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Analysis of recent trends of global radiation ground measurements

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Contents

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1 Abstract

This analysis is focused on long time series of global radiation with a duration of at least 40 years within the period 1950 - 2009. Like this work lies in-between the analysis for worldwide (satellite) data with approx. 20 years of duration and those for some few sites with very long measurements. A total of 25 sites based on Global Energy Balance Archive (GEBA) have been used, which have been grouped to 10 regional clusters including 2 – 13 stations.

The following three questions have been investigated: 1. Trend of the time series of monthly data (full period and several sub periods); 2. Trends of 5, 10 and 20 years means; 3. Dependence of the variability on the length of a measured period.

For the whole period between 1950 and 2009 and all sites a negative and statistically significant trend of -1.6 W/m^2 per decade could be found. For most grouped sites no significant trend is visible. Nevertheless for Germany / Austria a slightly positive trend can be seen and for Switzerland, Asia, India and Canada a negative trend. For the two sub periods 1950 – 1985 and 1985 – 2009 a significant trend could be found for most groups and stations. For the first period 1950-1985 only negative trends were found. For the second period 1985-2009 (including data for most sites up to 2006) all regions except India and Canada showed a positive trend.

For the mean of all sites the dimming for the period 1950 – 85 and the brightening for the period 1985 – 2009 is statistically significant. The negative trend during the dimming period is clearly stronger (approx. factor 2) than the positive trend during the brightening phase. The individual regions and groups show a great variety of different trends for the analyzed sub periods. The negative trend found in Hinkelman et al. (2009) for the period after 2000 could be found only at 2 stations out of the 25.

Similar to the trends of the monthly values also the trends of the 5, 10 and 20 year means show a big dependence on the station. Also here the dimming and brightening phase is clearly visible. For 20 year means most sites show variations lower than 5-10%. However some sites in India, Beijing and Weissfluhjoch (Swiss mountain top station) do show a big negative trend with a decline of more than 20% during the analyzed period.

The variation depending on the duration of measurement is also quite different from site to site. Most sites have a standard deviation of 5-7% for a 12 month mean which decreases to 2-4% at 10 years and 2% at 20 years. The biggest decline happens in the first 5 years. As a general rule it can be stated, that a climatology of global radiation should include at least 10 years. Only for regions with very high trends (more than 5 W/m^2 and decade) it makes sense to get as current data as possible.

2 Introduction

During the last years the discussion about trends of recent global radiation did leave the scientific circles. Especially engineers in the field of solar energy were getting aware, that climatological values of global radiation are not constant.

Since trends in the main solar installation market Germany have been noticed, the question is raised regularly, how long and how current the used global radiation climatology should be. These questions were the main driver of this short analysis.

Up to now different publications about this topic have been presented (Pinker et al., 2005, Wild et al., 2005; Wild et al., 2009, Wild, 2009, Gilgen et al., 2009, Hinkelman et al., 2009). They are connected to the “global dimming” and “global brightening” discussion. Most of them have tried to define worldwide or continental trends based on ground and/or satellite information. Other publications looked at very long time series of some few sites.

Compared to the work dealing with trends of temperature, the number of publications is nevertheless quite small. In general climate change analysis of recent trends of global radiation is rather seldom examined.

This analysis is focused on long time series with a duration of at least 40 years. Like this work lies in-between the broad analysis for worldwide data and those for some few sites with very long measurements. With a duration of at least 40 years some 30 – 50 sites do exist worldwide. This work is also focusing on some practical aspects which are linked to the use of solar databases like PVGIS (http://re.jrc.ec.europa.eu/pvgis/) or Meteonorm (www.meteonorm.com).

3 Data

The source of all analyzed stations is the Global Energy Balance Archive (GEBA, http://proto-geba.ethz.ch), which is based to a great extent on data from the World Radiation Data Centre (WRDC, http://wrdc.mgo.rssi.ru/).

The analyzed period lasts from 1950 till 2009 (60 years).

We examined only stations, where the measurements begin before 1964 and end after 2004. At least 40 years of measurements had to be available. The maximum length of periods with missing values was set to 5 years.

The data of the months after July 2006 have been added manually based on publications from DWD and Meteo Swiss.

A total of 25 stations could be found, which did fulfil the conditions (Figure 1 and Table 1). Also in North America and Australia stations exist, which begin at 1950 and end after 2004. The problem is the period 1980-1995 during which all those sites do have periods with missing values longer than 5 years. Time gaps for the Canadian stations of Edmonton and Toronto have been filled with data from Environment Canada (this is the only exception concerning the source of data) and therefore those two sites could be used in this analysis.

In Russia, Italy and Portugal there are also stations available with a start around 1964 and 40 years of measurements. Russian and Portuguese sites have partly large missing periods, so these sites couldn't be used. The reason for not using of Italian sites is the high uncertainty of those time series (large positive trends at the end of the sixties, which can't be linked to climatological trends).

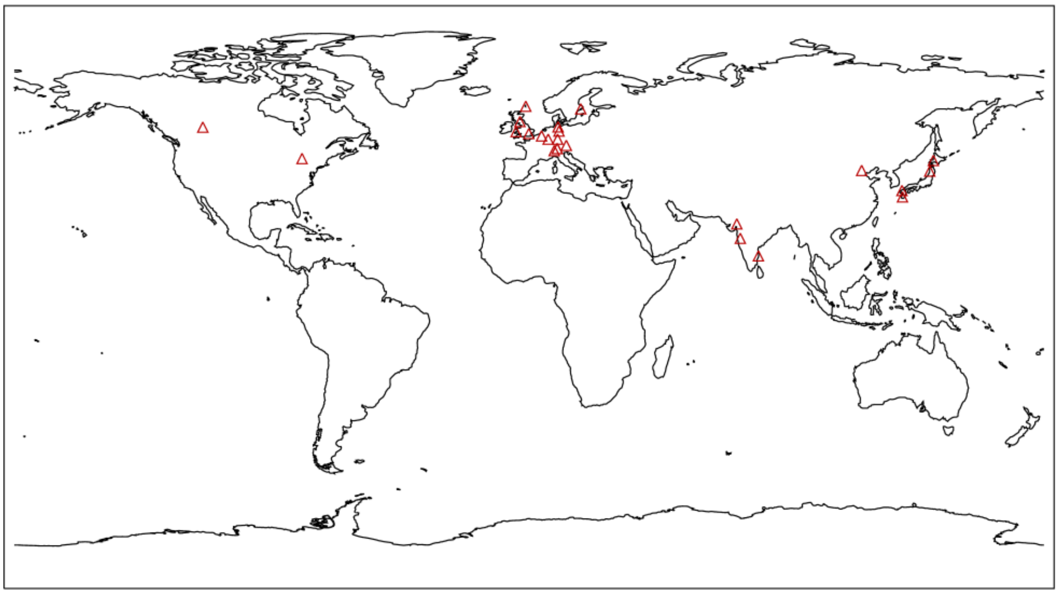

Figure 1: Distribution of the 25 stations used for this analysis.

The distribution of the analyzed sites is concentrated very much to regions of central Europe, India and Japan and all sites are from the northern hemisphere. Due to this no conclusions for the whole globe can be drawn.

Table 1: 25 sites used for trend analysis.

Nr	Name	Longitude [°]	Latitude [°]	Altitude [m]	Period
1	Braunschweig, DE	10.45	52.30	81	1958-2009
2	Hamburg, DE	10.117	53.65	49	1958-2009
3	Salzburg, AT	13.00	47.80	435	1957-2005
4	Trier, DE	6.667	49.75	278	1958-2009
5	Uccle, BE	4.35	50.80	105	1961-2006
6	Würzburg, DE	9.967	49.767	275	1958-2009
7	Potsdam, DE	13.100	52.383	33	1950-2009
8	London Weather Station, UK	-0.117	51.517	77	1958-2005
9	Aberporth, UK	-4.567	52.133	134	1957-2006
10	Eskdalemuir, UK	-3.200	55.317	242	1956-2006
11	Lerwick, UK	-1.183	60.133	55	1952-2006
12	Stockholm, SW	18.05	59.333	52	1950-2006
13	Locarno-Monti, CH	8.787	46.173	366	1950-2009
14	Davos, CH	9.844	46.813	1590	1950-2009
15	Weissfluhjoch, CH	9.806	46.833	2690	1950-2009
16	Akita, JP	140.10	39.717	9	1961-2006
17	Fukuoka, JP	130.383	33.583	3	1959-2006
18	Kagoshima, JP	130.55	31.567	4	1961-2006
19	Sapporo, JP	141.333	43.05	17	1957-2006
20	Beijing, CN	116.283	39.933	55	1957-2005
21	Ahmadabad, IN	72.633	23.067	10	1964-2005
22	Poona, IN	73.850	18.533	555	1957-2005
23	Madras, IN	80.183	13.000	10	1957-2005
24	Edmonton, CA	-114.100	53.550	767	1950-2006
25	Toronto, CA	-79.400	43.667	116	1950-2001

4 Method

Only a few sites with long term measurements have been examined. This makes this analysis different to other investigations of long term measurements, where more sites with shorter periods have been examined.

