spatiotemporal sampling of CLARA-A2 is limited during the early period, which leads to an increased number of missing data to estimate monthly means in the region of interest, reaching up to 50% missing data in Southern Europe. From 1992 onwards the spatiotemporal coverage is more complete. After 1992 the local overpass times of the used polar orbiting satelltes are in the morning and afternoon – at about 7.00 and 15.00 local time, respectively. Since 2002 a third satellite observes Europe at about 10.00 local time. Detailed information on the satellite orbits can be found in Figure 1 from *Karlsson et al.* [2017b].

2.3. Surface Solar Radiation dataset - Heliosat, Edition 2

The Surface Solar Radiation Dataset - Heliosat, Edition 2 (SARAH-2, *Pfeifroth et al.* [2017]) is the latest CM SAF climate data record of surface radiation based on the geostationary METEOSAT satellite series covering Africa, Europe and the Atlantic Ocean. It is the follow-up of the widely used SARAH climate data record [e.g. *Müller et al.*, 2015; *Riihelä et al.*, 2015; *Zăk et al.*, 2015]. SARAH-2 covers the time period 1983-2015 and offers global and direct radiation parameters as well as the effective cloud albedo. SARAH-2 is provided as daily and monthly means, and as half-hourly instantaneous data. Furthermore, sunshine duration and spectrally resolved radiation are available [*Kothe et al.*, 2017]. SARAH-2 covers the region of -65° to $+65^\circ$ in longitude and latitude and offers a high spatial resolution of $0.05^\circ \times 0.05^\circ$. A thorough overview of the basic retrieval principle of the SARAH climate data record series can be found in *Müller et al.* [2015]. SARAH-2 has been improved over the previous data record SARAH-1 especially by improving the stability in the early years and during the transition from the MVIRI to the SEVIRI instrument in 2006. Further a correction to better account for slant viewing geometries has been applied and topographically-corrected integrated water wapor data has been used.

The accuracy of the new SARAH-2 climate data record with reference to BSRN is documented in the CM SAF's Validation Report [*Pfeifroth et al.*, 2017] available at `http:`

//www.cmsaf.eu/. A positive bias of $+2\,W/m^2$ and an absolute bias of $5.1\,W/m^2$ for the monthly mean SARAH-2 SSR data has been found.

3. Methods

All data records are used as monthly means. For comparisons of the gridded satellite data with the station data, the satellite data is extracted at the station locations, by selecting the satellite pixel in which the station is located. The conducted trend calculations for the data records are based on linear regression analysis and based on monthly anomalies with reference to their long-term monthly means. Trends are analysed at the spatial and at the seasonal scale, which provides new insights on the temporal and, in case of the satellite data records, also on the spatial variability. The seasons are defined as follow: winter (DJF: December, January, February), spring (MAM: March, April, May), summer (JJA: June, July, August) and autumn (SON: September, October, November). In case of spatially averaged trends, the anomalies derived for the individual station or satellite pixel time series are first averaged in space and then the trends are calculated as described above. The obtained trends for each dataset are then presented either in the way of so-called Trendraster-plots or, in case of spatial trends, as spatial maps.

The Trendraster-plot, or running trend analysis [*Brunetti et al.*, 2006], is a way to represent, in a condensed way, the trends for different subperiods with different lengths. The advantage of the Trendraster-plots is that mid- and longer-term variability can be compared easily. Specifically, the y-axis represents the starting year while the x-axis represents the last year of the considered period. The color of each pixel shows the intensity (linear trend $W/m^2/decade$) of the trend in the considered period

In some cases 95%-confidence intervals of the linear trends are given. These confidence intervals are used to analyse wether a trend is statistically significantly positive (negative), which is the case if both the lower and upper 95%-confidence interval are positive (negative). Further, if the confidence intervals of trends derived from different data do overlap, they can be considered to be not statistically different.

4. Evaluation of Accuracy

In this section a basic validation of the CLARA-A2 and SARAH-2 climate data records with reference to the 53 stations in Europe is presented. A prerequisite for satellite climate data records be usable for climate purposes is to reasonably reproduce anomalies. Further a low bias and low mean absolute deviations (MAD) compared to reference measurements are desired.

Figure 2 shows the mean SSR based on the two CM SAF climate data records analysed in this study. Both data records overall agree in the general structure of SSR for Europe. For the CLARA-A2 climate data record, the limited number of observations during daylight in wintertime does not allow the calculation of monthly means for latitudes higher than about $55°N$ during the full year. Subsequently the data is set to missing in the CLARA-A2 climate data record of SSR for the corresponding area during twilight situations, as can be observed in Figure 2.

The validation of the CLARA-A2 monthly solar radiation data with the station data reveals on average a negative bias of $-0.4\,W/m^2$ and a MAD of $7.3\,W/m^2$ (cf. Table 2). The SARAH-2 monthly SSR data has a positive bias of $+2.7\,W/m^2$ and a MAD of $6.9\,W/m^2$. The correlation coefficient of monthly anomalies is 0.88 for CLARA-A2 and 0.89 for

SARAH-2, documenting that both data records are well suited for the monitoring of monthly anomalies.

The scatterplots of the monthly anomalies derived from CLARA-A2 and SARAH-2 versus the station data are shown in Figure 3, where it is distinguished between the time periods before and after 1992. In 1992, the temporal sampling of the CLARA-A2 climate data record is improved by the availability of a second AVHRR sensor [*Karlsson et al.*, 2017b]. As shown in Figure 3 (bottom), the correlation of anomalies substantially increased after 1991 from 0.848 to 0.904. For this reason, in the following analysis the first 10 years of the CLARA-A2 climate data record (1982-1991) are left out to ensure a high temporal stability of the satellite data. Moreover, there are, depending on latitude, up to 50% missing data before 1991 in the CLARA-A2 SSR and as a consequence the absolute bias for the early years increases to about 10 W/m^2 for CLARA-A2, which is more than 30% higher than for the period after 1991 (see Table 2). The correlation of anomalies is around 0.90 for both periods for the SARAH-2 climate data record (cf. Figure 3 allowing the analysis of SARAH-2 for the full period of 1983-2015 in this study.

Overall the basic evaluation of the CM SAF CLARA-A2 and SARAH-2 climate data records highlights their high quality and accuracy, which allows a detailed analysis of SSR using these satellite-based climate data records provided by the CM SAF.

5. Trend and Variability Analysis

In this part, variability and trends of SSR derived from the CM SAF's SARAH-2 and CLARA-A2 climate data records are evaluated using the station data. Further, the spatial distribution of trends based on the satellite data records are shown.

The mean anomaly time series of SARAH-2, CLARA-A2 and the stations for the 53 European locations are shown in Figure 4. It is thereby distinguished between the time periods of 1983-2015 and 1992-2015 (as noted in Section 4). Figure 4 shows that the time series of monthly anomalies agree well between the data records even though the differences are larger in some periods, for example around 1990 between SARAH-2 and the station-based data. Possible reasons for these slightly larger differences are satellite changes, the disregard of the aerosol radiative effect of the Pinatubo eruption in 1991, or other unknown issues in either the satellite or the station data.

Regarding the linear trends, all three data records agree reasonably well for both the longer and shorter time period (cf. Figure 4), even though both SARAH-2 and CLARA-A2 use an aerosol climatology as input. All data records exhibit positive trends in SSR between 1.9 to 2.4 $W/m^2/decade$ for the period 1983-2015, and between 2.7 to 3.0 $W/m^2/decade$ for the time period 1992-2015. The trends in the station data are overall larger than in the satellite data, while the SARAH-2 trends are somewhat closer to those observed at the stations than the trends derived from CLARA-A2. As shown in Figure 4, the mean trends do agree within their confidence intervals, as the intervals are overlapping each other.

A way to analyze trends during different time periods is by using running trend analysis as depicted by so-called Trendraster-plots. A Trendraster-plot for the 53 station mean SSR and of the corresponding data of SARAH-2 and CLARA-A2 (at the station locations) is shown in Figure 5. All three Trendraster-plots of SARAH-2, CLARA-A2 and the stations agree in an overall brightening in Europe, shown by the red squares in the lower right part of the Trendraster-plots, which represent the trends of the longest time periods.

Further there is not only a reasonable agreement in the overall positive trends, but there is also agreement in the shorter-term trends, i.e. the decadal variability. In the early years, from 1983 to the late 1990's there is a positive trend in SSR, which is followed by a zero or slightly negative trend during the time period of the late 1980's until about 2002. From the mid 1990's to the mid 2000's the trends are positive again with values between 6-8 $W/m^2/decade$ consistent between the data records. During the latest years (i.e. after ~2006) the SSR trends are small. The most positive trends are found in the 1990's in the CLARA-A2 climate data record with values of up to +8 $W/m^2/decade$. The mainly zero (or slightly negative) trends of SSR during about 1989-2000 are smaller in the SARAH-2 climate data record than those derived from the station data.

The regional trends over the 33 year time period are shown in Figure 6. For each of the 5 regions (c.f. Figure 1), a boxplot is used to depict the distribution of the linear trends for the locations in the different regions. Each boxplot shows the mean an the median of the trends as well as quartiles, percentiles and outliers. Figure 6 compares the regional trends during the time period 1983-2015, when SARAH-2 and the stations are used, and during the shorter time period 1992-2015, when also CLARA-A2 is used. It is shown that the mean regional trends are all positive and are mostly ranging between 2 and 4 $W/m^2/decade$. In all regions, except the region South, the trends between the two satellite climate data records and the stations agree well. An exception is found in the region South, where the trends based on station data are much larger than in the CM SAF's satellite climate data records, for both analyzed time periods. In the region South, the mean trend based on the station data are in the order of 5 to 6 $W/m^2/decade$, while the trends based on SARAH-2 and CLARA-A2 data are consistently lower in the order of 2 $W/m^2/decade$. The larger spread in the trends among the stations in region South is evident, in particular for the shorter time period (cf. outliers in Figure 6), when trends range from 3 to 10 $W/m^2/decade$.

