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RESEARCH ARTICLE
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Key Points:
- Global irradiance has been studied for the period 1939–2012 over Europe
- There is no statistically significant increase since the 1950s or before
- Stabilization since 2000 may be due stabilization of anthropogenic emissions

Supporting Information:
- Data Set S1

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Reassessment and update of long-term trends in downward surface shortwave radiation over Europe (1939–2012)

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Abstract This paper presents trends in downward surface shortwave radiation (SSR) over Europe, which are based on the 56 longest series available from the Global Energy Balance Archive that are mainly concentrated in central Europe. Special emphasis has been placed on both ensuring the temporal homogeneity and including the most recent years in the data set. We have generated, for the first time, composite time series for Europe covering the period 1939–2012, which have been studied by means of running trend analysis. The mean annual SSR series shows an increase from the late 1930s to the early 1950s (i.e., early brightening), followed by a reduction until mid-1980s (i.e., global dimming) and a subsequent increase up to the early 2000s (i.e., global brightening). The series ends with a tendency of stabilization since the early 21st century, but the short time period is insufficient with regard to establishing whether a change in the trend is actually emerging over Europe. Seasonal and regional series are also presented, which highlight that similar variations are obtained for most of the seasons and regions across Europe. In fact, due to the strong spatial correlation in the SSR series, few series are enough to capture almost the same interannual and decadal variability as using a dense network of stations. Decadal variations of the SSR are expected to have an impact on the modulation of the temperatures and other processes over Europe linked with changes in the hydrological cycle, agriculture production, or natural ecosystems. For a better dissemination of the time series developed in this study, the data set is freely available for scientific purposes.

1. Introduction

The downward surface shortwave radiation (SSR) is a basic component of life on our planet as it plays a crucial role in the global energy balance. Hence, during the last decades high priority has been placed on the development of a network of meteorological stations and satellites providing SSR data [*Wild*, 2009]. Satellite-derived SSR have a better spatial coverage than ground-based observations, but they are only available since the 1980s and are frequently affected by artifacts that can jeopardize the temporal homogeneity of the data [*Wild*, 2009; *Sanchez-Lorenzo et al.*, 2013b]. Regarding surface-based measurements, although there are a few pyranometer records of SSR dating back to the 1920s, these observations only become more frequent after the International Geophysical Year 1957/1958 [*Stanhill*, 1983]. Long-term SSR series, with most of them available in the Global Energy Balance Archive (GEBA) [*Gilgen et al.*, 1998], have been used to suggest that this variable has not remained constant on decadal time scales (for a review, see *Wild* [2009]).

Specifically, the ground-based observations show a widespread reduction in SSR from the 1950s to the 1980s, a phenomenon that has been called "global dimming" [*Ohmura and Lang*, 1989; *Stanhill and Cohen*, 2001; *Liepert*, 2002]. Since the 1980s a stabilization and recovery in SSR has been detected in many regions of the world, especially in the industrialized nations [*Wild et al.*, 2005; *Wang et al.*, 2012; *Augustine and Dutton*, 2013]. The satellite-derived SSR records available since the 1980s partially agree with the increase in SSR observed from the surface [e.g., *Pallé et al.*, 2004; *Hatzianastassiou et al.*, 2005; *Pinker et al.*, 2005]. Overall, this widespread increase in SSR since the 1980s has been coined as the "brightening period" [*Wild et al.*, 2005].

Changes in the transparency of the atmosphere due to variations in anthropogenic aerosol emissions and/or cloudiness are considered as the major factors explaining this dimming/brightening phenomenon

[*Stanhill and Cohen*, 2001; *Long et al*., 2009; *Ohmura*, 2009; *Wild*, 2009; *Gan et al*., 2014; *Parding et al*., 2014; *Cherian et al*., 2014; *Mateos et al*., 2014; *Wang et al*., 2014]. However, analysis of the SSR series still poses some challenges that are necessary to overcome in order to better understand their trends during the last decades. One of the most important issues is the lack of records before the 1960s, even over the areas with the highest density of stations [*Stanhill*, 1983; *Chiacchio and Wild*, 2010; *Allen et al*., 2013]. Thus, for example, in Europe most studies have either analyzed the SSR series available since the 1970s [*Norris and Wild*, 2007; *Chiacchio and Wild*, 2010; *Cherian et al*., 2014; *Nabat et al*., 2014; *Parding et al*., 2014], studied individual stations with the longest records [*Ohmura*, 2009], or examined specific regions within Europe [e.g., *Liepert*, 1997; *Ruckstuhl et al*., 2010; *Sanchez-Lorenzo et al*., 2013a]. Equally, most records used in the literature have not been updated beyond after around 2005. Consequently, it is not known if there is a continued brightening over Europe or a dimming as observed in other countries such as India and Iran [*Wild et al*., 2009; *Hatzianastassiou et al*., 2012; *Rahimzadeh et al*., 2015].

Although most of the SSR records are quality-controlled (i.e., by the meteorological services and in databases such as GEBA), another important limitation in the published SSR trends is the lack of an evaluation of the temporal homogeneity in most of the studies [*Wild*, 2009]. It is well known that SSR series are often affected by temporal inhomogeneities due to nonclimatic changes such as relocation and changes in the instrumentation [*Hakuba et al*., 2013b; *Tang et al*., 2011; *Wang*, 2014; *You et al*., 2012; *Manara et al*., 2015]. These changes can affect the homogeneity of a time series by introducing breaks, which need to be considered prior to the assessment of the trends [*Peterson et al*., 1998; *Venema et al*., 2012].

Although previous attempts have been made to analyze SSR trends in Europe based on surface observations [e.g., *Ohmura and Lang*, 1989; *Russak*, 1990, 2009; *Norris and Wild*, 2007; *Stjern et al*., 2009; *Chiacchio and Wild*, 2010; *Ruckstuhl et al*., 2010], an analysis that includes a systematic assessment of the homogeneity of the long-time series available since the 1930s and updated beyond 2005 is still lacking. Thus, the main objective of this study is to generate a data set of homogeneous long-term SSR series (40+ years) over Europe and second to study their temporal changes for the whole of Europe and in different regions.

2. Data and Methods

The 56 SSR series (expressed as mean irradiance, in W m^{-2}) starting before the 1970s are available over Europe on a monthly basis up to December 2007. They were extracted from a data set homogenized by *Sanchez-Lorenzo et al*. [2013b] (Figure 1, top), which is originally available in the GEBA (http://www.geba.ethz.ch/). In brief, GEBA is a database that contains worldwide measurements of energy fluxes at the surface on a monthly basis, mainly SSR measurements [*Gilgen and Ohmura*, 1999; *Wild et al*., 2013]. GEBA contains data for more than 2000 stations, while the highest density of long-term SSR series is located in Europe. Most SSR measurements in GEBA are performed with a single pyranometer instead of summing the direct and diffuse components as it has been recommended by the Baseline Surface Radiation Network [*Dutton and Long*, 2012]. The absolute accuracy of pyranometer measurements in GEBA is unknown, but relative random error has been estimated at 5% (2%) for the monthly (annual) means [*Gilgen et al.*, 1998].