The investigation is focussed on the analysis of the difference of climatological global radiation products like PVGIS or Meteonorm, which include often 10 or 20 year means.

The following three questions have been looked at:

1. Trend of the time series of monthly data:
   Are there general trends or trends in sub periods visible?
   This question was tested with the total dataset between 1950 and 2009 and two periods between 1950 – 1985 and 1985 – 2009. Additionally the subsets 1970 – 85, 1990 – 2005 and 2000 – 2009 have been analyzed.
2. Trend of 10 and 20 years means:
   How much are means of time periods of the past different compared to more recent periods?
3. Dependence of the variability on the length of a measured period:
   How much is the standard deviation of a mean of a measurement series depending on its duration? Is this value site dependent?

The time series have been corrected for the seasonal effects. This has been done by adding the difference between the yearly means and the monthly means to each month. The results have been tested for each site separately and for groups of sites. The sites have been clustered to 10 regional groups (Table 2).

Table 2: Ten groups of stations used for analysis

Nr	Group	Stations
1	all	All stations (25 stations)
2	Europe	All European sites (14 stations; Weissfluhjoch excluded)
3	Northern Europe	Uccle, London, Aberporth, Eskdalemuir, Lerwick, Stockholm and Hamburg (7)
4	Germany / Austria	Hamburg, Braunschweig, Würzburg, Trier, Potsdam and Salzburg (6)
5	Switzerland	Davos, Weissfluhjoch and Locarno-Monti (3)
6	United Kingdom	London, Lerwick, Aberporth and Eskdalemuir (4)
7	Asia	Akita, Fukuoka, Kagoshima, Sapporo, Beijing, Ahmadabad, Madras and Poona (8)
8	Japan	Akita, Fukuoka, Kagoshima and Sapporo (4)
9	India	Ahmadabad, Madras and Poona (3)
10	Canada	Edmonton and Toronto (2)

Weissfluhjoch station has been excluded from European subset as this station has a very different behaviour compared to all other stations.

Linear trends have been calculated with help of a standard software. As measure of significance the two sided t-test probability has been used. A threshold of 5% has been set for significance.

For making the group means for the regions at least 90% of the data of all stations had to be available.

Additionally to the linear trends we tried to adopt sine waves to the time series. The idea about this investigation is that long term global radiation variations have more wavelike structures than linear ones. For this work we used smoothed time series with a smoothing length of 12 months (to level out seasonal effects). Before adapting the sine waves the linear trends over the whole period were corrected, if the trend was significant.

We adapted two additional waves: first waves with wave lengths over 9 years (max. 90 years) and in a second run wave lengths shorter than 12 years. The following model was used (1):

$$Gh_w = a_1 \cdot \sin\left(2 \cdot \pi \cdot (t - c_1) \big/ p_1\right) + a_2 \cdot \sin\left(2 \cdot \pi \cdot (t - c_2) \big/ p_2\right) + \overline{Gh} \qquad (1)$$

where Gh_w is the modelled global radiation (12 month mean), t the time in years, a1, c1, and p1 the factors for the long period and a2, c2, and p2 the factors for the short period.

The chose of the optimal sine waves has been done with a simple method: The parameters a, b and c have been varied in the range of possible values. The correlation factor was used to determine the optimal adoption.

As a measure of added quality by the sine model in comparison to the linear model the following method has been used: first the standard deviations of the difference between the linear model and the measured values and the standard deviation of the difference between the sine model and measured values are calculated. The enhancement induced by the sine model is calculated as the percentage of the lowering of the standard deviation.

5 Results

5.1 Trend of monthly means

For the whole period between 1950 and 2009 and all sites a negative and statistically significant trend of -1.6 W/m^2 per decades could be found. For most grouped sites no significant trend is visible. Nevertheless for Germany / Austria a slightly positive trend can be seen and for Switzerland, Asia, India and Canada a negative trend (Table 3).

Table 3: Result of linear trend analysis for the period 1950-2009.

Nr	Group	Number of sites (N)	Trend [W/m^2 10y]	R^2	P
1	all	429	-1.63	0.259	0.000
2	Europe	547	0.40	0.052	0.220
3	Northern Europe	478	0.30	0.038	0.406
4	Germany / Austria	534	1.23	0.119	0.006
5	Switzerland	679	-3.47	0.359	0.000
6	United Kingdom	518	-0.23	0.031	0.475
7	Asia	234	-2.28	0.343	0.000
8	Japan	516	-0.11	0.011	0.807
9	India	258	-5.05	0.522	0.000
10	Canada	595	-1.28	0.146	0.000

The large negative trend for Switzerland was mainly induced by the station Weissfluhjoch, but also without this site the trend is significant and negative (-1.0 W/m^2 per decade).

For the two sub periods 1950 – 1985 and 1985 – 2009 a significant trend could be found for most groups of stations (Tables 4 and 5).

For the first period 1950-1985 only negative trends were found. For all regions beside Northern Europe, UK and Germany/Austria this trends are significant. The overall trend is -4.7 W/m^2 per decade. Strongest gradients are found in Switzerland, Japan and India.

Table 4: Result of linear trend analysis for the period 1950-1985 (mostly 1960-1985)

Nr	Group	N	Trend [W/m^2 10y]	R^2	P
1	all	256	-4.70	0.412	0.000
2	Europe*	325	-1.95	0.149	0.007
3	Northern Europe	279	-0.22	0.015	0.801
4	Germany / Austria	326	-1.43	0.086	0.120
5	Switzerland	404	-7.69	0.465	0.000
6	United Kingdom	306	-1.27	0.095	0.097
7	Asia	141	-5.59	0.430	0.000
8	Japan	284	-6.43	0.345	0.000
9	India	164	-6.48	0.356	0.000
10	Canada	426	-1.88	0.168	0.001

* without Weissfluhjoch

For the second period 1985-2009 (including data for most sites up to 2005) all regions except India and Canada showed a positive trend. For all regions except Canada and UK the trend was significant. The strongest gradients were found in Japan (5.3 W/m^2 per decade) and Germany/Austria. The overall trend was 1.8 W/m^2 per decade. The only region, which was clearly different, is India with a significant negative trend of -5.4 W/m^2 per decade.

Table 5: Result of linear trend analysis for the period 1985-2009 (mostly 2005).

Nr	Group	N	Trend [W/m^2 10y]	R^2	P
1	all	213	1.66	0.149	0.069
2	Europe*	262	4.28	0.253	0.000
3	Northern Europe	228	2.94	0.181	0.006
4	Germany / Austria	255	4.88	0.223	0.000
5	Switzerland	323	3.07	0.162	0.003
6	United Kingdom	241	1.52	0.097	0.134
7	Asia	105	1.43	0.133	0.177
8	Japan	279	5.25	0.316	0.000
9	India	106	-5.44	0.331	0.001
10	Canada	217	-0.21	0.008	0.909

* without Weissfluhjoch

The individual sites do show a great variety of trends (Tab. 6). Nevertheless all sites show a negative trend for the period 1950 – 85. Additionally all European sites show a positive trend for the period 1985 – 2009.

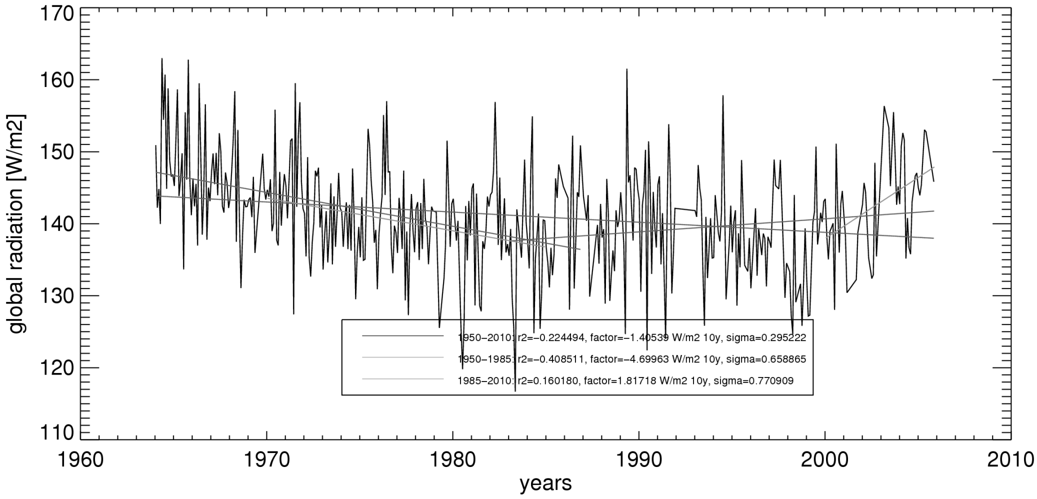

Figure 2: Linear trends for the average of all sites with significant linear trends of the analyzed periods.

Figure 3 shows seasonally corrected time series with smoothed values over 1 and 5 years. In this figure a gentle oscillation of the radiation values can be seen. Local maxima are visible around 1970 and 2003 (heat wave over Central and Western Europe).