A worthwhile characteristic of satellite data is its provision of spatially complete information. The spatial pattern of the linear trends of SSR in Europe given by the CM SAF SARAH-2 and CLARA-A2 are shown in Figure 7. For comparison the SSR trends of the station data are added. In the left part of Figure 7 the trend of SARAH-2 for the full 33-year period is shown. The largest positive trend is found in Eastern Europe (especially east of the Carpathian Mountains). Strong positive trends of SSR are also visible in parts of Central Europe and over the North and Baltic Sea. Some regions experience a low or negative trend during the time period 1983-2015 e.g. parts of France and Great Britain.

Figure 7 also provides the SSR trends for the time period 1992-2015 for the CLARA-A2 and the SARAH-2 data records. There is a remarkable agreement between both data records in the mean trends at the stations (cf. Figure 4), and in its spatial pattern, especially over land. During the time period 1992-2015 the most positive trends can be found in Eastern Europe while slightly negative trends are derived in parts of the Eastern Mediterranean region in both data records. Over the oceans, especially over the Atlantic Ocean and the North Sea, the trends are more positive in the CLARA-A2 climate data record than in the SARAH-2 climate data record. The CLARA-A2 SSR also has a more distinct land-ocean difference in trends compared to the SARAH-2 SSR.

The mean seasonal trends of SSR for the five regions are shown in Figure 8. In all regions, except in the region South, the strongest positive trends in SSR are observed in the spring season, with values in the range of about 4 to 6 $W/m^2/decade$. In summer, the trends are also positive, with extreme positive trends given by the station data in the region South, where the mean trend is around 9 $W/m^2/decade$, in line with results from *Sanchez-Lorenzo et al.* [2015] and *Manara et al.* [2016]. Again we find an overall tendency of a slight underestimation of the positive trends of the satellite data with reference to the station data, mainly in spring and summer. Based on the sign and magnitude of the SSR trends(cf. Figure 8), we conclude that there is a reasonable agreement between the CM SAF's satellite and the station data. Notable exception it the region South during summer, which will be discussed in more detail in Section 5.2.

Similar to the trend over the 33-years time period shown in Figure 8, Figure 9 presents the regional and seasonal trends for the shorter time period of 1992-2015, for which the CLARA-A2 climate data record is analysed as well. We find larger differences in the trends of the different data records for the shorter time period. As expected, the absolute trends in the different regions and seasons are partly different to the ones derived for the 33-year time period (Figure 8). For example, in the region Central-West, the strongest positive trends between 1992 and 2015 occur in autumn and not in spring. Again, disagreements in the trends are obvious in the region South. Especially during the summer season, the station data show strong positive trends of more than 10 $W/m^2/decade$ (see dot at the top of Figure 9), while the satellite-based data indicate trends of about 3 to 4 $W/m^2/decade$. Figure 9 also shows that there are some negative trends for the time period 1992-2015, e.g. in the region North's winter season. Still, the trends in the majority of regions and seasons are positive, documenting the general increase of SSR. There is a good agreement between the three data records in the regions Central-East, Central-West and North-West, while differences are larger in the regions South and North.

The spatial distribution of the seasonal trends in SSR based on the CMSAF's climate data records are shown in Figure 10 and 11. In Figure 10, the trends based on SARAH-2 and the station data are shown for the time period 1983-2015. It is obvious that there are large differences between the trends in the different seasons. The smallest trends (negative in some regions like Eastern Europe) are observed in winter while the largest ones are observed in spring (c.f. Figure 10, top right) when in large areas of Central and Eastern Europe the trends exceed 5 $W/m^2/decade$. In summer, the trends remain positive in the East, but some areas in the West, namely parts of France and Great Britain show slightly negative trends, in line with the station data (c.f. Figure 10, bottom left). In autumn, there are small positive trends in most of Europe, while the trends are mainly negative in the South East of Europe. These negative trends in autumn (i.e. in the Balkan states) have also been found by *Alexandri et al.* [2017] for the time period 1983-2013.

To compare the trends derived from SARAH-2 and CLARA-A2, the spatial trend maps are shown in Figure 11 for the common time period of 1992-2015. The Figure 11 reveals similar spatial patterns of seasonal trends in Europe of SARAH-2 and CLARA-A2, which indicates a consistency of the independently derived climate data records. It should be noted that the overall agreement in the trends between the satellite and stations data is also valid for the individual stations (with the exception of region South). By comparing the seasonal trend patterns given by Figure 10 and 11, it is visible that the spatial variability of trends in Europe is large, especially on shorter time scales. In general, it has been found that the trends can substantially vary, even if the time period considered is only slightly changed.

Motivated by the results shown in Figure 8 and 9, we present additional analysis for the regions North and South in the following sections.

5.1. Focus: Region North

In the region North the trends derived from the satellite-based data records and the from the station data agree in spring and autumn in the region North, but there are larger differences in the summer and winter season, in particular during the time period 1992-2015 (as shown in Figure 9). In this period, during the summer season, both SARAH-2 and CLARA-A2 have negative trends of -1 to $-2\,W/m^2/decade$ while the station data has a positive trend of 2 to $3\,W/m^2/decade$. In the winter season the differences are the opposite with positive values for SARAH-2 and negative trends based on the station data (no CLARA-A2 data analyzed here due to missing data). However, for the full time period of 1983-2015, the trends of SSR agree (cf. Figure 8).

To further investigate these differences between the trends the Trendraster-plots for region North are shown for the winter and summer season for both the station data and SARAH-2 (cf. Figure 12). In winter, it is visible that even though the long term trend agrees (no trend during the period 1983-2015), there are substantial differences on the shorter term (cf. Figure 12, upper part). Most obvious are the relatively strong positive trends during the winter season in the SARAH-2 data starting in mid 1990's onwards. During that period, SARAH-2 shows a larger positive trend in SSR than the surface observations. Relative trends can reach up to +15% SSR per decade, which is due to the low absolute values SSR levels in winter. One possible reason for the trend overestimation by SARAH-2 is related to the fact that snow on the ground can be misinterpreted as clouds in the satellite retrieval scheme used in the generation of SARAH-2 resulting in an underestimation of SSR under snow-covered conditions. A change in the snow cover would result in an artifcial change in SSR in the SARAH-2 climate data record, because the underestimation of SSR under snow-covered conditions would be reduced. Hence the negative trend in snow cover during the mid 1990's in the region North [*Brown et al.*, 2011], might have contributed to the positive trend inthe SARAH-2 data record in wintertime SSR in the region North. Nevertheless, it should be noted that a slight positive trend is also observed also by the stations during that time period even if it is smaller compared to SARAH-2. However, at this stage we cannot rule out an impact of the change in the satellite instruments used in the generation of SARAH-2 in 2006 on the differences in the trends we are finding in the region North in winter.

During the summer, the trends are higher than during the winter, and the trend is overall positive in both the station data and the SARAH-2 data (cf. Figure 12, lower part). The temporal variability of the trends is high in both data records. The SARAH-2-based trends ending after 2007 tend to be smaller than the trends based on station data. Possible reasons are a change in the onset of snow coverage or an inhomogeneity from the change in the satellite instruments.

Overall we conclude that the trends based on satellite data in the region North need to be considered with case. The study of *Riihelä et al.* [2015] finds a good correspondence betwen satellite- and station-based trends, but did not assess seasonal trends, where the larger differences appear in the present study.

5.2. Focus: Region South

The region South exhibits the largest differences in trends between the satellite climate data records and the station data (cf. Figures 6,8,9). To get more insights, additional

Trendraster-plots based on SARAH-2, CLARA-A2 and the station data for the region South are presented in Figure 13 for all seasons. In winter, spring and autumn, there is a general agreement between the satellite data and the station data, even though there is a small tendency of the satellite data to underestimate the trends in SSR with reference to the station data. For the common time period of 1992-2015, the SARAH-2 Trendrasters compared better with the station-based Trendraster than the CLARA-A2 Trendrasters.

The largest differences are evident in the summer season (see Figure 13, third row), where SARAH-2 and CLARA-2 clearly disagree with the station data. In fact, the satellite data show a much smaller positive trend than the station data. It is remarkable, that SARAH-2 and CLARA-A2 agree well for the summer season with each other, even though they are based on different sensors on different satellites and so they are independent.

However, there is one relevant aspect that both SARAH-2 and CLARA-A2 have in common: the use of a constant monthly climatology of aerosol information as input [*Müller et al.*, 2015 b]. A decreasing aerosol load, as for example reported in Spain [*Sanchez-Romero et al.*, 2016] or over the mainland Europe [*Ruckstuhl et al.*, 2008] since the 1980s would lead to a positive trend in SSR, due to the reduced direct aerosol effect on SSR, which would not be captured by SARAH-2 or CLARA-A2. This fact might be one explanation of the underestimation of the trend by both SARAH-2 and CLARA-A2 with reference to the station data. This hypothesis seems to be confirmed also considering recent results published by *Georgoulias et al.* [2016b]. They investigated the spatio-temporal evolution (since 2000s) of the aerosol optical depth over the greater Mediterranean Region finding that the sub-regions with the stronger negative Aerosol Optical Density (AOD550) trend are the Central Mediterranean and the Iberian Peninsula, attributed to the positive precipitation trends all over the region and to the decrease of anthropogenic emissions in the area.