In addition to the homogenization procedure described in *Sanchez-Lorenzo et al*. [2013b] by using the Standard Normal Homogeneity Test (SNHT) [*Alexandersson and Moberg*, 1997], two other different relative homogeneity tests have been applied to a subset of this data set of 56 series in order to check the results of this previous homogenization. Specifically, we have used an automatic version of the SNHT [*Venema et al*., 2012; *Guijarro*, 2014] and the Craddock test [*Brunetti et al*., 2006a; *Sanchez-Lorenzo et al*., 2007]. In brief, for the Craddock test, each series is tested against around 10 other series by means of the Craddock test [*Craddock*, 1979] in a pairwise comparison. When a break is identified in the test series, the preceding portion of the series is corrected by using some reference series chosen among those that prove to be homogeneous in a sufficiently large period centered on the break and that correlate well with the test series. Regarding the automatic version of the SNHT, the R-package CLIMATOL 2.2 [*Guijarro*, 2014] has been used. Specifically, this automatic method begins by normalizing all series, and then runs the SNHT on the series of differences between the observed and estimated reference series to detect significant shifts and split them into more homogeneous subseries. In a first stage, SNHT is applied in stepped overlapping windows to avoid masking effects of multiple shifts in the mean, but in a second stage SNHT is applied to the whole series, when the test reaches its full power. This method has been proven as one of the most suitable automatic methods to

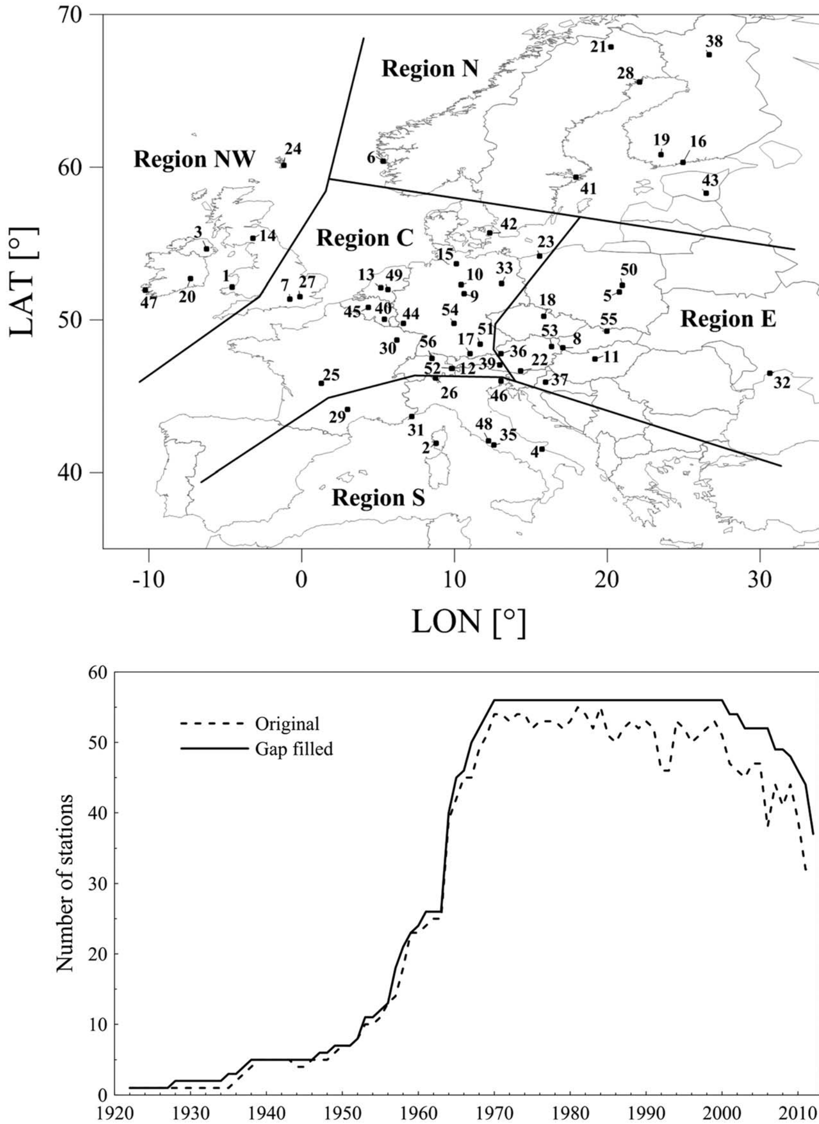

Figure 1. (top) Location of the 56 GEBA stations with long-term downward surface shortwave radiation (SSR) records over Europe used in this study. The stations are numbered and their details are available in Table 1. The boundaries of a schematic regionalization (bold lines) based on a principal component analysis (PCA) are indicated too. (bottom) Time evolution of data availability for the SSR data set during the period 1922–2012, both for the original (solid line) and gap filled (dashed lines) SSR series.

homogenize climate data [*Guijarro*, 2011, 2012; *Venema et al*., 2012]. For more details about the automatic version of the SNHT and the Craddock test, please refer to their references [*Brunetti et al*., 2006a; *Guijarro*, 2014].

Specifically, a subset of 35 stations (Table 1) has been used as it was not possible to run the Craddock test on the full SSR data set due to the difficulty to run this method at some of the stations with few reference stations in their surroundings. Equally, these two different relative homogeneity tests have been limited to the period 1961–2007 due to the lower number of records for this initial period. The results of this comparison show small differences at individual series according to the method used, but different homogenization methods provide similar results when the series are averaged, except for some slight differences of the Craddock test as compared to the SNHT tests during the late 1990s (Figure 2). On the other hand, there is also a good agreement between the original and homogenized data sets, especially for the one provided by the SNHT tests, which gives some confirmation that those studies that used the raw GEBA series over

Table 1. Details of the 56 GEBA Stations With SSR Series Used in This Study, Including the Period With Data Available at Each Station