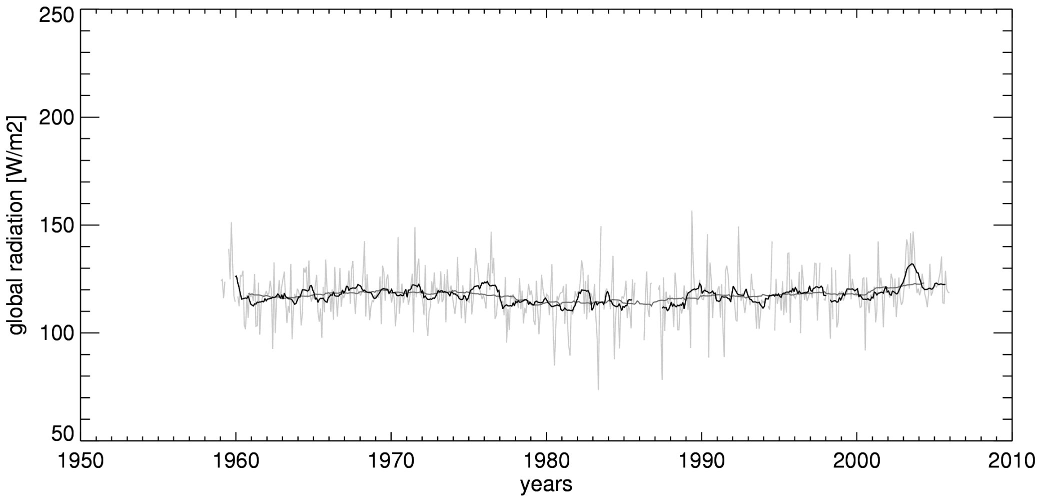

Figure 3: Seasonally corrected time series with smoothed values for 1 and 5 years for Europe.

This evaluation is consistent to the theory of global dimming and global brightening. Only for the UK where the trends are very small and for India and Beijing, where the trends are negative for all periods, the theory can't be backed statistically. As the changes in aerosol concentration based mainly on industrial processes (which is dependent on the production and air pollution control) are one of the main reasons

for brightening and dimming this conclusions are not astonishing. In India and China industry and power production based on coal still has a strong growth, whereas in Europe and Japan industry has lowered the output of aerosols after 1985. There are no big differences seen between Eastern and Western Germany, although mainly in Eastern Germany the industrial production and therefore the aerosol production has been lowered dramatically.
The negative trends after the year 2000 seen in Hinkelman et al. (2009) could be found in Akita and Poona only (Tab. 6). For the mean of all sites as well as for some European sites strong positive trends are seen. The time series of all single sites are shown in the Appendix.

Table 6: Result of linear trend analysis for the different periods.

Nr	Station	Trend [$W/m^2 10y$] 1950-2009	Trend [$W/m^2 10y$] 1950-85	Trend [$W/m^2 10y$] 1985-2009	Trend [$W/m^2 10y$] 1970-85	Trend [$W/m^2 10y$] 1990-2005	Trend [$W/m^2 10y$] 2000-2009
1	Braunschweig, DE	1.96	-	4.04	-	-	-
2	Hamburg, DE	-	-	5.32	-7.61	7.18	13.60
3	Salzburg, AT	1.79	-	5.94	-	6.27	-
4	Trier, DE	1.55	-	-	-	-	-
5	Uccle, BE	2.58	3.26	3.76	-	6.41	-
6	Würzburg, DE	-	-2.32	3.45	-7.02	-	-
7	Potsdam, DE	-	-3.22	5.80	-	-	-
8	London, UK	2.55	-	4.32	-	-	23.72
9	Aberporth, UK	-1.24	-3.66	-	-	-	-
10	Eskdalemuir, UK	-1.06	-	-	-	-	-
11	Lerwick, UK	-	-	-	-6.51	-	-
12	Stockholm, SW	-1.99	-3.10	4.96	-8.61	-	-
13	Locarno-Monti, CH	-	-4.54	6.85	-7.98	-	19.2
14	Davos, CH	-1.30	-4.34	5.45	-	14.70	-
15	Weissfluhjoch, CH	-8.45	-14.19	-3.10	-	-	-
16	Akita, JP	-	-5.43	-	-	-	-27.51
17	Fukuoka, JP	-	-7.91	5.73	33.82	9.97	-
18	Kagoshima, JP	-	-9.87	7.95	12.64	9.98	-
19	Sapporo, JP	-	-2.50	4.17	-	6.14	-
20	Beijing, CN	-7.94	-8.09	-	-15.83	-	-
21	Ahmadabad, IN	-8.11	-4.90	-12.61	-10.09	-7.28	-
22	Poona, IN	-4.94	-6.61	-	-	7.58	-22.15
23	Madras, IN	-4.58	-5.77	-4.49	-6.12	-6.99	-
24	Edmonton, CA	-1.33	-1.95	-	-	-	-
25	Toronto, CA	-11.2	-	-	-	-	-
All	All	-1.41	-4.70	1.82	-4.53	-	16.94

5.2 Trend of 10 and 20 year means

In this chapter the moving 10 and 20 year means have been compared to the values with an end time of 2005 (1986 – 2005 and 1996 – 2005). This shows how much climatologies of different time periods are different compared to most current ones (Tables 7 and 8). Due to missing values for Poona and Madras no 10 and 20 year means could be calculated.

Figure 4 shows the comparison of all sites. Periods with end time of 1990 and later show for many sites a consistent growth of 5-8%. Before 1990 the situation is much more diverse.

Five sites are quite different compared to all other: Weissfluhjoch, Beijing and Ahmadabad do show a very strong decline of more than 20%. Fukuoka and Akita show a strong decline followed by a strong rise for the periods ending between 1975 and 80.

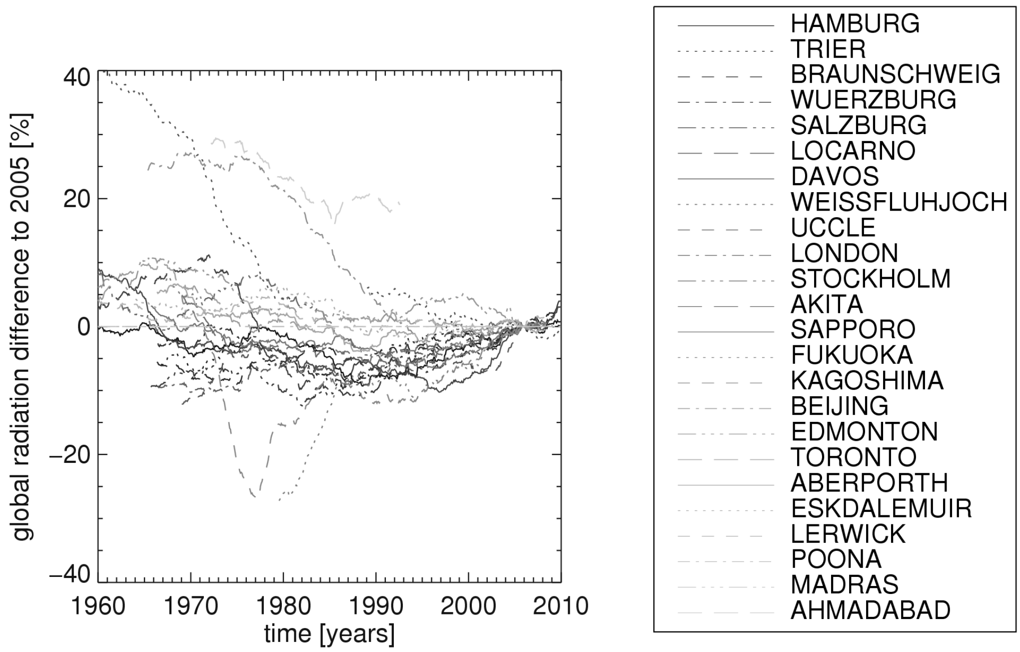

Figure 4: Variation of decadal means in % compared to 1996-2005. Time shows the end point of the 10 years period.

Looking at 20 year means, the differences are much smoother (Fig. 5). For many sites the growth between 1971-1990 and 1986-2005 is in the range of 3-4%. The situation before end time of 1990 is much more diverse than the situation afterwards.