On the other hand, the major part of the variability and trends in Europe are reasonably captured by the CM SAF's SARAH-2 and CLARA-A2 climate data records, including the region Central-East. The region South's summer season is an exception in this respect. However, it should be considered that in this region, the SSR is likely being more affected by potential changes of the aerosol direct effect [*Nabat et al.*, 2014], as clear-sky days are more frequent in the Mediterranean summer than in other European areas. This is coherent with the findings of *Kambezidis et al.* [2016], who found higher values under clean skies (without aerosols but including clouds) compared to those under clear skies (without clouds but including aerosols) using reanalysis data of surface net shortwave radiation during June-August, indicating that aerosols attenuate more the shortwave radiation compared to clouds over the Mediterranean in summer. Moreover, a positive trend in clear-sky SSR in Europe has been found by *Bartók* [2017] during the time period 2001-2012, which is partly attributed to a reduced aerosol load. This signal is confirmed both by *Manara et al.* [2016] for the Italian territory and by *Sanchez-Lorenzo and Wild* [2012] over Switzerland. The former found during the brightening period stronger positive SSR tendencies under clear-sky conditions than under all-sky conditions suggesting that cloud cover variations have partially masked the variations caused by aerosols variations (both anthropogenic and natural) especially during winter and autumn. The latter found in the clear sky SSR series during the sub-period 1981-2010 a positive trend especially in spring and summer attributing them to the direct aerosol effect [Ruckstuhl et al., 2008; Ruckstuhl and Norris 2009].

While the neglect of the change in the aerosol loading is the satellite retrieval provide a possible and likely reason for the underestimation of the trend by the satellite data sets, the impact of the change in the instrumentation to measure the SSR at the surface stations has not yet been quantified and a possible impact on the trend calculation based on station data cannot be ruled out at this stage.

6. Discussion and Conclusions

In this study, the variability and trends of surface solar radiation are analyzed in Europe during the time period 1983-2015. Here, the CM SAF's SARAH-2 and CLARA-A2 climate data records of SSR are compared to surface observations to assess their ability to reproduce the surface observations. It is found that the overall variability and the trends agree well between the CMSAF's SARAH-2, CLARA-A2 and the station data in Europe. It is important to mention that the CLARA-A2 and the SARAH-2 data records are independent from each other, as they are based on different satellite systems and algorithms. So, the agreement in trends and variability (especially over the continent) for the time period for which both data records are used (1992-2015) is remarkable and documents the high quality of SARAH-2 and CLARA-A2 (see e.g. Figures 7 and 11). Possible reasons for the remaining differences between the SSR trends in the satellite and station data might be connected to the neglection of changes in the aerosol loading [e.g. *Bartók*, 2017; *Sanchez-Lorenzo et al.*, 2017] and to effects of a change in snow cover, as described in section 5.1. It is important to mention that the clear-sky radiation given by SARAH-2 (and CLARA-A2), which are only driven by the time varying water vapor input, do show negligible trends of SSR of mostly below $\pm$ 0.2 $W/m^2/decade$ (not shown), consistent with previous results [*Posselt et al.*, 2014]. The largest negative trends in the SARAH-2 clear-sky radiation are found the Balkan region and in South Eastern Europe with up to -0.6 $W/m^2/decade$, which is still much smaller than most of the all-sky SSR trends.

The CM SAF's SARAH-2 and CLARA-A2 have reached a high quality and stability, that enables the analysis of variability and trends in SSR. The observed positive trends of SSR (considering both the satellite data records and the station data) are about 1.9 to 2.4 $W/m^2/decade$. Stronger positive trends of about 2.7 to 3.0 $W/m^2/decade$ are observed during the shorter time period of 1992-2015 (cf. Figure 4). Figure 5 shows that also the variability of SSR agrees between the CM SAF's satellite climate data records and the station data. The spatial view on the long-term SSR trends reveal that the strongest brightening is found for the spring season, and mainly in Eastern Europe and in the North Western Europe (cf. Figures 7 and 10). Overall the spatial trend patterns and its seasonal variability are similar to findings by *Sanchez-Lorenzo et al.* [2017] over the 1983-2010 period. An exception is seen for the summer season in region South, where the trends based on the satellite data records and the station data disagree (cf. Figure 8). There, the positive trend observed by the station data is underestimated by the satellite data (cf. Section 5.2). However, the spread between the trends in the station data is also largest in the region South (cf. Figure 6), which indicates that regional to local causes for trends might potentially exist as well. In general, even though care has been taken in the data compilation, remaining data inhomogeneities (e.g. due to instrumental changes) in either satellite or stations data can not be fully excluded.

Aerosol information is kept constant for both SARAH-2 and CLARA-A2, because of the non-availability of high quality aerosol information for the full time period of the satellite data at the time of data generation [*Müller et al.*, 2015 b]. It is important to note, that, even though the aerosol information is kept constant within SARAH-2 and CLARA-A2, changes of the aerosol indirect effect is expected to be captured [*Müller et al.*, 2015 b], i.e. through the changes in cloud brightness and life time.

The Mediterranean region is affected by large aerosol loads for anthropogenic and natural reasons. It is affected by sea salt aerosols from the Mediterranean Sea and the Atlantic Ocean, pollution aerosols from Europe, dust from the Sahara desert and biomass burning aerosols from Eastern Europe. Moreover, depending on the season, different types of aerosols reach different parts of the region (e.g., dust peaks in spring over the Eastern Mediterranean, in summer over the Western Mediterranean and in spring and summer over the transitional region of Central Mediterranean) [*Georgoulias et al.*, 2016a, b; *Floutsi et al.*, 2016; *Kanakidou et al.*, 2011; *Lelieveld et al.*, 2002]. For this reason, the influence of the aerosol direct effect on SSR is supposed to be large in the region South [*Bartók*, 2017; *Sanchez-Lorenzo et al.*, 2017; *Kambezidis et al.*, 2016; *Nabat et al.*, 2014]. This allows to conclude that at least parts of the differences between satellite and station data found in the region South's summer (cf. section 5.2) might be attributed to the missing of changes in the aerosol direct effect in the satellite data records [*Sanchez-Lorenzo et al.*, 2017]. *Sanchez-Lorenzo et al.* [2017] also found, for a shorter time period, that for the majority of Europe the differences in trends between the satellite-based SSR data and station data were small, even though a constant aerosol approach [*Posselt et al.*, 2012] has been used in generating the satellite data record, which is overall in line with the findings of this study. For the time period since the 2000s *Mateos et al.* [2014] states that over the Iberian Peninsula three fourths of the SSR trend is explained by changes in clouds.

Another peculiarity is found in the region North, where the running-trend analysis revealed that for the time period from the mid 1990's onwards, the trends are overestimated by the SARAH-2 climate data record with reference to the station data. As noted in section 5.1, a reduction in snow cover could potentially lead to a positive trend in SSR in the satellite data records.

However, for the other regions in Europe, the trends and variability of SSR between satellite and station data agree reasonably well for all seasons, which suggests that aerosol changes (especially aerosol direct effects) play only a minor role for the observed trends in SSR in these regions. Further, based on the algorithms and their input used to generate the SARAH-2 and CLARA-A2 climate data records [cf. *Müller et al.*, 2015; *Karlsson et al.*, 2017b], and based on an analysis of trends in water vapor, which is found to be negligible, it can be concluded, that the large majority of the observed positive trends in SSR in Europe are due to changes in clouds. This finding is also consistent with the results of Sanchez-Lozeno 2017, based on satellite- and surface-based cloud data records, including the first version of the CLARA data record, who found a decrease in cloud coverage in Europe. The results are robust when using the CLARA-A2 data record (not shown).

In general, the changes in cloud radiative effects reproduced by SARAH-2 and CLARA-A2 can be due to natural cloud variability and/or changes in the aerosol effects on clouds, and consequently aerosol effects can not be ruled out completely through indirect aerosol effects. Nevertheless, it is worth noting that at present most of the literature using ground-based data or climate model simulations have reported that the major cause of the brightening in Europe, especially in Central Europe, is related to the direct aerosol effects via a decrease in anthropogenic aerosol emissions since the 1980s [e.g. *Norris and Wild*, 2007; *Philipona et al.*, 2009; *Zubler et al.*, 2011; *Nabat et al.*, 2014]. *Boers et al.* [2017] found that positive trends in SSR in the Netherlands are due to changes in both aerosols and clouds.

Consequently, the results of this study add new information to the available literature. Also in some previous studies the dimming period observed between the 1950s and 1980s was mainly attributed to cloud changes instead of direct aerosol effects [*Liepert*, 1997]. *Stjern et al.* [2009] and *Parding et al.* [2016] also found that changes in clouds are the main reason for trends in SSR in Northern Europe, and in the Mediterranean observations indicate fewer clouds for the period 1971 to 2005 [*Sanchez-Lorenzo et al.*, 2017b]. In the United States, observed positive trends in SSR since the 1990s are also mainly attributed to changes in cloud cover [*Augustine et al.*, 2013].

While it can be assumed that the quality of the satellite-based data records as documented here is representative also for other regions available in the satellite data record, a comparison with high-quality surface data is always recommended when possible. Since no reliable data are available for large parts of th world satellite data will remain the only observational source of climatic information.

In any case, further research is needed to consolidate the reasons and the mechanisms behind the variability and trends in SSR since the 1980s in Europe. This study documents the quality of the satellite-derived data records to help addressing those topics in future studies and investigations. In particular the capturing of the spatial structure of the trends in SSR might help to identify the relevant processes.

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The used EUMETSAT CMSAF's SARAH-2 and CLARA-A2 climate data records are freely available via `http://www.cmsaf.eu/wui`. The majority of station data used (except for some Spanish and Italian stations) can be obtained from the GEBA archive via `http://www.geba.ethz.ch/`. The authors thank the data providers for free data access. ASL was supported by a postdoctorial fellowship JCI-2012-12508 and the projects CGL2014-55976-R and CGL2014-52135-C3-1-R funded by the Spanish Ministry of Economy and Competitiveness.