Number	Station	GEBA ID	Longitude (deg)	Latitude (deg)	Altitude (m)	Country	Period	Region
1	Aberporth[a]	1293	−4.57	52.13	134	Great Britain	1959–2012	NW
2	Ajaccio[a]	1274	8.80	41.92	4	France	1970–2012	S
3	Aldergrove	1284	−6.22	54.65	81	Great Britain	1968–2012	NW
4	Amendola[a]	1361	15.72	41.53	56	Italy	1964–2010	S
5	Belsk	1391	20.78	51.83	180	Poland	1970–2012	E
6	Bergen	1384	5.32	60.40	45	Norway	1965–2012	N
7	Bracknell	1301	−0.78	51.38	74	Great Britain	1965–2002	C
8	Bratislava	1195	17.10	48.17	289	Slovakia	1964–2012	E
9	Braunlage[a]	1209	10.62	51.72	615	Germany	1957–2000	C
10	Braunschweig[a]	1205	10.45	52.30	81	Germany	1958–2011	C
11	Budapest	1320	19.18	47.43	138	Hungary	1964–2006	E
12	Davos[a]	1187	9.85	46.82	1590	Switzerland	1935–2012	C
13	De Bilt	1381	5.18	52.10	40	Netherlands	1964–2012	C
14	Eskdalemuir[a]	1283	−3.20	55.32	242	Great Britain	1956–2012	NW
15	Hamburg[a]	1203	10.12	53.65	49	Germany	1949–2011	C
16	Helsinki[a]	1659	24.97	60.32	53	Finland	1957–2012	N
17	Hohenpeissenberg[a]	1226	11.02	47.80	990	Germany	1953–2012	C
18	Hradec Kralove[a]	1189	15.85	50.25	241	Czech Republic	1953–2012	E
19	Jokioinen[a]	1238	23.50	60.82	104	Finland	1957–2012	N
20	Kilkenny[a]	1334	−7.27	52.67	64	Ireland	1969–2009	NW
21	Kiruna[a]	1412	20.23	67.85	505	Sweden	1969–2012	N
22	Klagenfurt[a]	1173	14.33	46.65	452	Austria	1964–2012	E
23	Kolobrzeg	1386	15.58	54.18	16	Poland	1964–2012	C
24	Lerwick[a]	1276	−1.18	60.13	82	Great Britain	1952–2012	NW
25	Limoges[a]	1257	1.28	45.82	282	France	1967–2012	C
26	Locarno-Monti[a]	1188	8.78	46.17	380	Switzerland	1938–2012	S
27	London[a]	1299	−0.12	51.52	77	Great Britain	1958–2006	C
28	Lulea[a]	1413	22.13	65.55	16	Sweden	1965–2012	N
29	Millau[a]	1264	3.02	44.12	715	France	1967–2012	S
30	Nancy-Essey[a]	1246	6.22	48.68	225	France	1967–2012	C
31	Nice[a]	1266	7.20	43.65	4	France	1967–2012	S
32	Odessa	1421	30.63	46.48	64	Ukraine	1964–2011	E
33	Potsdam[a]	1197	13.10	52.38	33	Germany	1937–2012	C
34	Reykjavik	1338	−21.90	64.13	52	Iceland	1957–2012	-
35	Rome	1360	12.58	41.80	131	Italy	1964–2009	S
36	Salzburg	2413	13.05	47.78	420	Austria	1957–2012	E
37	Sljeme	1438	15.97	45.92	988	Croatia	1966–2012	E
38	Sodankyla[a]	1237	26.65	67.37	178	Finland	1953–2012	N
39	Sonnblick[a]	1171	12.95	47.05	3106	Austria	1964–2012	C
40	St. Hubert	1179	5.40	50.03	563	Belgium	1968–2008	C
41	Stockholm	1414	17.95	59.35	24	Sweden	1922–2012	N
42	Taastrup	1227	12.30	55.67	28	Denmark	1965–2002	C
43	Toravere[a]	2901	26.47	58.27	70	Estonia	1955–2012	N
44	Trier[a]	1217	6.67	49.75	278	Germany	1958–2011	C
45	Uccle[a]	1176	4.35	50.80	105	Belgium	1961–2011	C
46	Udine	2513	13.03	45.98	51	Italy	1964–2010	S
47	Valentia[a]	1335	−10.25	51.93	30	Ireland	1964–2012	NW
48	Vigna di Valle	1359	12.22	42.08	262	Italy	1964–2012	S
49	Wageningen[a]	2867	5.65	51.97	7	Netherlands	1928–2006	C
50	Warszawa	1389	20.98	52.27	130	Poland	1964–2012	E
51	Weihenstephan[a]	1224	11.70	48.40	469	Germany	1961–2011	C
52	Weissfluhjoch[a]	1570	9.83	46.82	2760	Switzerland	1947–2000	C
53	Vienna	1479	16.37	48.25	202	Austria	1965–2012	E
54	Wuerzburg[a]	1216	9.97	49.77	275	Germany	1960–2011	C
55	Zakopane	1393	19.97	49.28	857	Poland	1964–2012	E
56	Zuerich[a]	1572	8.53	47.48	436	Switzerland	1959–2012	C

[a]Subset of stations tested for inhomogeneities by means of the Craddock test.

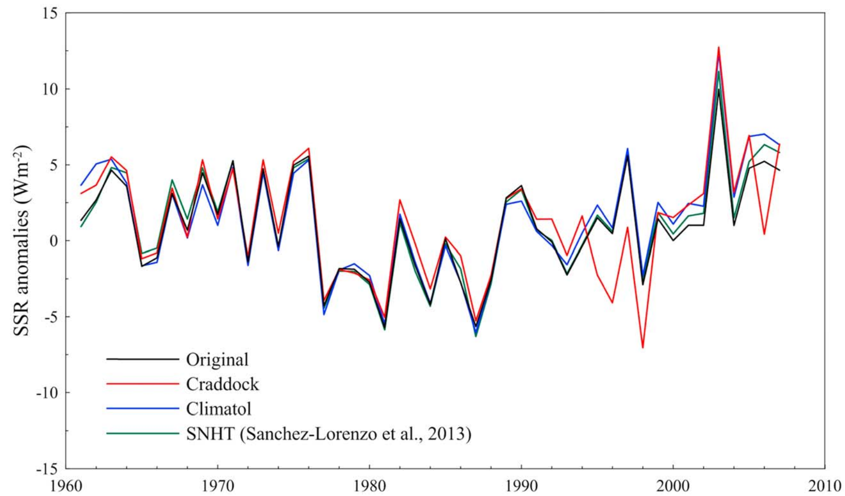

Figure 2. Temporal evolution of the mean annual downward surface shortwave radiation (SSR) series in Europe over the period 1961–2007 for the original series (black) and homogenized by using the Standard Normal Homogeneity Test (SNHT) as described in *Sanchez-Lorenzo et al.* [2013b] (green), an automatic version of the SNHT implemented in the package Climatol (blue), and the Craddock test (red). The anomalies are expressed as differences from the 1971–2000 mean.

Europe [e.g., *Norris and Wild*, 2007; *Chiacchio and Wild*, 2010; *Allen et al.*, 2013] did not include large biases due to inhomogeneity effects. Considering these results, for the subsequent analysis of this study, including those described in section 3, only the data set homogenized in *Sanchez-Lorenzo et al*. [2013b] is considered as it provides similar results as compared to the other methods. The series obtained by the other two methods are also available on request, although for the Craddock test only the subset of 35 series is available.

Subsequently, the SSR series from *Sanchez-Lorenzo et al.* [2013b] have been updated to include data from January 2008 to December 2012 where possible, mainly using the data stored in the World Radiation Data Center (WRDC). As in *Sanchez-Lorenzo et al*. [2013b], all monthly gaps of each updated series were filled with estimates based on the most correlated time series. The final data set consists of 56 series distributed over Europe, mainly concentrated in central Europe and few of them over the Mediterranean area (Figure 1, top). The longest series is from Stockholm, with records starting in 1922, while most of the series are available since the 1970s (Figure 1, bottom and Table 1).

Each of the stations were assigned into five different regions across Europe by using the same regionalization procedure as described in *Sanchez-Lorenzo et al*. [2013b], which is based on a principal component analysis (PCA) that aims to cluster the stations into regions with similar temporal variability. The five regions characterize different areas across Europe (Figure 1, top and Table 1): the center (region C, comprising 22 stations), the east (region E, 11 stations), the north (region N, 8 stations), the south (region S, 8 stations), and the northwest (region NW, 6 stations). As a reference, Table 2 shows the annual and seasonal climatic means of SSR for all of Europe and different regions for the period 1971–2012. The annual SSR shows a latitudinal gradient from north to south, with a minimum in the northern regions (100.8 and 105.3 W m^{-2} in regions N and NW, respectively) and maximum in the south (164.1 W m^{-2} in region S).