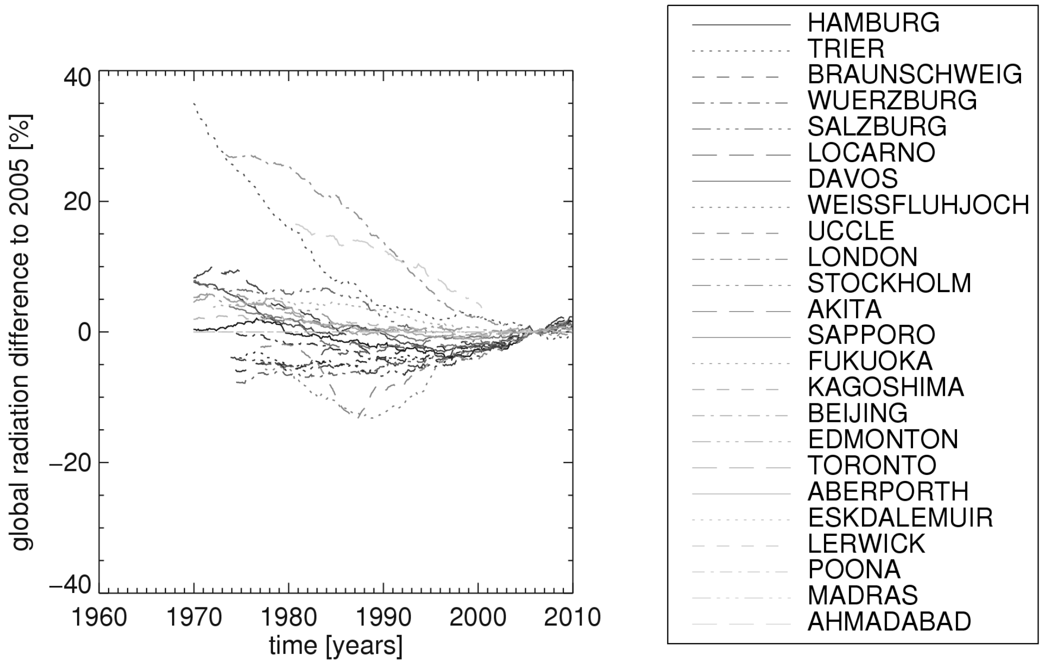

Figure 5: Variation of 2-decadal means in % compared to 1986-2005 for all sites. Time shows the end point of the 20 years period.

The analysis shows also that for most sites 20 years are quite stable and are within 5-10%. Nevertheless for some sites up to 20% of variations can happen only based on different time periods of the measurements.

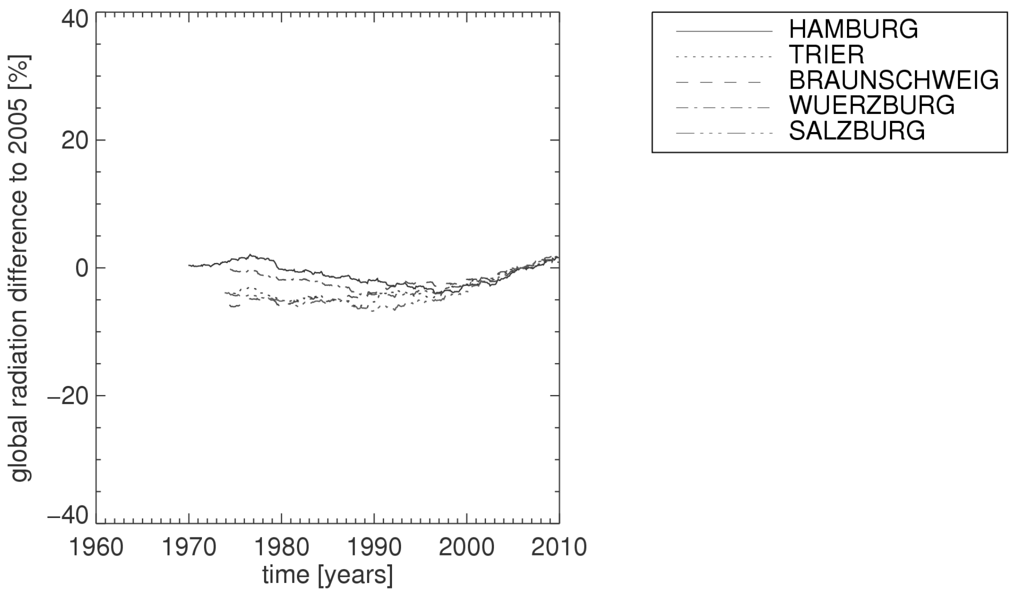

Figure 6: Variation of 2-decadal means in % compared to 1986-2005 for German sites. Time shows the end point of the 20 years period.

Trends of 2-decade means in Germany are very stable and are in the range of +/-5% (Fig. 6). The positive trend of the 20 year means are visible also after 2005.

Table 7: Difference of 10 year means relative to period 1996-2005.

Nr	Name	1971-80 [%]	1981-90 [%]	1991-2000 [%]
1	Braunschweig, DE	-4.83	-3.93	-1.48
2	Hamburg, DE	-1.99	-7.8	-2.63
3	Salzburg, AT	-10.71	-8.16	-4.04
4	Trier, DE	-5.26	-4.73	-1.11
5	Uccle, BE	-5.56	-4.62	-6.72
6	Würzburg, DE	-5.23	-6.45	-1.26
7	Potsdam	-6.18	-6.25	-0.23
8	London Weather Station, UK	-6.35	-6.15	-2.29
9	Aberporth, UK	1.04	-1.16	-0.76
10	Eskdalemuir, UK	3.66	-0.44	-0.78
11	Lerwick, UK	1.8	0.02	-0.01
12	Stockholm, SW	3.96	-5.51	-2.8
13	Locarno-Monti, CH	-7.87	-6.15	-3.1
14	Davos, CH	-4.96	-7.16	-7.17
15	Weissfluhjoch, CH	-	4.88	0.86
16	Akita, JP	-3.3	-4.39	-2.19
17	Fukuoka, JP	-25.97	-6.19	-5.97
18	Kagoshima, JP	-14.64	-10.96	-5.08
19	Sapporo, JP	-3.38	-4.33	-3.87
20	Beijing, CN	14.68	1.66	-0.82
21	Ahmadabad, IN	22.96	18.79	-
22	Poona, IN	-	-	-
23	Madras, IN	-	-	-
24	Edmonton, CA	2.86	1.73	3.39
25	Toronto, CA	0.68	0.89	-0.51

Table 8: Difference of 20 year means relative to period 1986-2005.

Nr	Name	1961-80 [%]	1971-90 [%]	1981-2000 [%]
1	Braunschweig, DE	-5.55	-3.43	-1.77
2	Hamburg, DE	-0.37	-2.24	-2.63
3	Salzburg, AT	-5.65	-6.04	-2.76
4	Trier, DE	-5.21	-4.14	-2.06
5	Uccle, BE	-5.4	-2.27	-2.84
6	Würzburg, DE	-1.92	-4	-2.04
7	Potsdam, DE	-3.17	-4.94	-1.96
8	London Weather Station, UK	-6.53	-4.76	-2.64
9	Aberporth, UK	2.04	0.43	-0.54
10	Eskdalemuir, UK	2.99	2.17	-0.12
11	Lerwick, UK	1.14	0.56	-0.36
12	Stockholm, SW	6.26	1.57	-1.83
13	Locarno-Monti, CH	3.43	-4.89	-2.5
14	Davos, CH	1.03	-1.21	-2.32
15	Weissfluhjoch, CH	15.2	3.55	1.91
16	Akita, JP	1.61	-2.06	-1.51
17	Fukuoka, JP	-7.26	-11.46	-1.71
18	Kagoshima, JP	-2.36	-8.15	-3.37
19	Sapporo, JP	1.65	-0.68	-0.92
20	Beijing, CN	17.7	9.05	1.3
21	Ahmadabad, IN	-	-	-
22	Poona, IN	-	-	-
23	Madras, IN	-	-	-
24	Edmonton, CA	3.43	0.05	0.31
25	Toronto, CA	2.39	0.34	-0.26

5.3 Dependence of variation with duration of measurements

Figure 7 shows the dependence of the standard deviation of the mean of a time series on the time period of the measurements for all individual sites.

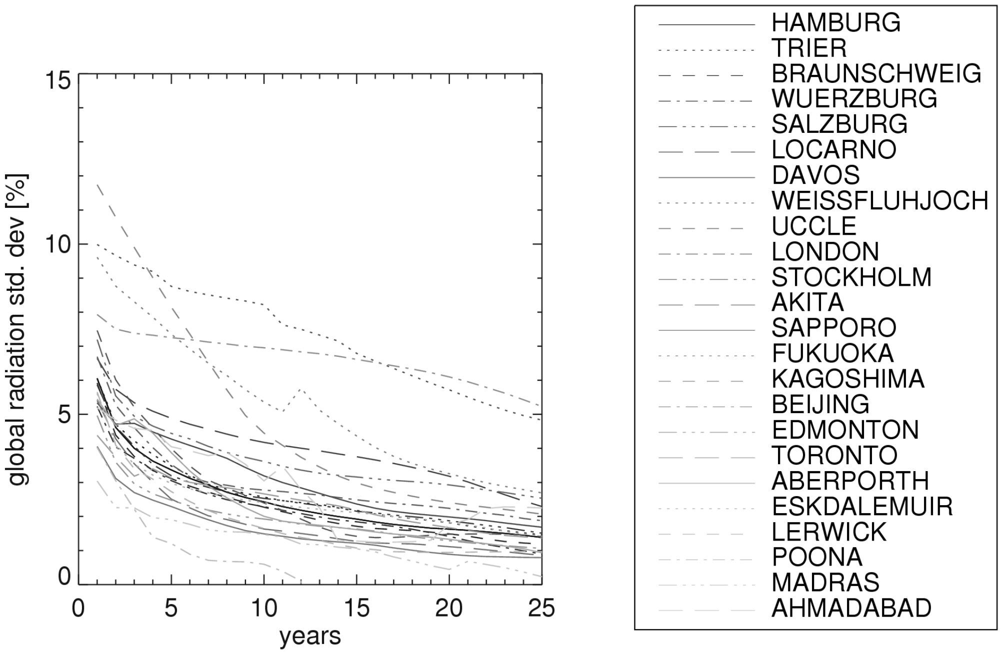

Figure 7: Variation of measurements depending on duration of measurement

The variation is quite different from site to site (Table 9). Most sites have a standard deviation of 5-7% for a 12 month means which goes down to 2-4% at 10 years and 2% at 20 years. The biggest decline happens in the first 5 years.