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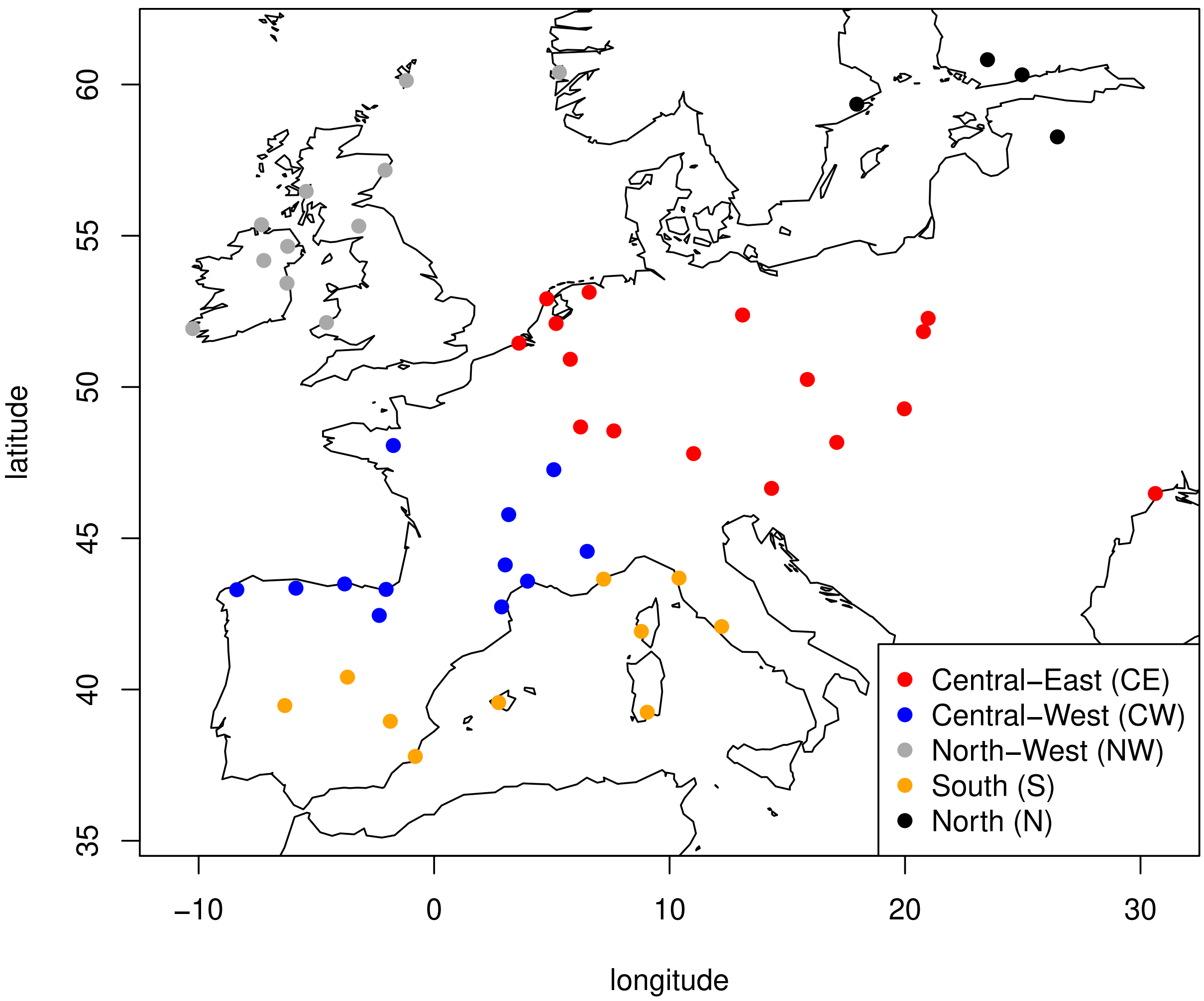

Figure 1. Stations used to evaluate satellite climate data records. The colors represent the corresponding regions as defined by a Principal Component Analysis (red - Central East, blue - Central West, grey - North-West, orange - South, black - North).

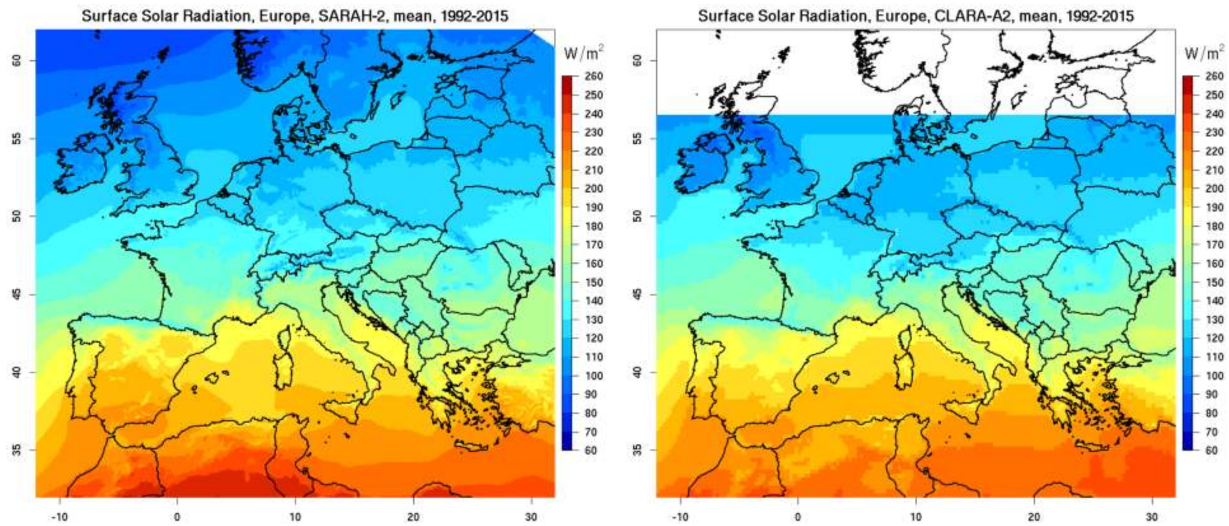

Figure 2. Mean surface solar radiation $[W/m^2]$ (1992-2015) based on the (left) SARAH-2 and (right) CLARA-A2 climate data record.

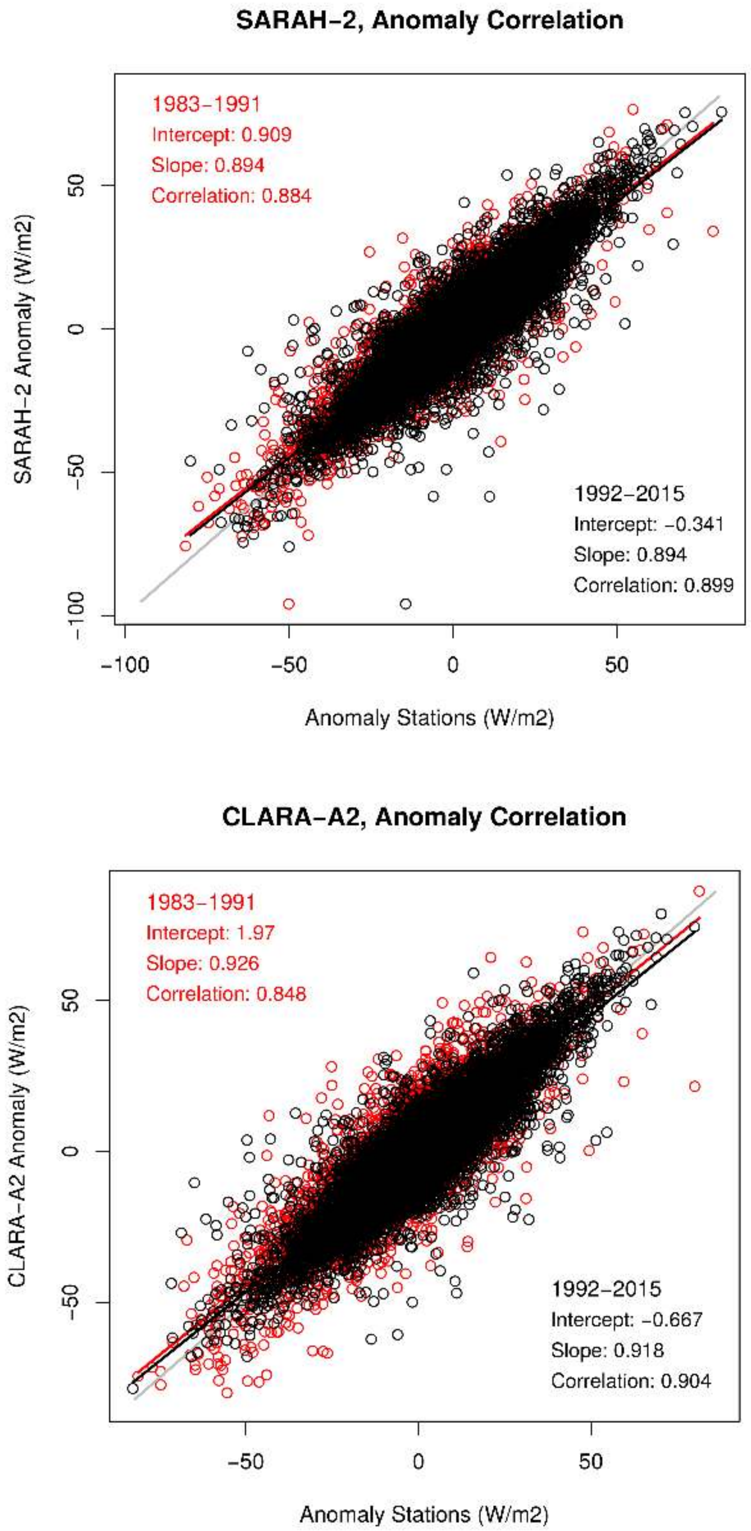

Figure 3. Scatterplot of monthly anomalies of surface solar radiation $[W/m^2]$ of SARAH-2 (top) and CLARA-A2 (bottom) versus station data, including correlation coefficient, slope and intercept of the regression line. The red color refers to the 1983-1991 period while the black color refers to the 1992-2015 period.