Table 2. Annual and Seasonal Mean (Period 1971–2012) of Downward Surface Shortwave Radiation (SSR) in Europe and the Five Regions Considering the 56 Stations Within Each Region, Respectively[a]

	Stations	Annual	Winter	Spring	Summer	Autumn
Europe	56	125.4 (3.7)	42.6 (1.8)	163.9 (7.5)	211.6 (7.8)	83.5 (4.0)
Region C	22	125.6 (5.8)	44.7 (2.6)	164.5 (11.6)	206.5 (12.3)	86.8 (6.6)
Region N	8	100.8 (4.0)	15.3 (1.6)	145.6 (8.5)	195.7 (13.3)	46.7 (3.4)
Region E	11	130.3 (5.0)	45.8 (2.8)	167.5 (10.4)	218.5 (9.3)	89.7 (5.9)
Region S	8	164.1 (5.2)	75.3 (5.8)	196.5 (10.4)	261.6 (7.9)	123.1 (6.7)
Region NW	6	105.3 (4.1)	29.3 (2.2)	144.9 (8.0)	180.5 (11.2)	66.6 (3.6)

[a]Values in parentheses show the interannual variability expressed by their standard deviation. Units are in W m^{-2}.

In this study, the linear trends of the series were calculated by means of least squares linear fitting and their significance (at confidence level $P < 0.1$) estimated by the Mann-Kendall nonparametric test. Moreover, the time series were smoothed with a 21 year Gaussian low-pass filter, which improves the visualization of the decadal variability when plotted together. The filter only takes into account the values on one side at the start and end of the time series in order to filter the whole period.

In order to extract as much information as possible regarding the decadal variability and trends of the annual mean series, and taking into account that significance and slope of the trends strictly depend on the selected period, a trend analysis was also applied on running windows of variable width [*Brunetti et al*., 2006b; *Sanchez-Lorenzo et al*., 2007], which provides results that are more comparable with previous studies. The slopes of the trends were estimated within temporal windows of widths ranging from 20 years up to the entire series length (i.e., 74 years).

3. Results and Discussion

3.1. Trends of the Mean Series in Europe (1939–2012)

The annual and seasonal anomalies were calculated first for each of the 56 SSR series, considering the period 1971–2012 as the reference period as most of the series are available during this time. The use of anomalies reduces the bias from the variation in the number of available series over time and the differences in their absolute mean values. The seasons in this study are defined as winter (December-January-February), spring (March-April-May), summer (June-July-August), and autumn (September-October-November).

Afterward, annual and seasonal mean series were computed as an arithmetic mean of all annual and seasonal anomalies time series. The use of composite series permits a better identification of the variations in the time series as they enhance the signal-to-noise ratio, as well as reduce the impact of remaining inhomogeneities and biases due to local features. Although there are some SSR series with records before the late 1930s, the low density of such stations forced us to limit the extension of the composite series to 1939, when 5 series (Stockholm, Wageningen, Davos, Potsdam, and Locarno-Monti) are already available within Europe (Figure 1, bottom). Consequently, the analyses are performed for the period 1939–2012, but with greater confidence since the 1960s, as most of the series are available during this time.

Figure 3 (Figure 4) shows the mean annual (seasonal) SSR anomaly series (in $W m^{-2}$) in Europe from 1939 to 2012, together with the low-pass filter. The linear trends of the series (in $W m^{-2}$) estimated over the whole period 1939–2012 and different subperiods, based on the minimum and maximum years of the annual filtered series, are shown in Table 3.

Figure 5 shows the same mean annual and seasonal SSR anomaly series, but expressed as relative anomalies (%) estimated using the mean SSR values shown in Table 2. Figure 5 also includes the mean series over Europe obtained using only the 5 stations with the longest SSR series (Stockholm, Wageningen, Davos, Potsdam, and Locarno-Monti). The mean series shows that the subset of longest stations seems to capture almost the whole variability of the full data set. The coefficient of determination between the two mean annual series is 0.83 and increases to 0.92 if low-pass filtered series are used, which suggests very similar interannual and decadal variations in both mean series, respectively. For the seasonal nonfiltered (filtered) series, the coefficients of determination range between a minimum in winter of 0.68 (0.87) and maximum around 0.85 (0.98) in the other seasons. A similar month-to-month variability is also shown in the correlation coefficients obtained between the mean monthly SSR series over Europe and the satellite-derived SSR provided by the Satellite Application Facility on Climate Monitoring (CM SAF) [*Posselt et al*., 2011] during the period 1983–2005 (Figure 6). Also, trend values (not shown) estimated from the mean series over Europe obtained using the 56 series and that with the subset of 5 stations are very similar. These results highlight that due to the strong spatial correlation in the SSR series, few series are enough to capture almost the same interannual and decadal variability as using a dense network of stations, as suggested in previous studies [*Dutton et al*., 2006; *Hakuba et al*., 2013a; *Makowski et al*., 2009]. Equally, the mean series obtained using a subset of 5 stations proves that the changes in data availability during the period 1939–2012 do not negatively impact the temporal stability of the composite series shown in Figures 3–5, although it is worth noting that these composite series are especially representative of central areas of Europe where more measurements are available (for regional details, see section 3.2).