There are also sites with significantly different variations. At Weissfluhjoch and Beijing the standard deviations stays high (at 5% for 25 years), which is most presumably induced by the big (negative) trend seen at these stations (more than 15% reduction; see Tab. 7). At the two Japanese sites Kagoshima and Fukuoka the yearly variation starts at very high levels (10%) but sinks quite strongly to standard values. At Poona, Madras and Sapporo the variations already start at low levels (around 3-4%) for yearly values. Some very maritime sites like Lerwick or tropical sites like Poona have low levels of variation. Continental sites tend to have generally a higher level of variations.

As a general rule it can be said, that a climatology of global radiation should include at least 10 years. Only for regions with very high trends (more than 5 W/m^2 and decade) it makes sense to get as current data as possible.

German and Austrian sites all have a similar level of variations, which start at 6% for 1 year and are at 2.5% for 10 years and 1.5-2% at 20 years (Fig. 8).

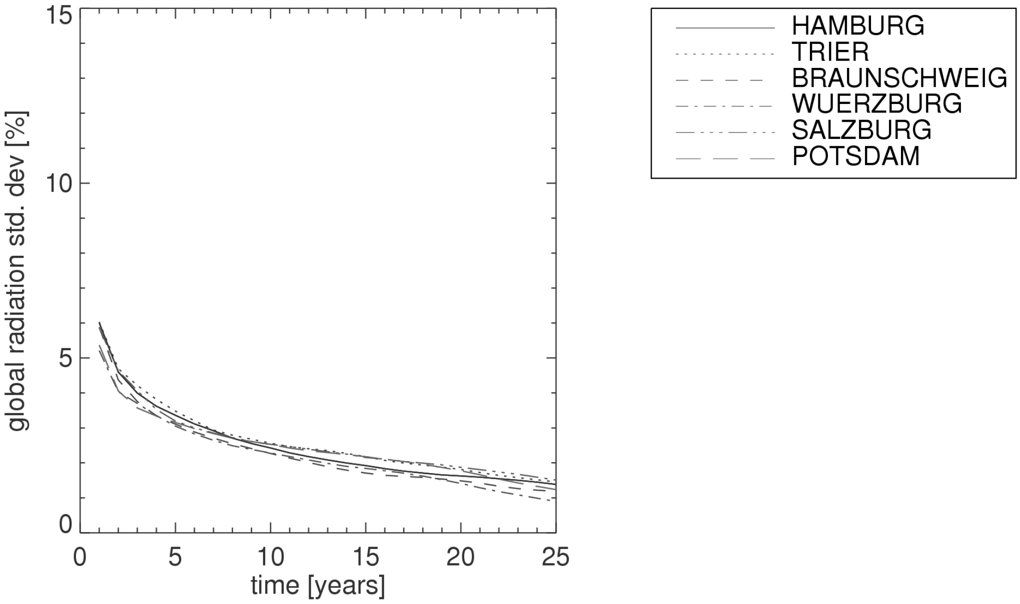

Figure 8: Variation of measurements depending on duration of measurement for Germany and Austria.

Table 9: Standard deviation in percent of means depending on duration of time period.

Nr	Name	1 year [%]	2 years [%]	3 years [%]	5 years [%]	10 years [%]	20 years [%]
1	Braunschweig, DE	5.84	4.36	3.74	3.09	2.26	1.48
2	Hamburg, DE	5.94	4.57	3.98	3.35	2.42	1.62
3	Salzburg, AT	5.86	4.64	4.07	3.20	2.53	1.87
4	Trier, DE	6.01	4.68	4.21	3.47	2.56	1.80
5	Uccle, BE	7.46	6.01	5.21	3.99	2.40	1.48
6	Würzburg, DE	5.23	4.03	3.70	3.04	2.28	1.41
7	Potsdam, DE	5.37	4.06	3.57	3.16	2.53	1.77
8	London Weather Station, UK	6.69	5.27	4.61	3.52	2.77	2.24
9	Aberporth, UK	5.48	4.69	4.91	3.90	2.02	1.33
10	Eskdalemuir, UK	5.63	4.13	3.54	2.97	2.40	1.81
11	Lerwick, UK	5.69	4.10	3.41	2.73	1.64	0.93
12	Stockholm, SW	7.19	5.54	4.94	4.44	3.61	2.93
13	Locarno-Monti, CH	6.64	5.73	5.34	4.88	4.18	3.18
14	Davos, CH	5.33	4.71	4.73	4.27	3.19	1.98
15	Weissfluhjoch, CH	9.99	9.66	9.39	8.76	8.22	5.72
16	Akita, JP	5.41	4.28	3.55	2.51	1.63	1.11
17	Fukuoka, JP	9.61	8.76	8.30	7.35	5.36	3.26
18	Kagoshima, JP	11.74	10.79	9.90	8.15	4.45	2.41
19	Sapporo, JP	4.05	3.12	2.70	2.29	1.49	0.89
20	Beijing, CN	7.94	7.51	7.39	7.26	6.96	6.11
21	Ahmadabad, IN	5.20	4.83	4.58	4.05	3.06	1.78
22	Poona, IN	4.03	3.02	2.19	1.22	0.63	-
23	Madras, IN	3.03	2.28	2.23	1.89	1.44	0.41
24	Edmonton, CA	4.96	3.59	2.96	2.48	1.92	1.29
25	Toronto, CA	4.38	3.75	3.18	3.13	2.66	1.67

5.4 Analysis of wave structures

We have been looking for wave structures in the time series, which have been smoothed over 12 months (to avoid seasonal waves).

First long waves with more than 10 years have been adapted to the series and then as an addition waves with lengths shorter than 20 years. Figure 9 shows the waves found for the mean of all sites and Figure 10 shows the waves found for Stockholm time series.

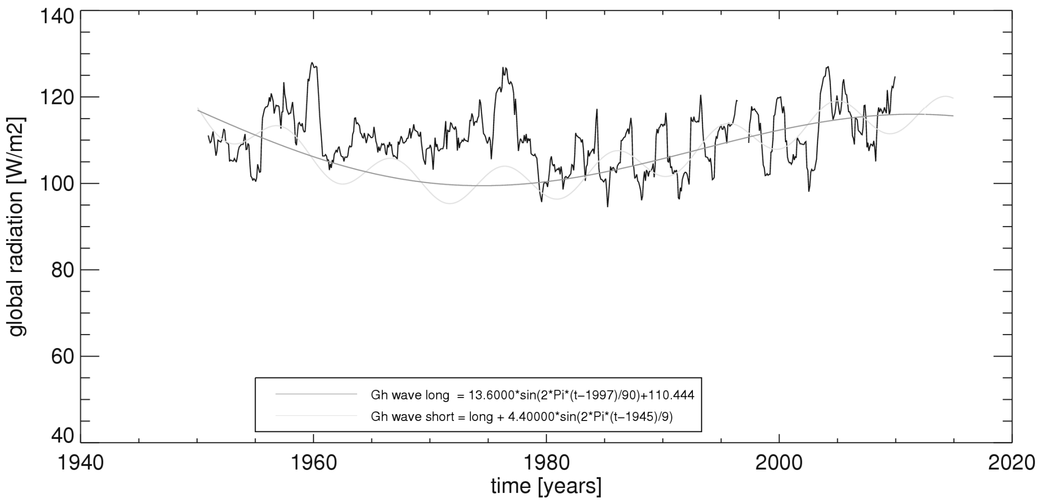

Figure 9: Waves found for the mean of all sites (12 month smoothed monthly means of global radiation).

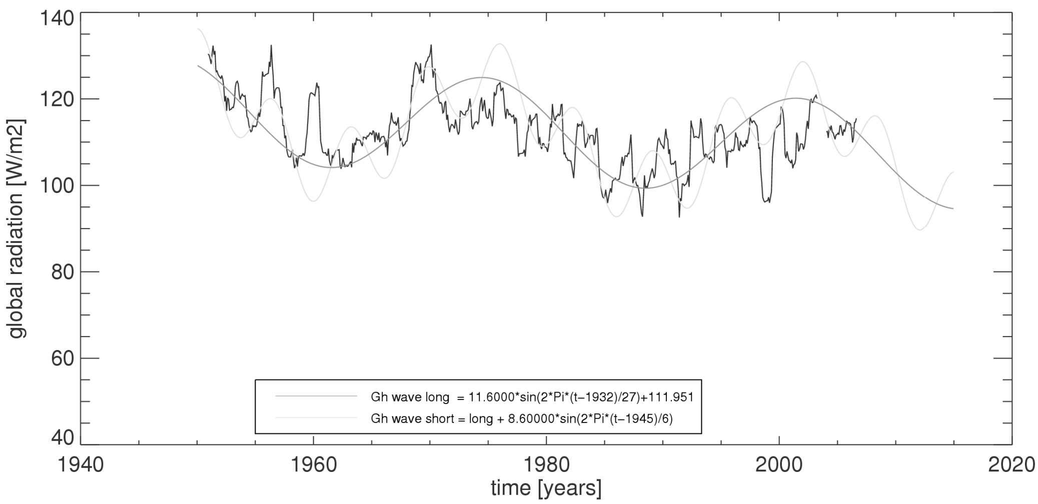

Figure 10: Waves found for Stockholm (12 month smoothed monthly means of global radiation).