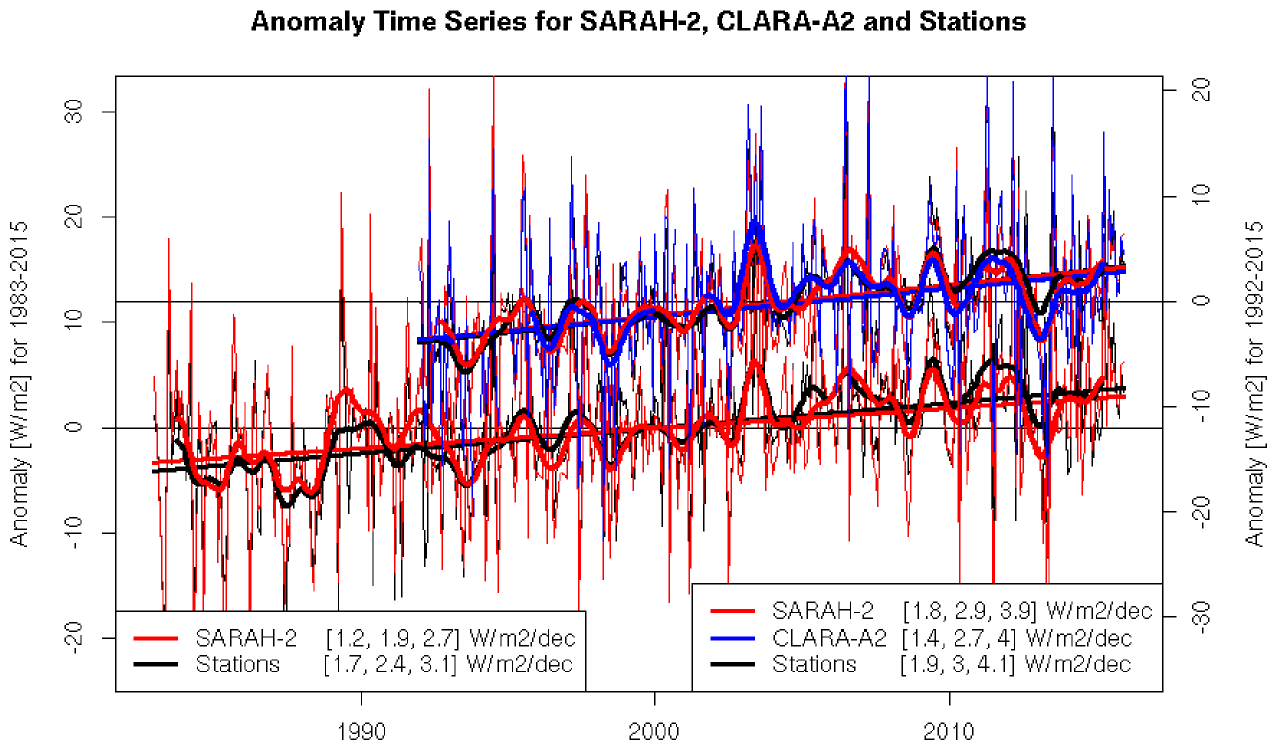

Figure 4. Mean monthly anomaly $[W/m^2]$ time series for the time periods of 1983-2015 (lower lines, y-axes on the left) and 1992-2015 (upper lines, y-axis on the right). Additionally shown are the linear trends (solid straight lines) and the smoothed time series (using 12-month Gauss-filter) for (black) Stations, (red) SARAH-2 and (blue) CLARA-A2 (only for the time period 1992-2015). The values in the brackets show: lower 95%-percentile, mean trend, upper 95%-percentile. Note that the y-axis are shifted by $12\,W/m^2$ from each other.

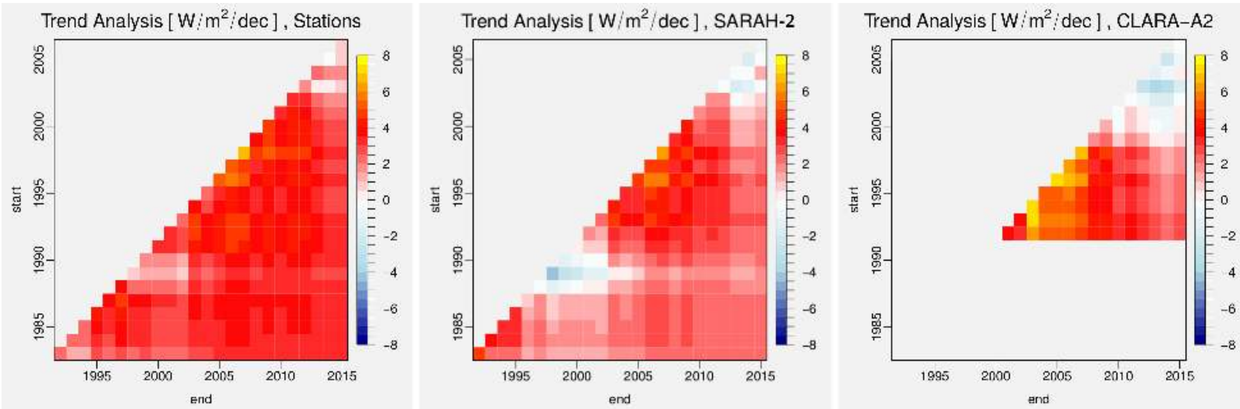

Figure 5. Trendraster-Plots of mean SSR trends derived from Stations (left), SARAH-2 (middle) and CLARA-A2 (right). The y-axis denotes the start-years and the x-axis shows the end-years of the individual trends, respectively. Trendrasters show linear trends [$W/m^2/decade$] during time periods of at least 10 years (at the diagonal); the trend over the maximum time period analysed (33 years for station data and SARAH-2; 24 years for CLARA-A2) is shown by the pixel at the lower right end.

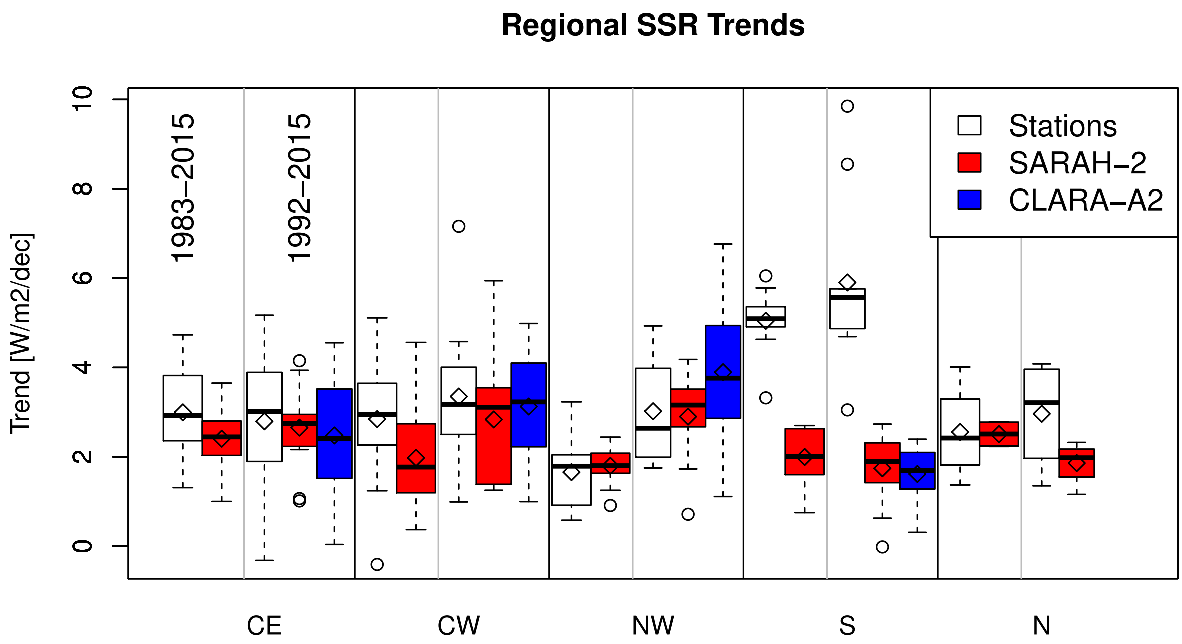

Figure 6. Boxplot of the regional trends $[W/m^2/decade]$ of surface solar radiation at the station locations (white) based on Stations, (red) SARAH-2, and (blue) CLARA-A2 data, including mean trends (diamonds). Outliers are shown as dots. Regions: CE=Central East, CW=Central West, NW=North West, S=South, N=North. For each region the plot area is divided into trends for the full time period 1983-2015 (for Stations and SARAH-2) and trends for the time period 1992-2015 (for Stations, SARAH-2 and CLARA-A2).