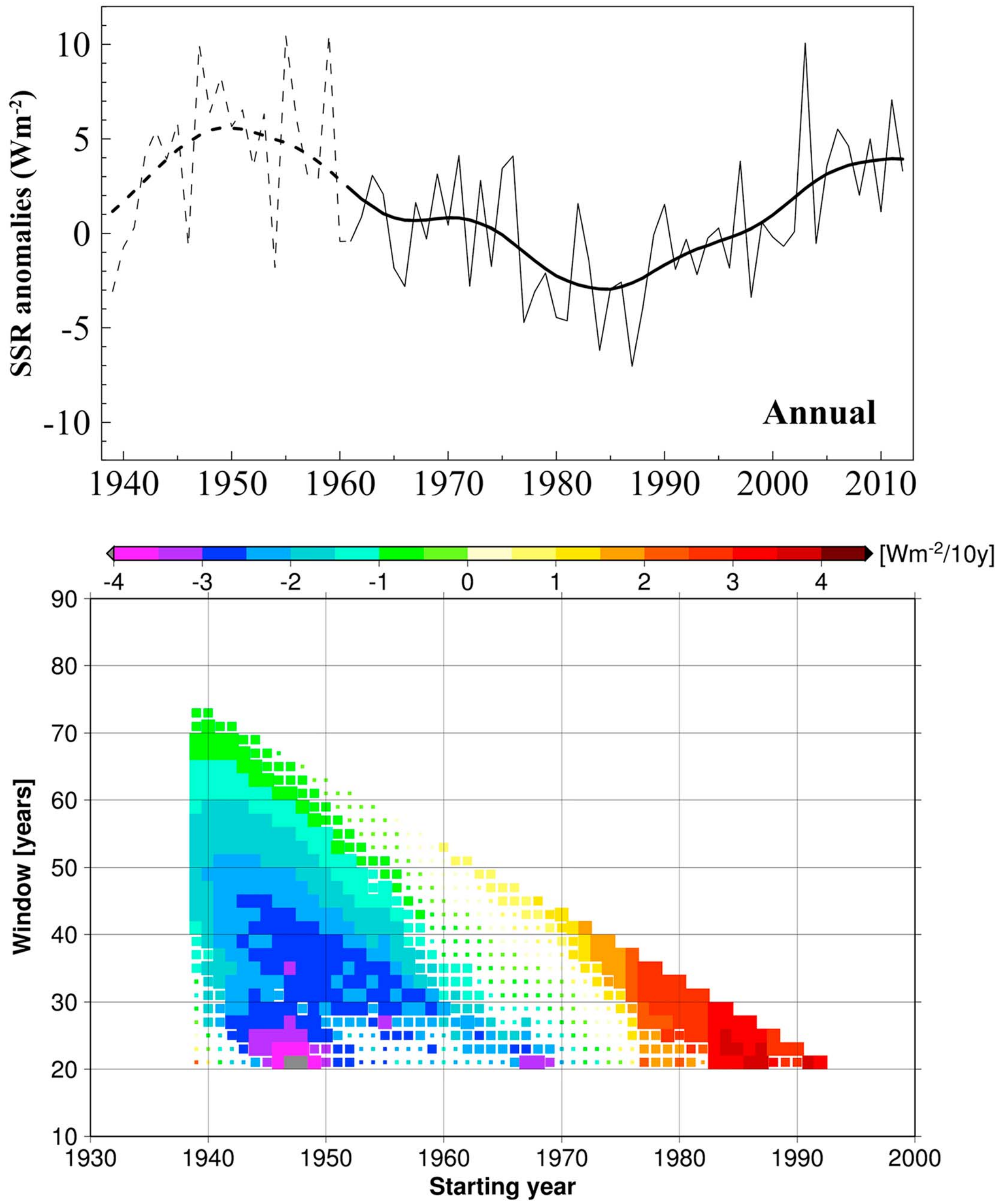

Figure 3. (top) Composite annual downward surface shortwave radiation (SSR) series (thin line) from 1939 to 2012 in Europe, plotted together with a 21 year Gaussian low-pass filter (thick line). The series are expressed as anomalies (W m^{-2}) from the 1971–2012 mean. Dashed lines are used prior to 1961 due to the lower number of records for this initial period. (bottom) Running trend analysis for the mean annual SSR series. The *y* axis represents window width, and the *x* axis represents the first year of the window over which the trend is calculated (e.g., the square of coordinates (1950, 40) corresponds to the trend from 1950 to 1989). Colors indicate the trend amount; dimension of squares indicates the significance level ($P < 0.01$ large, $P < 0.1$ medium, and $P > 0.1$ small).

The annual SSR series (Figure 3, top) starts with an increase until around 1950 (absolute maximum of the filtered series) in line with the early brightening period previously detected in SSR and sunshine duration series in Europe [*Sanchez-Lorenzo et al*., 2008; *Ohmura*, 2009; *Stanhill and Ahiman*, 2014; *Manara et al*., 2015] although it is less evident if direct solar radiation is analyzed [*Ohvril et al*., 2009; *Lachat and Wehrli*, 2013; *Antón et al*., 2014]. This early brightening period is then followed by a decrease until the

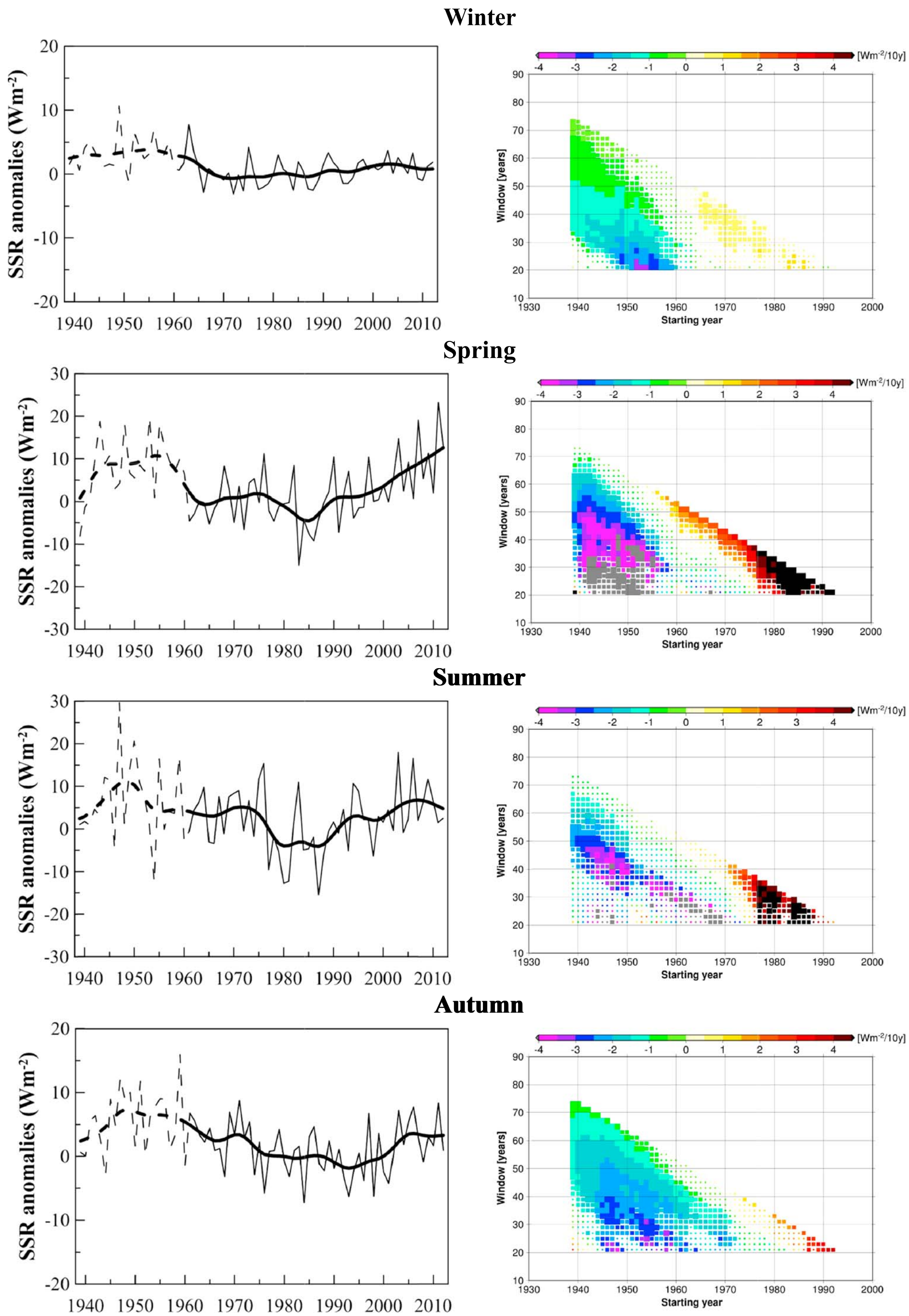

Figure 4. (left column) Composite seasonal downward surface shortwave radiation (SSR) series (thin line) from 1939 to 2012 in Europe, plotted together with a 21 year Gaussian low-pass filter (thick line). The series are expressed as anomalies ($W\,m^{-2}$) from the 1971–2012 mean. Note that winter and autumn *y* axis plot ranges are different as compared to summer and spring. (right column) As Figure 3 (bottom) but for the mean seasonal SSR series. The seasons are defined as December-January-February for winter, March-April-May for spring, June-July-August for summer, and September-October-November for autumn.