For the mean of all sites wave lengths of 90 years (long period) and 9 years (short period) have been found. Table 10 shows the wave parameters for chosen regions and sites (with very long time series).

Table 10: Wave parameters for chosen regions and sites (Eq. 1).

Nr	Group	Long periods			Short periods		
		Amplitude [W/m^2]	Length [years]	Difference [years]	Amplitude [W/m^2]	Length [years]	Difference [years]
		a_1	p_1	c_1	a_2	p_2	c_2
1	all	13.6	90	1997	4.4	9	1945
2	Europe*	5.4	44	1947	3.0	9	1935
4	Germany / Austria	9.6	56	1953	4.8	9	1935
5	Switzerland	13.4	38	1982	6.8	10	1963
6	United Kingdom	8.2	90	1999	6.8	6	1957
7	Asia	9.6	53	1963	1.8	8	1956
8	Japan	3.6	90	1982	8.2	8	1948
10	Canada	13.4	10	1977	6.2	10	1952
11	Stockholm	11.6	27	1932	8.6	6	1945
12	Hamburg	5.4	44	1947	3.0	9	1935
13	Würzburg	9.0	34	1941	4.0	6	1943
14	Salzburg	7.4	52	1957	3.4	5	1938
15	Locarno	14.0	47	1996	3.0	11	1944
16	Akita	3.6	90	1982	8.2	8	1948

* without Weissfluhjoch

The waves found are very different from region to region and especially from site to site. For some sites the adoption does work very well, for some not. For most site the sine model (in combination with linear models) describe the reality better than the linear models. The use of sine models lowers the standard deviation of the differences between the modelled and measured values by 0 – 80% (mean value: 40%).

Long term wave lengths are often around 50 years and short time periods are mostly in the range of 6-9 years. The 11 years cycle of the sunspots is visible at Locarno, Switzerland and Canada.

The amplitude for long term variations is in the range of 10 W/m^2 whereas the short time cycle has an average amplitude of 5 W/m^2. Different behaviours have been found in Japan, UK and for the mean of all sites, where the time period goes up to 90 years (which shows, that long term variations are small). For Canada the long term and short cycle has an optimum at 10 years.

6 Conclusions

The distribution of the analyzed sites is concentrated very much to regions of central Europe and Eastern Asia and all sites are from the northern hemisphere. Due to this the no conclusions for the whole globe can be drawn.

For the mean of all sites the dimming for the period 1950 – 85 and the brightening for the period 1985 – 2009 is statistically significant. The negative trend during the dimming period is clearly stronger (approx. factor 2) than the positive trend during the brightening phase. The individual regions and groups show a great variety of different trends for the analyzed sub periods. The negative trend found in Hinkelman et al. for the period after 2000 could be found only at 2 stations out of the 24.

Similar to the trends of the monthly values also the trends of the 10 and 20 year means show a big dependence on the station. Also here the dimming and brightening phase is clearly visible. Some sites in India, Beijing and Weissfluhjoch (Swiss mountain top station) do show a big negative trend with a decline of more than 20% during the analyzed period.

It is also obvious, that aerosol concentration based on the industrial processes produced in the surrounding are not the single reason for the changes. There are no significant differences between Eastern and Western Germany visible, although mainly in Eastern Germany the industrial production has been lowered since 1989. The strong negative trends in Switzerland (mainly Weissfluhjoch) can't be explained only with aerosol changes, but must be also induced by changes in the cloud coverage.

The variation depending on the duration of measurement is also quite different from site to site. Most sites have a standard deviation of 5-7% for a 12 month means which goes down to 2-4% at 10 years and 2% at 20 years. The biggest decline happens in the first 5 years.

As a general rule it can be stated, that a climatology of global radiation should include at least 10 years. Only for regions with very high trends (more than 5 W/m^2 and decade) it makes sense to get as current data as possible.

The use of 20 year means – used e.g. in Meteonorm - lowers the variability induced by the period of the measurements compared to 10 year means by approx. 50%. Due to this fact, those climatologies can be updated less frequently.

A short analysis about sine wave structures of the time series showed, that many global radiation time series show clear wave signals and are better described in form of sine waves as with linear models.

7 References

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Wild M., 2009, Global dimming and brightening: A review, *Journal of Geophysical Research*, Vol. 114, D00D16, doi:10.1029/2008JD011470, 2009

8 Annex

Time series of each 24 sites are shown in the following Figures 9 – 15.

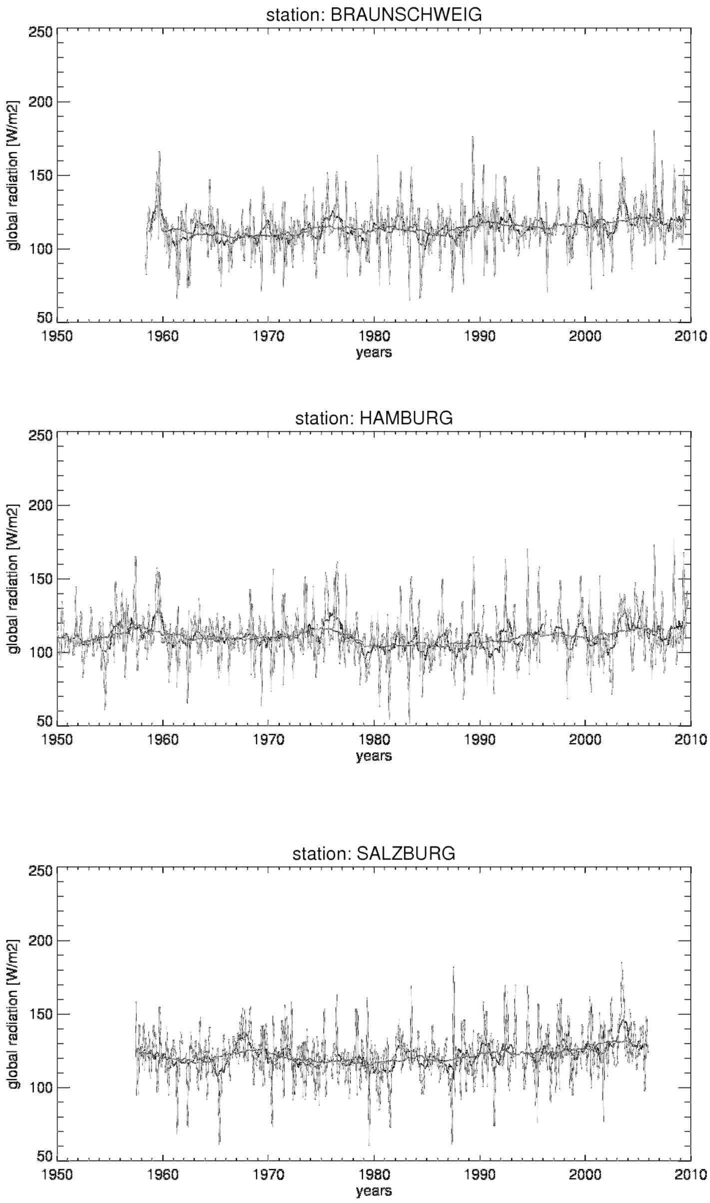

Figure 11: Seasonally corrected time series with smoothed values for 1 and 5 years.