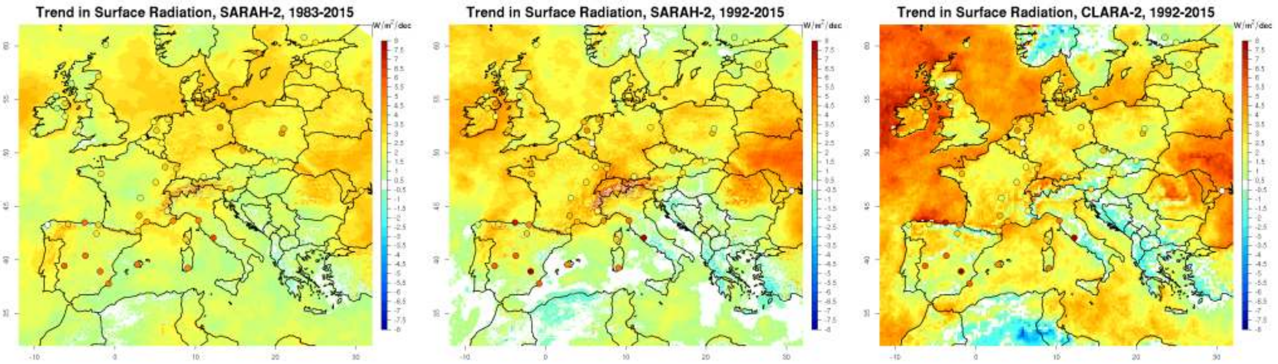

Figure 7. Spatial distribution of the linear trends $[W/m^2/decade]$ of surface solar radiation during 1983-2015 for (left) SARAH-2 and during 1992-2015 for (center) SARAH-2 and (right) CLARA-2. The respective trends for the 53 stations are shown as coloured dots.

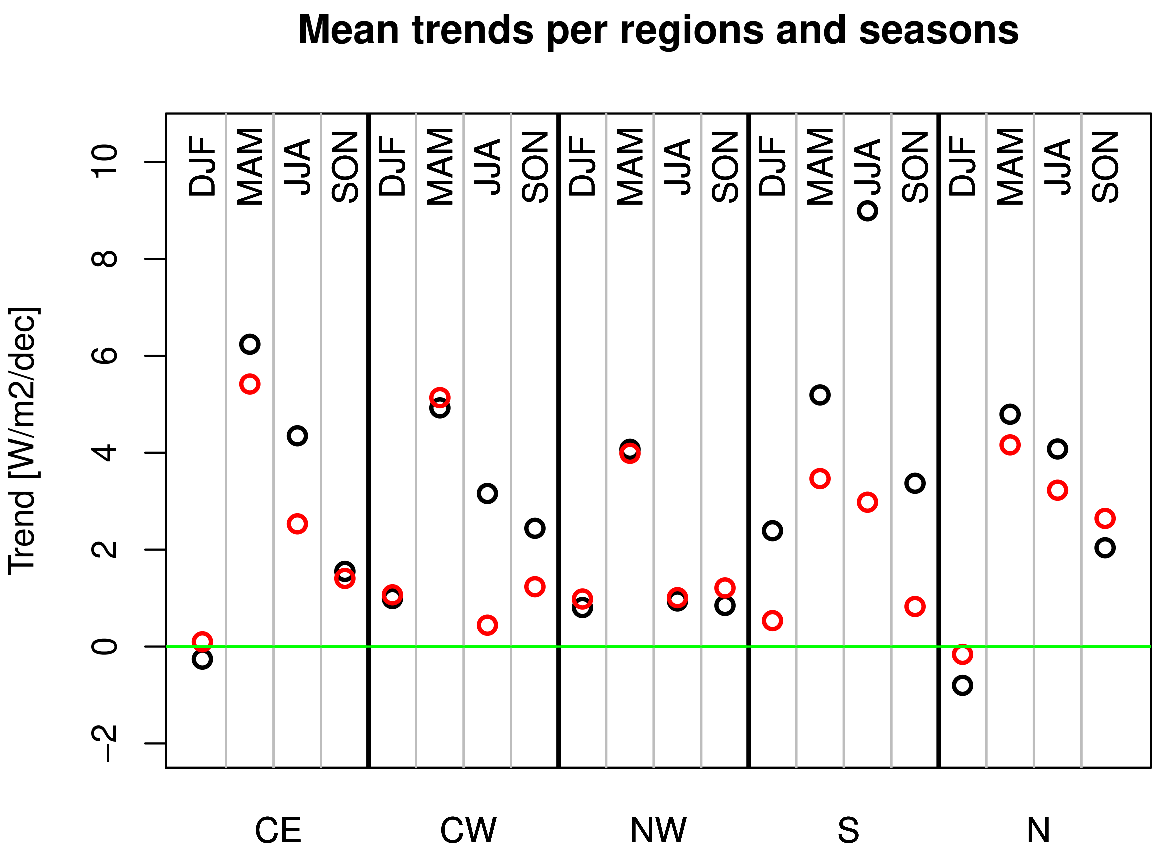

Figure 8. Trends $[W/m^2/decade]$ of surface solar radiation of (black) Stations and (red) SARAH-2 data, shown separately for region and season during the full time period of 1983-2015. Regions: CE=Central East, CW=Central West, NW=North West, S=South, N=North.

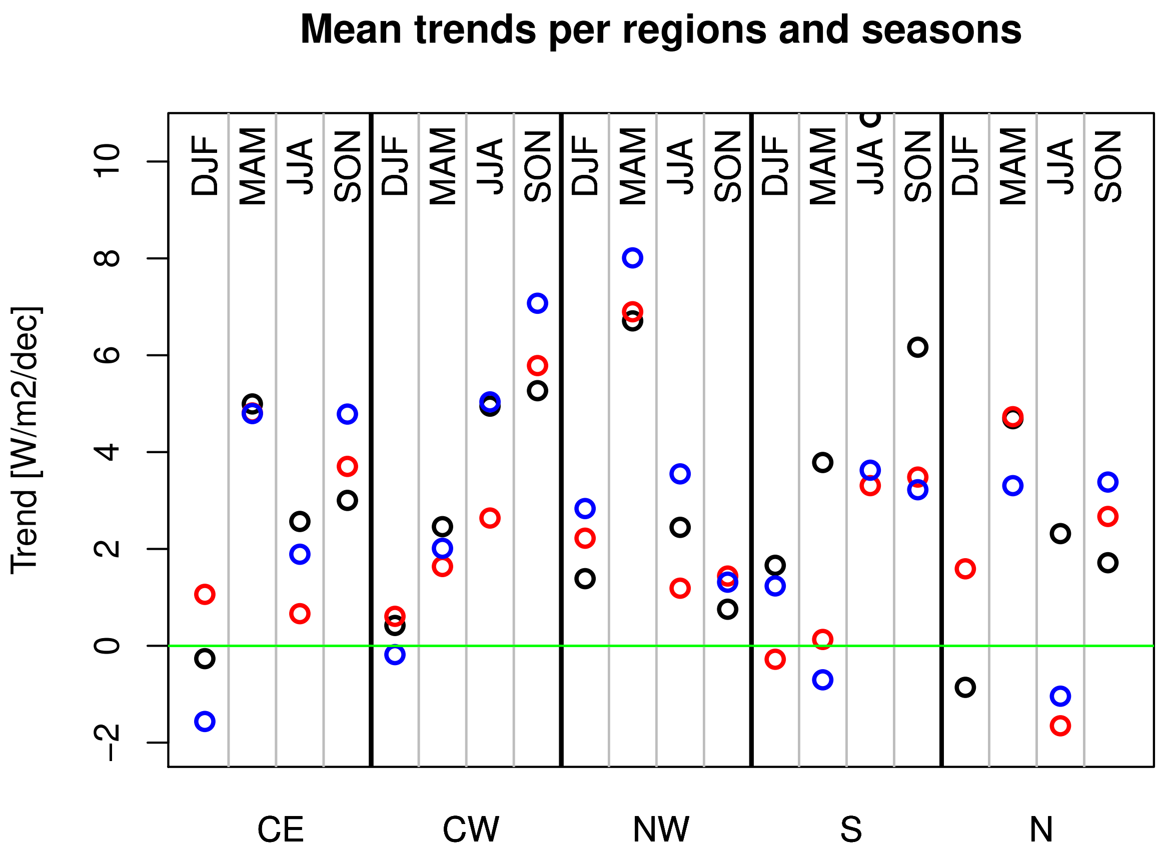

Figure 9. Trends $[W/m^2/decade]$ of surface solar radiation of (black) Stations, (red) SARAH-2 and (blue) CLARA-A2 data, shown separately for region and season during the time period of 1992-2015. Regions: CE=Central East, CW=Central West, NW=North West, S=South, N=North.