Table 3. Annual and Seasonal Trends for the Downward Surface Shortwave Radiation (SSR) Mean Series in Europe Over the Period 1939–2012 and Different Subperiods, Together With the 95% Confidence Intervals[a]

	1939–1949	1950–1985	1986–2012	1939–2012
Annual	**+9.6 [3.5, 15.6]**	**−2.5 [−3.6, −1.5]**	**+3.2 [1.8, 4.6]**	*−0.4 [−0.8, 0.0]*
Winter	**+**	**−1.3 [−2.1, −0.4]**	+	−0.4 [−0.6, −0.1]
Spring	**+**	**−3.8 [−5.8, −1.8]**	**+5.9 [2.8, 9.0]**	**-**
Summer	+	−2.9 [−5.5, −0.3]	+4.2 [1.0, 7.3]	-
Autumn	+9.8 [1.8, 17.8]	**−2.2 [−3.5, −0.8]**	*+2.0 [0.0, 3.9]*	**−0.7 [−1.1, −0.2]**

[a]Bold, regular, and italic numbers indicate trends with significance level $P < 0.01$, $P < 0.05$, and $P < 0.1$, respectively, and for lower levels of significance only the sign of the trend is indicated. The values are expressed as W m^{-2} per decade. The seasons are defined as December-January-February for winter, March-April-May for spring, June-July-August for summer, and September-October-November for autumn.

mid-1980s (i.e., dimming period), with a brief period of stabilization in the second half of the 1960s. There is a clear change in the series around 1985 (absolute minimum of the filtered series) and the SSR shows a tendency toward an increase until the early 2000s (i.e., brightening period) that partially compensates the previous decrease, followed by a slight increase or stabilization in the final years of the series. It is interesting to note that the absolute maximum of the series anomalies is not reached in 2003 as previously indicated if shorter composite series were considered [*Makowski et al*., 2009; *Allen et al*., 2013]. In fact, as shown in Figure 3 (top), the absolute maximum is reached in the years 1955, and 1959 with an anomaly of around 10.5 W m^{-2}. The linear evolution, estimated over the whole 1939–2012 period, shows a slight but significant decrease of −0.4 W m^{-2} (−0.3% in relative terms, which is estimated using the mean SSR values shown in Table 2) per decade, or −3.0 W m^{-2} (−2.4%) over the whole 74 year period. If the series is divided in different subperiods, significant trends are found in the 1939–1949 (+9.6 W m^{-2} per decade), 1950–1985 (−2.5 W m^{-2} per decade), and 1986–2012 (+3.2 W m^{-2} per decade) subperiods.

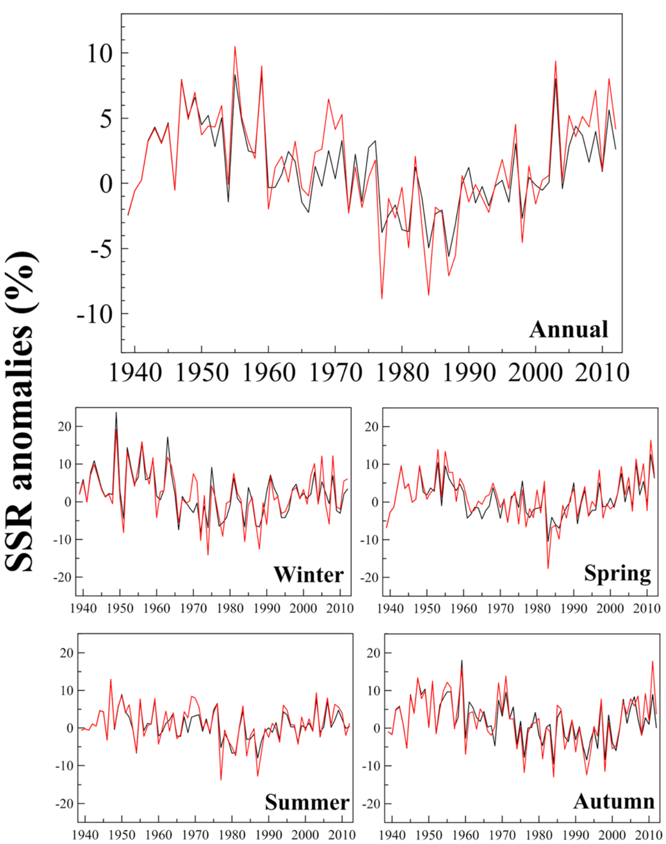

Figure 5. Mean annual and seasonal downward surface shortwave radiation (SSR) series from 1939 to 2012 using the 5 stations with the longest records (red line), plotted together with the mean series obtained with all series available (black line), as the thin lines in Figure 2. The series are expressed as relative deviations (%) from the 1971–2012 mean.

Figure 3 (bottom) shows the results of the running trend for the annual mean series. The results show that there are negative trends for all the time scales greater than around 55 years. Equally, there is a clear negative-positive sequence (dimming/brightening) of significant trends at time scales shorter than 40–50 years after the 1940s, as discussed above. Overall, the absence of statistically significant trends around the 1950s at the maximum window length (or even negative significant values for previous starting years) highlights the lack of increase in SSR from the 1950s to the present, which seems to support that trends in SSR since the 1950s cannot be the origin of the warming over Europe over the same period [*van der Schrier et al*., 2013]. Finally, it is worth noting that the early brightening signal is not significant if a 20 year window is

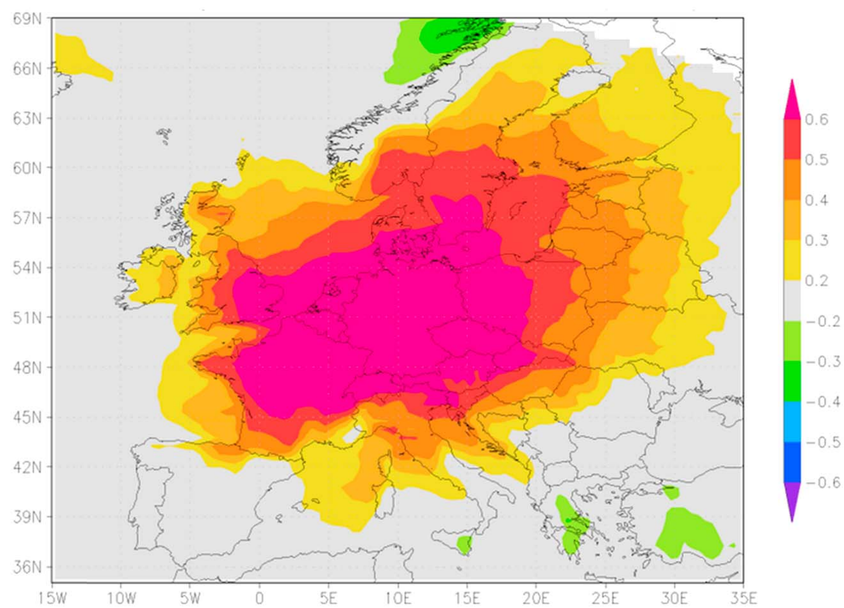

Figure 6. Correlation coefficients ($P < 0.05$) between the detrended mean monthly downward surface shortwave radiation (SSR) anomaly series over Europe and each of the monthly anomalies SSR series derived from the Satellite Application Facility on Climate Monitoring (CM SAF) satellite product [*Posselt et al.*, 2011] during the period 1983–2005. High and positive significant correlations are observed in most of the area covered by the 56 SSR series (Figure 1), which suggest that the mean SSR series is representative of a regional area.

considered during the first years of the study period, which highlights the low data availability before the 1950s and the necessity of further studies using longer time series (e.g., proxy records such as sunshine duration series [*Sanchez-Lorenzo and Wild*, 2012; *Sanchez-Romero et al.*, 2014]) in order to confirm the reliability of this early increase in SSR and its possible causes as, for example, global climate simulations do not show evidence of this early brightening [*Romanou et al.*, 2007].