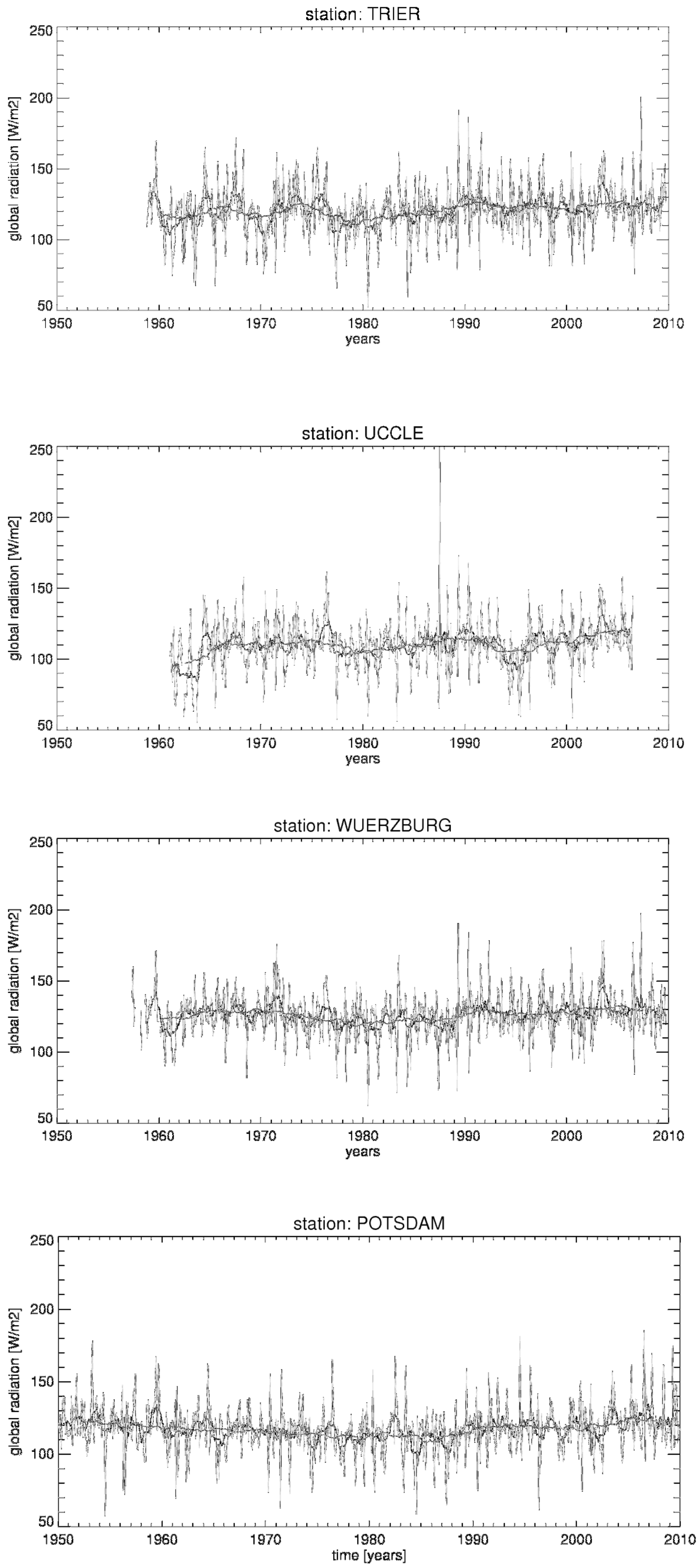

Figure 12: Seasonally corrected time series with smoothed values for 1 and 5 years.

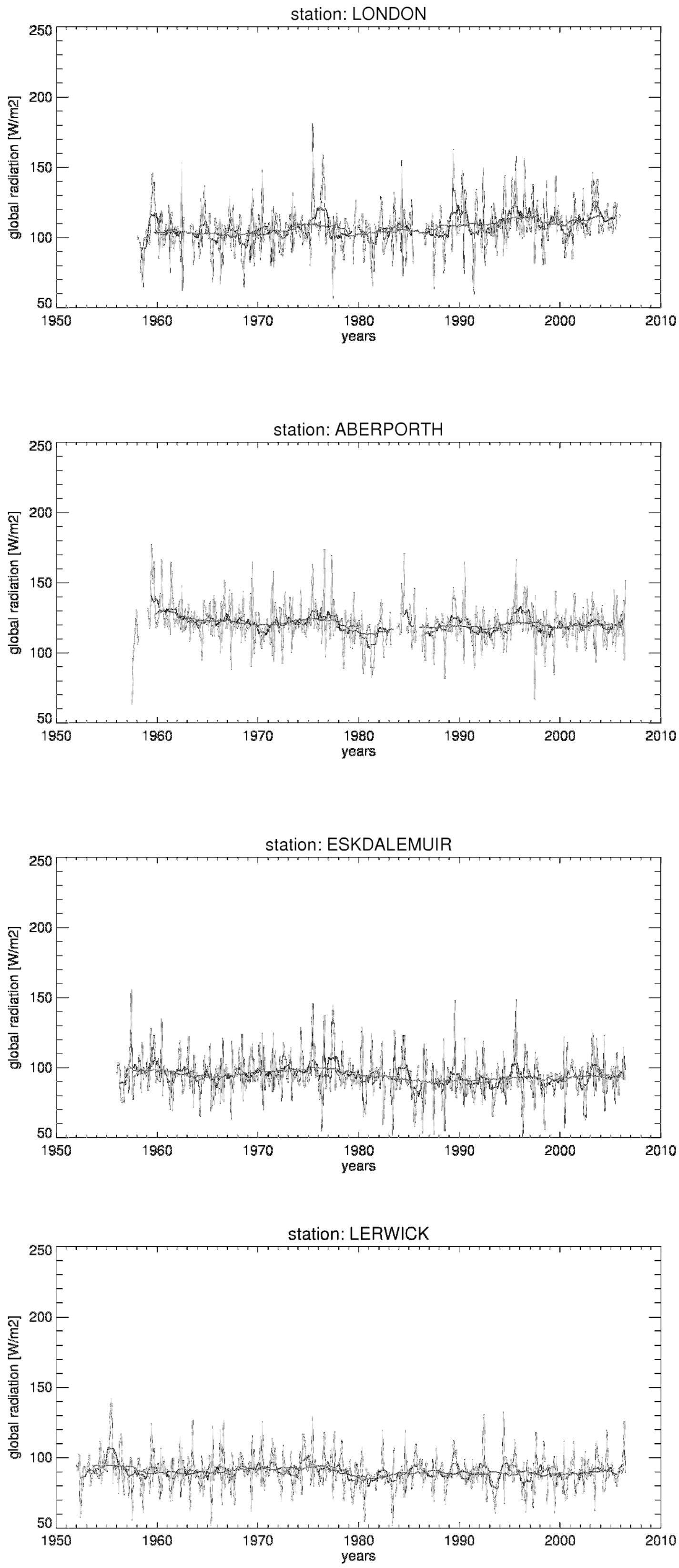

Figure 13: Seasonally corrected time series with smoothed values for 1 and 5 years.

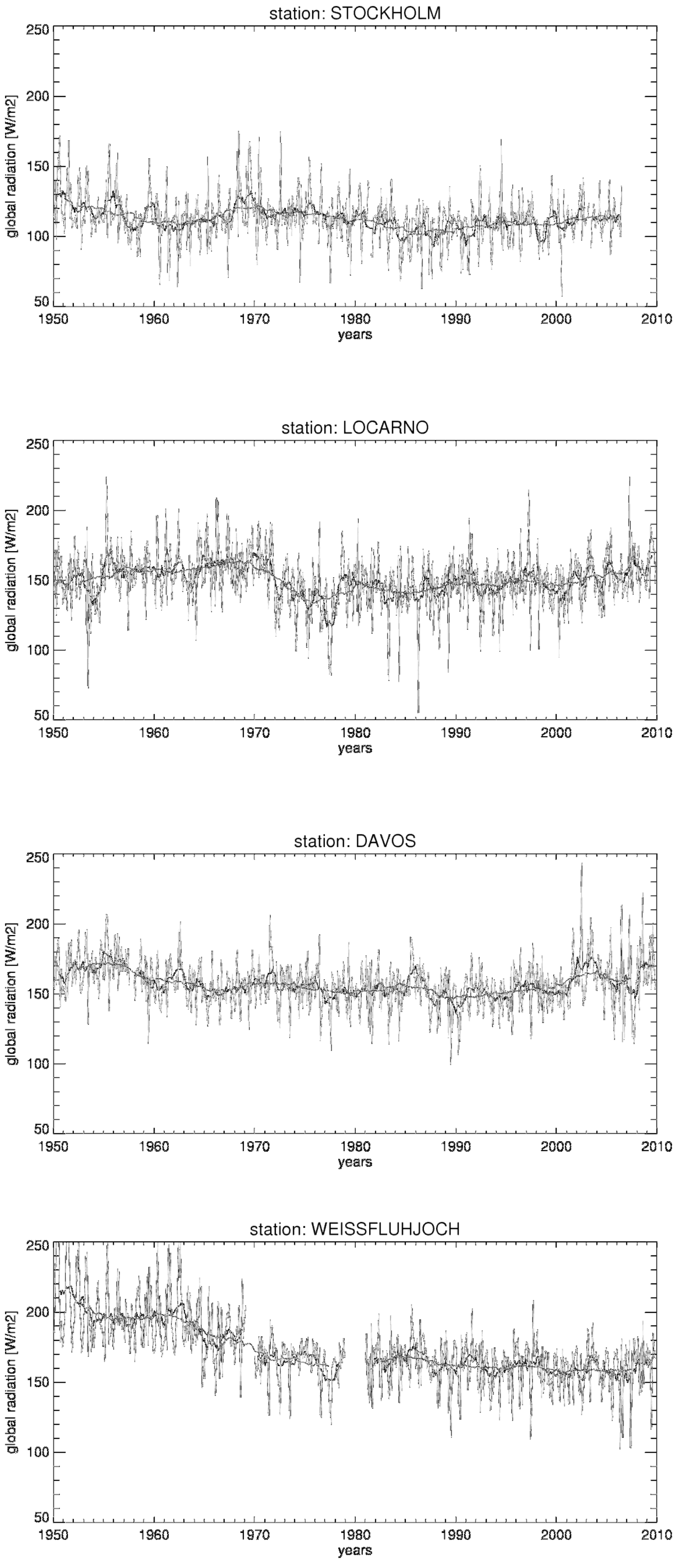

Figure 14: Seasonally corrected time series with smoothed values for 1 and 5 years.