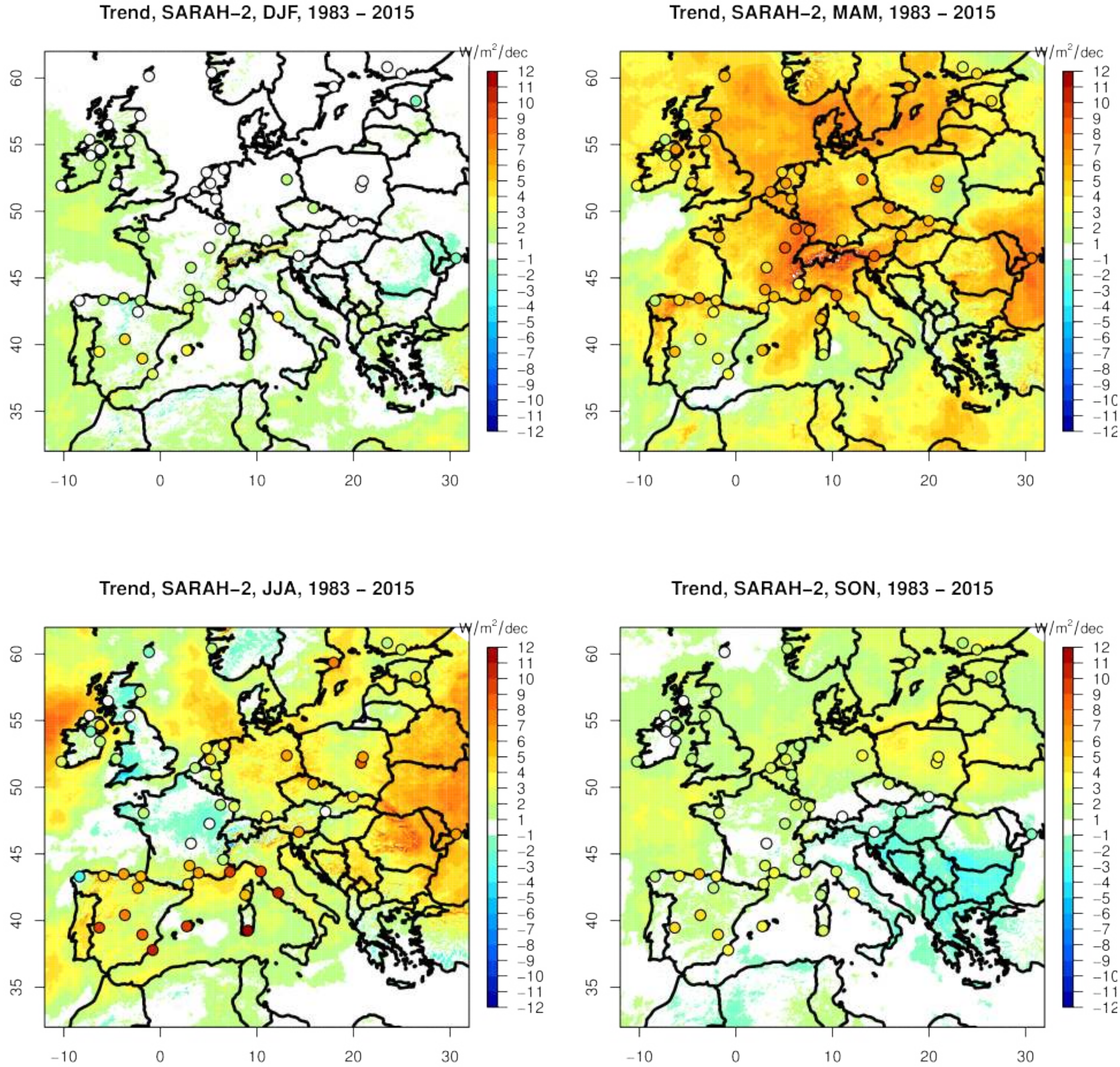

Figure 10. Spatial distribution of the linear trends [$W/m^2/decade$] of surface solar radiation during 1983-2015 for the four seasons (DJF, MAM, JJA, SON) based on the SARAH-2 climate data record. The trends for the respective season and time period given by the 53 stations are shown as coloured dots.

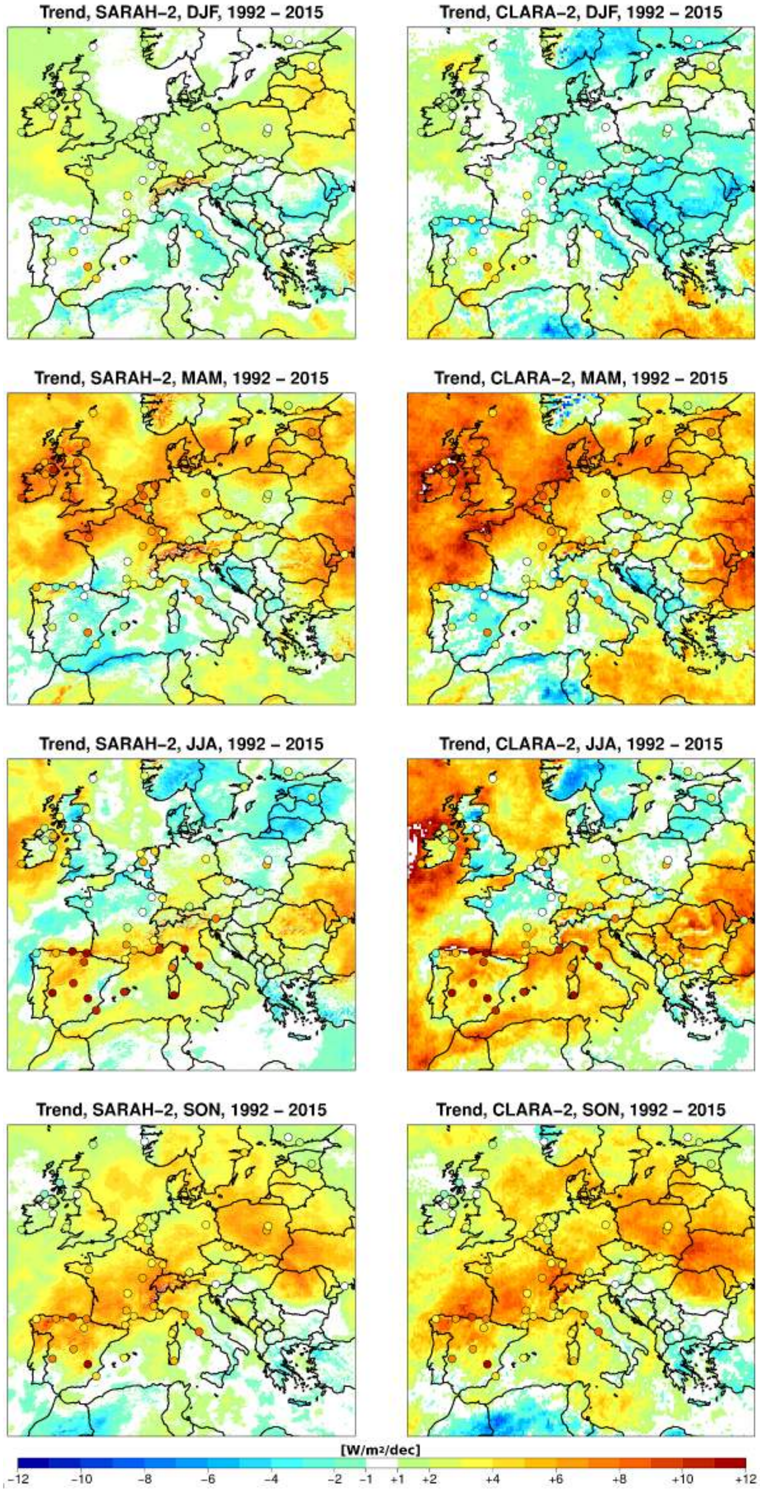

Figure 11. Spatial distribution of the linear trends [$W/m^2/decade$] of surface solar radiation during 1992-2015 for the four seasons (DJF, MAM, JJA, SON) (top to bottom) based on the (left) SARAH-2 and (right) CLARA-A2 climate data records. The trends for the respective season and time period given by the stations are shown as coloured dots.

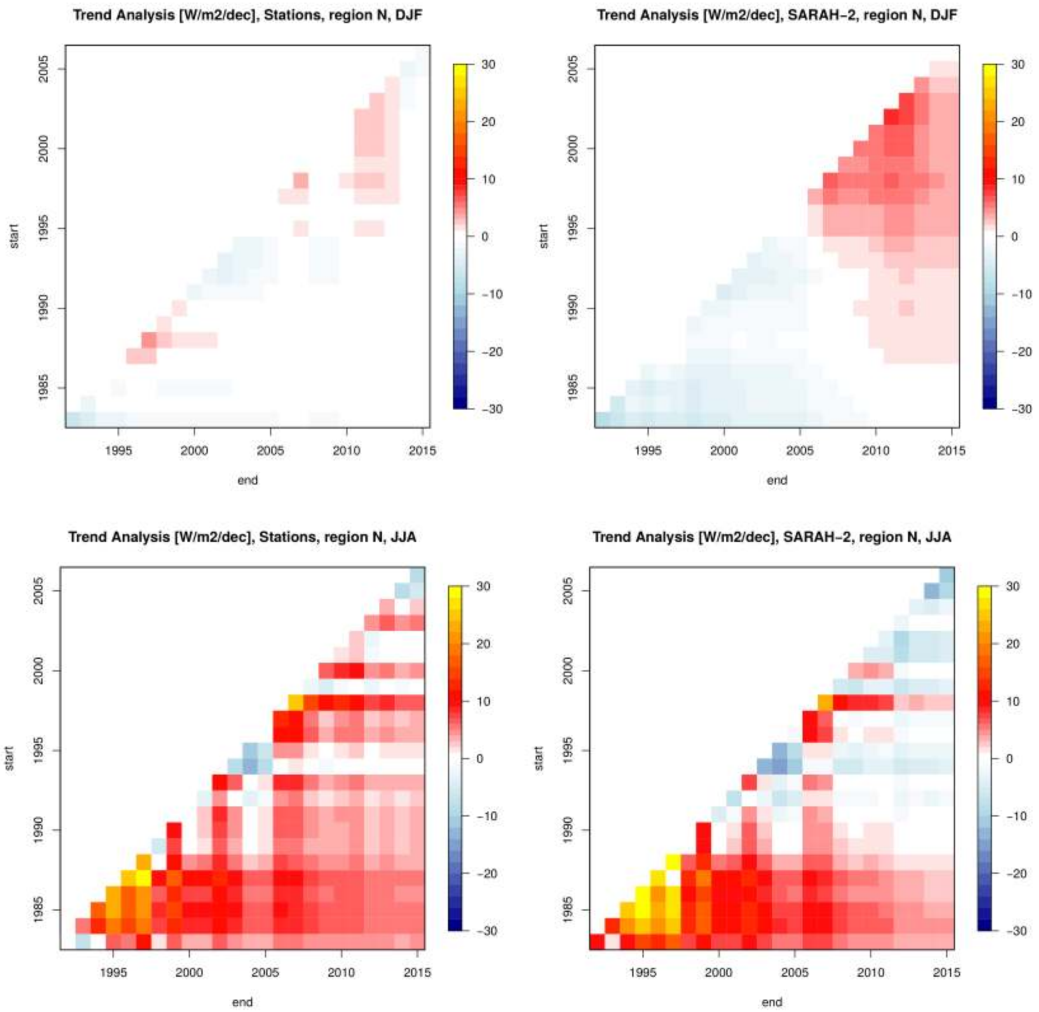

Figure 12. Trendraster-Plots of mean SSR trends derived from (left) Stations and (right) SARAH-2, for the (top) winter and (bottom) summer season for the region North. The y-axis denotes the start-years and the x-axis shows the end-years of the individual trends, respectively. Trendrasters show linear trends $[W/m^2/decade]$ during time periods of at least 10 years (at the diagonal); the trend over the maximum time period analysed is shown by the pixel at the lower right end.