On a seasonal basis (Figure 4, left column), the interannual variability and decadal variability of the spring and summer series are slightly more similar to the annual series, as expected due to the larger contribution of these two seasons to the annual total (Table 2). Nevertheless, it is important to note that over the whole period 1939–2012 only winter and autumn show significant negative trends like the annual series, with a rate of decrease of $-0.4\,\mathrm{W\,m^{-2}}$ (-0.9%) and $-0.7\,\mathrm{W\,m^{-2}}$ (-0.8%) per decade, respectively. This fact is mainly because the recent brightening take primarily in spring and summer. Thus, it is not a continued dimming but a lack of brightening in the recent period that gives us this negative long-term trend in winter and autumn.

In addition, in all seasons there are statistically significant negative trends during the 1950–1985 subperiod, as well as significant positive trends during the 1986–2012 subperiod except for the winter series (Table 3). Spring shows the largest absolute decrease ($-3.8\,\mathrm{W\,m^{-2}}$ per decade) and increase ($+5.9\,\mathrm{W\,m^{-2}}$ per decade) during the dimming and brightening period, respectively. It is worth noting that the strongest relative decrease (increase) during the dimming (brightening) period is found in winter (spring) with a negative (positive) trend of -3.0% (+3.6%) per decade. These results are in line with previous seasonal decadal variations reported by *Chiacchio and Wild* [2010] over the period 1971–2000, although, for example, in the present study we detect significant trends in the dimming and brightening subperiods during spring and summer, which were not significant in this previous study. These differences compared to *Chiacchio and Wild* [2010] are possibly due to the longer period considered in our study that enable us to reach the significance level, which confirm the need of updating records of SSR in order to establish trends. Finally, all seasons show an increase during the 1939–1949 subperiod, but only the autumn trend is found to be significant. The running trends for the seasonal series are shown in Figure 4 (right column). It is worth mentioning that the spring and summer running trends fairly agree with the running trend of the annual mean series (Figure 3, bottom).

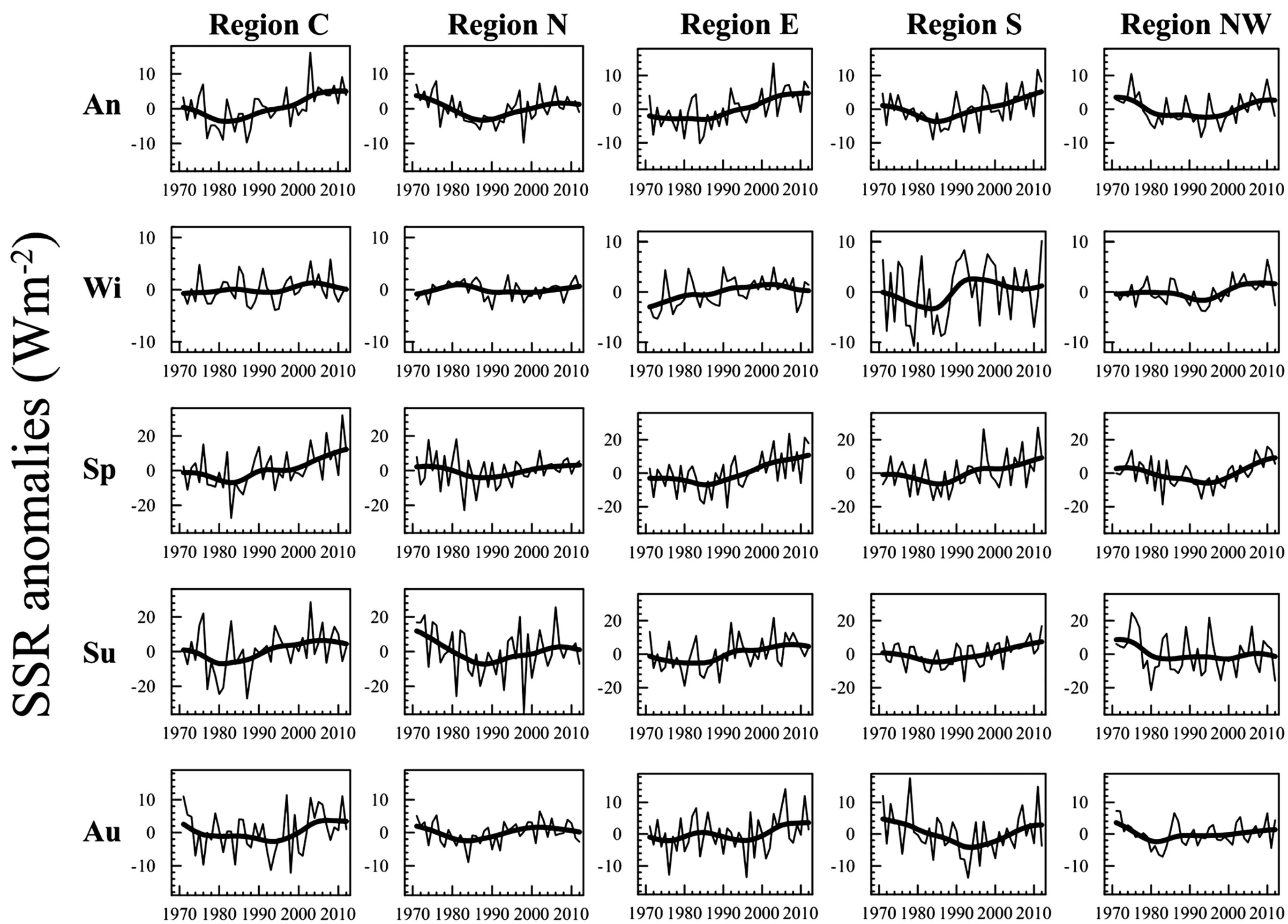

Figure 7. Mean annual and seasonal downward surface shortwave radiation (SSR) regional series (thin line) over Europe during the period 1971–2012, together with a 21 year Gaussian low-pass filter (thick line). (An, annual; Wi, winter; Sp, spring; Su, summer; Au, autumn). Note that annual, winter, and autumn *y* axis plot ranges are different as compared to summer and spring. The five regions over Europe have been defined by means of a principal component analysis (PCA) applied to the 56 SSR series and characterize different areas across Europe (Figure 1 and Table 1): the center (region C, comprising 22 stations), the east (region E, 11 stations), the north (region N, 8 stations), the south (region S, 8 stations), and the northwest (region NW, 6 stations). The regional mean series are only evaluated after 1971 and are expressed as anomalies (W m^{-2}) from the 1971–2012 mean.