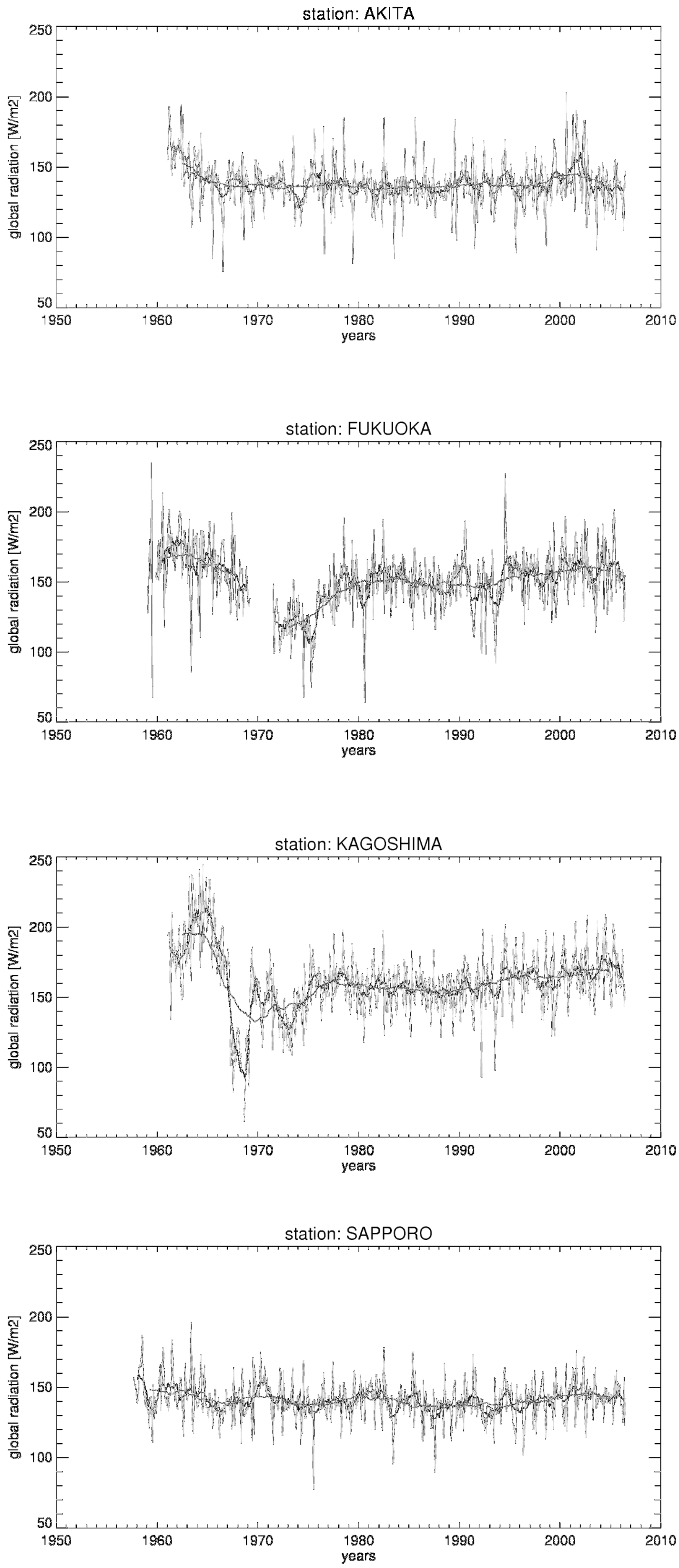

Figure 15: Seasonally corrected time series with smoothed values for 1 and 5 years.

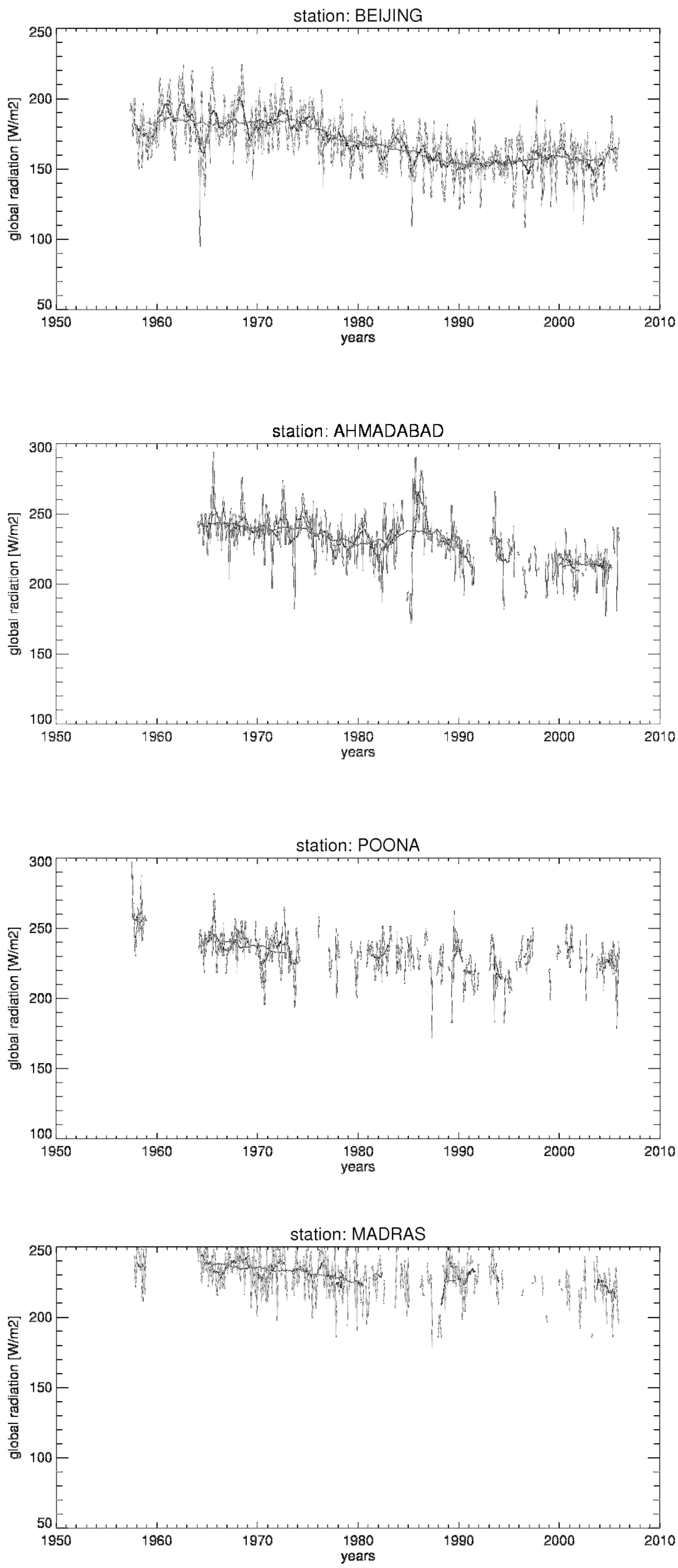

Figure 16: Seasonally corrected time series with smoothed values for 1 and 5 years.

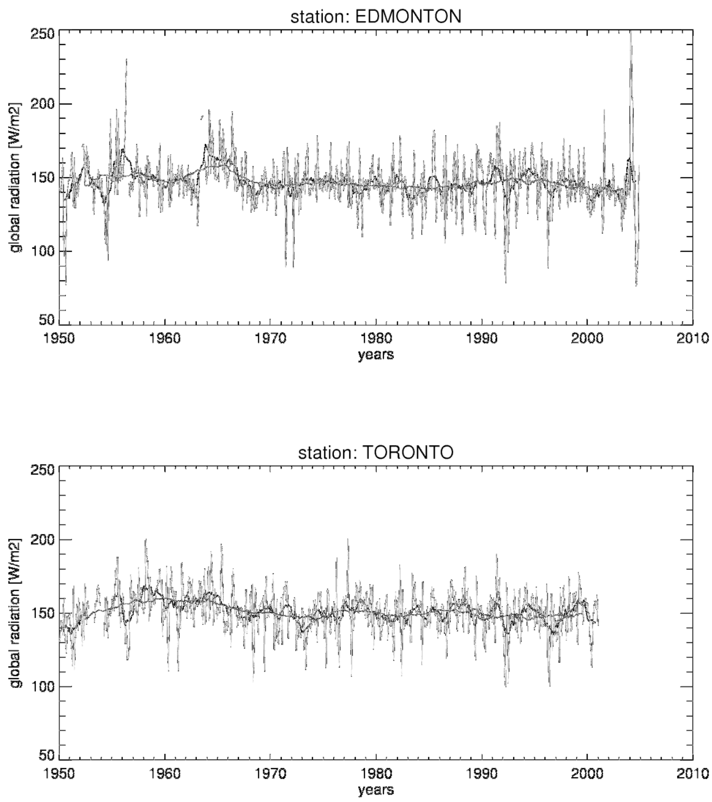

Figure 17: Seasonally corrected time series with smoothed values for 1 and 5 years.