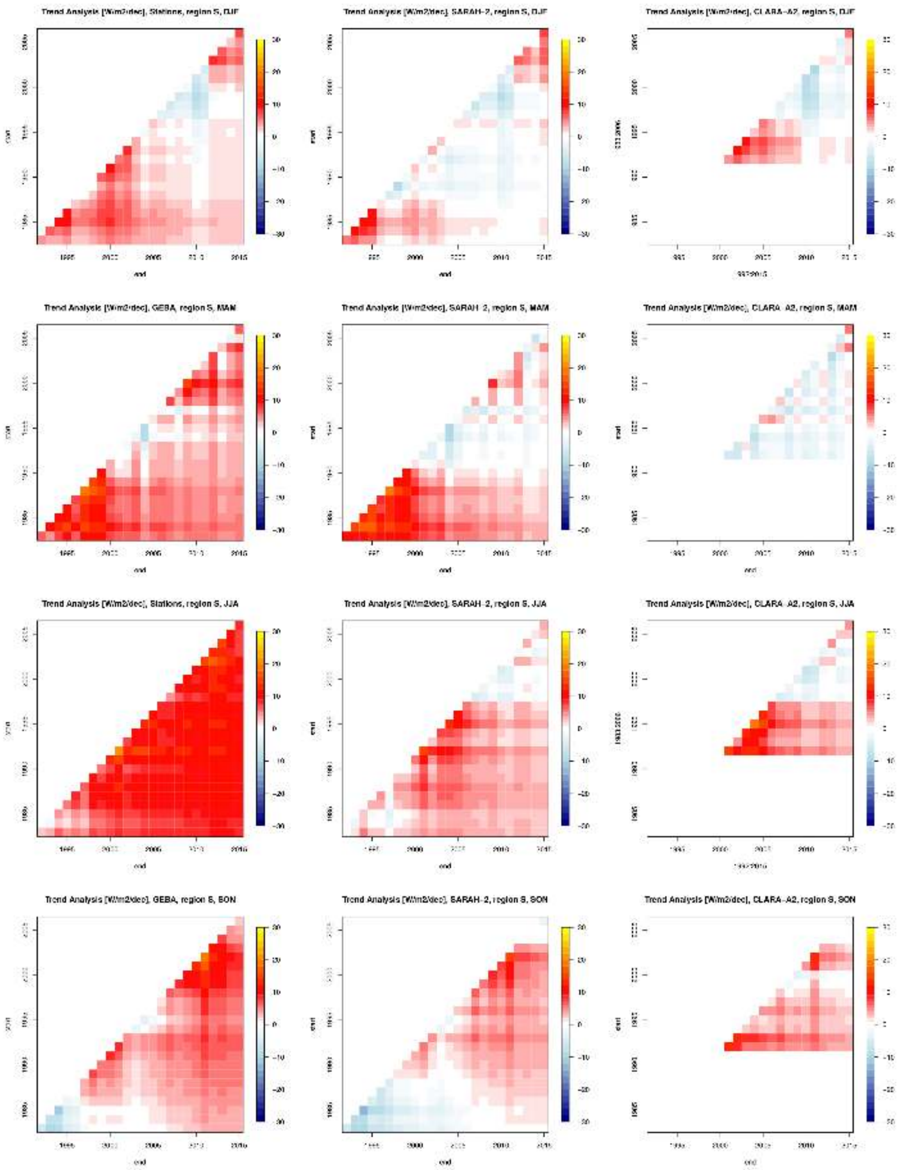

Figure 13. Trendraster-Plots of mean SSR trends derived from (left) Stations, (center) SARAH-2 and (right) CLARA-A2 for the seasons (from top to bottom: DJF, MAM, JJA, SON) for the region South. Trendrasters show linear trends [$W/m^2/decade$] during time periods of at least 10 years (at the diagonal); the trend over the maximum time period analysed (33 years for station data and SARAH-2; 24 years for CLARA-A2) is shown by the pixel at the lower right end.

Table 1. List of the 53 stations used in this study.

Station	Lon [°W]	Lat [°N]	Country	Region
Aberdeen	-2.083	57.167	Great Britain	NW
Aberporth	-4.570	52.130	Great Britain	NW
Ajaccio	8.800	41.920	France	S
Albacete	-1.860	38.950	Spain	S
Aldergrove	-6.220	54.650	Great Britain	NW
Belsk	20.780	51.830	Poland	CE
Bergen	5.320	60.400	Norway	NW
Bratislava	17.100	48.170	Slovak Republic	CE
Caceres	-6.340	39.470	Spain	S
Cagliari	9.050	39.250	Italy	S
Clermont-Ferrand	3.167	45.783	France	CW
Clones	-7.233	54.183	Ireland	NW
Coruna	-8.380	43.300	Spain	CW
De Bilt	5.180	52.100	Netherlands	CE
De Kooy	4.783	52.917	Netherlands	CE
Dijon	5.083	47.267	France	CW
Dublin	-6.250	53.433	Ireland	NW
Dunstaffnage	-5.433	56.467	Great Britain	NW
Eelde	6.583	53.133	Netherlands	CE
Embrun	6.500	44.567	France	CW
Eskdalemuir	-3.200	55.320	Great Britain	NW
Helsinki	24.970	60.320	Finland	N
Hohenpeissenberg	11.020	47.800	Germany	CE
Hradec-Kralove	15.850	50.250	Czech Republic	CE
Jokioinen	23.500	60.820	Finland	N
Klagenfurt	14.330	46.650	Austria	CE
Lerwick	-1.180	60.130	Great Britain	NW
Logrono	-2.330	42.450	Spain	CW
Maastricht	5.783	50.917	Netherlands	CE
Madrid	-3.680	40.410	Spain	S
Malin-Head	-7.333	55.367	Ireland	NW
Millau	3.020	44.120	France	CW
Montpellier	3.967	43.583	France	CW
Murcia	-0.800	37.790	Spain	S
Nancy-Essey	6.220	48.680	France	CE
Nice	7.200	43.650	France	S
Odessa	30.630	46.480	Ukraine	CE
Oviedo	-5.870	43.350	Spain	CW
Palma de Mallorca	2.740	39.570	Spain	S
Perpignan	2.867	42.733	France	CW
Pisa	10.400	43.683	Italy	S
Potsdam	13.100	52.380	Germany	CE
Rennes	-1.733	48.067	France	CW
San Sebastian	-2.040	43.310	Spain	CW
Santander	-3.800	43.490	Spain	CW
Stockholm	17.950	59.350	Sweden	N
Strasbourg	7.633	48.550	France	CE
Toravere	26.470	58.270	Estonia	N
Valentia	-10.250	51.930	Ireland	NW
Vigna di Valle	12.211	42.081	Italy	S
Vlissingen	3.600	51.450	Netherlands	CE
Warszawa	20.980	52.270	Poland	CE
Zakopane	19.970	49.280	Poland	CE

Table 2. Results of the validation of monthly SARAH-2 and CLARA-A2 surface radiation data with reference to station data in Europe. MAD=Mean Absolute Deviation [W/m^2], cor=Pearson's correlation coefficient of the anomaly series

	1983-1991		1992-2015		1983-2015	
	MAD	cor	MAD	cor	MAD	cor
CLARA-A2	9.7	0.85	6.5	0.91	7.3	0.88
SARAH-2	8.3	0.89	6.4	0.90	6.9	0.89

Table 3. Absolute [$W/m^2/decade$] and relative [$\%/decade$] trends of SARAH-2, CLARA-A2 and the station data during the time periods of 1983-2015 and 1992-2015 for the five regions analysed.

time period	data	CE	CW	NW	S	N
1983-2015	Stations	3.0 (2.4%)	2.9 (1.9%)	1.7 (1.6%)	5.0 (2.7%)	2.6 (2.4%)
	SARAH-2	2.4 (1.9%)	2.0 (1.3%)	1.8 (1.8%)	2.0 (1.0%)	2.5 (2.4%)
1992-2015	Stations	2.6 (2.0%)	3.3 (2.2%)	2.8 (2.7%)	5.7 (3.0%)	2.0 (1.8%)
	SARAH-2	2.7 (2.0%)	2.8 (1.8%)	2.9 (2.9%)	1.8 (0.9%)	1.9 (1.7%)
	CLARA-A2	2.4 (1.8%)	3.1 (2.0%)	3.7 (3.4%)	1.9 (1.0%)	/