3.2. Trends of the Regional Series (1971–2012)

Annual and seasonal series for the five regions were computed as an arithmetic mean of the available series in each region (Table 1). Due to the low number of stations with records before 1971 in some regions (i.e., regions N and S) the regional mean series are only constructed for the period 1971–2012. Figure 7 shows the mean annual series of the SSR for the five regions in Europe, together with the low-pass filter, during the period 1971–2012. The linear trends, calculated over the whole 1971–2012 period and the 1971–1985 and 1986–2012 subperiods, are summarized in Table 4.

The mean annual series for the regions C, E and S show the most similar temporal pattern and trends to that covering the whole of Europe. The trend analysis shows a significant increase of +2.0 W m^{-2}, +2.3 W m^{-2}, and +1.7 W m^{-2} per decade over the whole 1971–2012 period for the regions C, E, and S, respectively, which are slightly higher values than that for the mean European series (+1.3 W m^{-2}). Nevertheless, it is worth mentioning that all annual regional series show negative (dimming) and positive (brightening) trends during the 1971–1985 (1986–2012) subperiod. However, only in the regions N, S, and NW both trends are statistically significant. Meanwhile, in the regions C and E only the trends for the second subperiod reach the level of statistical significance. Thus, all regions show a statistically significant brightening since the mid-1980s.

Table 4. As in Table 3 but for the Mean Series of the Five Regions Defined in Europe, by Means of a Principal Component Analysis (PCA), Over the Period 1971–2011 and the 1971–1985 and 1985–2011 Subperiods[a]

	1971–1985	1986–2012	1971–2012
EOF-1, Region C			
Annual	−	**+3.7 [1.6, 5.8]**	**+2.0 [0.8, 3.2]**
Winter	+	+	+
Spring	−	+6.4 [1.7, 11.0]	**+3.9 [1.4, 6.5]**
Summer	−	*+4.8 [0, 9.8]*	+2.9 [0, 5.9]
Autumn	−	+	+
EOF-2, Region N			
Annual	−6.3 [−10.4, −2.0]	**+2.5 [0.8, 4.3]**	+
Winter	**+2.1 [0.7, 3.5]**	+	+
Spring	−	+4.2 [1.3, 7.2]	+
Summer	−17.1 [−33.1, −1.1]	+	−
Autumn	−5.6 [−9.8, −1.5]	+	+
EOF-3, Region E			
Annual	−	**+3.5 [1.5, 5.5]**	**+2.3 [1.2, 3.4]**
Winter	*+2.8 [−1.0, 6.7]*	+	**+0.9 [0.3, 1.6]**
Spring	−	**+7.8 [3.2, 12.5]**	+4.2 [1.8, 6.6]
Summer	−	+	**+2.8 [0.5, 4.1]**
Autumn	+	+	+
EOF-4, Region S			
Annual	−4.8 [−8.9, −0.7]	+3.9 [1.6, 6.1]	*+1.4 [0.2, 2.5]*
Winter	−	-	+
Spring	−	+6.4 [1.3, 11.4]	+3.1 [0.6, 5.6]
Summer	−	**+5.8 [2.5, 9.1]**	+2.1 [0.3, 3.9]
Autumn	−	+	−
EOF-5, Region NW			
Annual	−5.7 [−10.5, −0.8]	+2.3 [0.5, 4.2]	+
Winter	−	+1.4 [0.2, 2.5]	+
Spring	−	**+6.4 [3.3, 9.5]**	+
Summer	−	+	−
Autumn	**−7.6 [−11.3, −3.9]**	+	−

[a]Bold, regular, and italic numbers indicate trends with significance level $P < 0.01$, $P < 0.05$, and $P < 0.1$, respectively, and for lower levels of significance only the sign of the trend is indicated. The values are expressed as W m^{-2} per decade. The seasons are defined as December-January-February for winter, March-April-May for spring, June-July-August for summer, and September-October-November for autumn.

With respect to the seasonal series, in winter only in the region E there is a significant increase of SSR during the period 1971–2012, with a rate of +0.9 W m^{-2} (+2.0%) per decade. During spring, the most remarkable feature is the strong increase in the SSR in all regions, especially since 1985 when all trends are significant with rates of change greater than 4 W m^{-2} per decade. The summer series also show a widespread increase in SSR, but with lower rates than in spring and without statistical significance in the regions N, E, and NW. Finally, the autumn series present less relevant decadal variations as compared to the spring and summer series, and the most interesting feature is the strong and significant decrease observed in the regions N (−5.6 W m^{-2}) and NW (−7.6 W m^{-2}) during the 1971–1985 period, in line with previous results [*Chiacchio and Wild*, 2010].

4. Conclusions

In this study we have analyzed the decadal variations and trends of a data set of downward surface short-wave radiation (SSR) in Europe. Special attention has been placed on records beyond 2005. Additional emphasis has been placed on the generation, for the first time, of a composite time series for all of Europe covering the period 1939–2012.

The mean annual series of SSR in Europe shows a slightly significant negative trend of −0.4 W m^{-2} per decade from 1939 to 2012, although substantial decadal variations are evident during the study period. Indeed, there is an early brightening period during the 1940s, followed by a dimming period from the 1950s to the mid-1980s, and ending with a brightening since the second half of the 1980s.

The results from the 1970s to the 2000s are in line with previous research over Europe, but in this study a homogenized data set has been used, which enables us to get more reliable conclusions due to the higher quality of the data set. Equally, the update of the records until 2012 does not show a renewed dimming in Europe since the early 21st century, although there is a tendency toward stabilization during the last years possibly due to the decreasing anthropogenic aerosol emissions [*Philipona et al*., 2009; *Kühn et al*., 2014]. Due to a lack of sufficient data, further research and additional proxy data of SSR are needed in order to study the spatial and temporal scale of the early brightening observed before the 1950s and its possible causes.

On a seasonal basis, the decadal variability observed during the spring, summer, and autumn is similar to the annual series, as well as similar in most of the regions across Europe, which highlights that the dimming/brightening phenomenon is detected during the majority of the year and on a regional scale [*Wang et al*., 2014]. In addition, this study highlights that due to the strong spatial correlation in the SSR series, few series over Europe are enough to capture almost the same interannual and decadal variability as using a dense network of stations.

Overall, the above results provide a unique data set over Europe to study long-term trends in SSR during the last eight decades, which is a fundamental variable for a better understanding of current climate change. Thus, the decadal variations in the SSR should have an expected impact on the modulation of the temperatures [*Wild et al*., 2007; *Wang and Dickinson*, 2013; van den Besselaar et al., Relationship between sunshine duration and temperature trends across Europe since the second half of the 20th Century, under review, *Journal of Geophysical Research*, 2015] observed since the 1930s in Europe, which needs further analysis. Moreover, it can also be crucial for other processes over Europe linked with changes in the hydrological cycle, agriculture production, or natural ecosystems [e.g., *Stanhill and Cohen*, 2001; *Wild*, 2009, 2012]. The availability of reliable SSR data is very important, particularly regarding the temporal homogeneity of the series and when used as validation to assess SSR variability derived from remote sensing [*Hatzianastassiou et al*., 2005; *Sanchez-Lorenzo et al*., 2013b] and simulated from climate models [*Folini and Wild*, 2011; *Allen et al*., 2013; *Nabat et al*., 2014].

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