Long-term total solar radiation variability at the Polish Baltic coast in Kołobrzeg within the period 1964-2013

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Abstract. This study is based on a 50-year data series (1964-2013) of total solar radiation (G) from the Kołobrzeg – station that is located on the Polish Baltic Sea coast and is characterised by a very high level of air quality. To find and remove gross errors, quality control checking procedures were applied in this study. Additionally, the homogeneity of the G series in this study has been tested on a monthly basis by using of the Standard Normal Homogeneity Test for single shifts.

We found a statistically non-significant decrease in G during the period from 1964 to 2013. The decrease in the 5-year mean total solar radiation is evident from the beginning of the 1980s, with the minimum mean value occurring in the second half of the 1990s, while G slightly increased from the early 2000s. The analysis of seasonal G patterns shows that total solar radiation in summer is the most similar to the annual pattern and only the summer series trend shows a statistically significant decrease in G. We have also found two noticeable tendencies in monthly anomalies of G over the studied decades; they are negative trends in May and August. The shape of the decadal daily G histogram remained unchanged during the analysed decades.

Key words: total solar radiation, Kołobrzeg, dimming, brightening

1. Introduction

The sum of the direct and diffuse radiation incident on the ground surface is variously called global solar radiation (Bogdańska, Podogrocki 2000; Podstawczyńska 2010), surface solar radiation (Sanchez-Lorenzo et al. 2013), total solar radiation (Matuszko 2014), surface insolation (Hinkelman et al. 2009) or solar/shortwave irradiance (Gilgen et al. 2009). The "solar radiation" nomenclature is discussed by Wild (2009) and Matuszko (2011 in Polish). In our study we will refer to it as total solar radiation (G).

Variability in the amount of total solar radiation that reaches the Earth's surface is caused by external factors, such as changes in the Earth's orbital parameters (these cause changes over the geological time scale), solar activity (via changes of the solar constant), atmospheric water vapour, aerosols and cloudiness (these cause changes over shorter time periods) (Wild 2009).

A decline in total solar radiation ("dimming") has been observed during the period from the 1950s to the 1980s. Since the 1980s, stabilisation and increases ("brightening") in G values have been detected in many places around the World, especially in industrialised regions (Sanchez-Lorenzo 2013). The causes of both the dimming and brightening phenomenon are very complex and studies conducted over the world show that fluctuations in total solar radiation are induced by changes in cloudiness (Russak 1990; Liepert 2002; Stjern et al. 2009; Chiacchio et al. 2010), cloud optical thickness (Liepert 1997, 2002) and atmosphere transparency (Uscka-Kowalkowska 2013). In addition, changes in aerosol emissions have also been identified as a cause of changes in the temporal dynamics of G (Stanhill et al. 1992, 2001).

The aim of this study was to analyse the local total solar radiation variability at Kołobrzeg station, which is located on the Polish Baltic Sea coast and is characterised by a very high level of air quality.

2. Material and methods

The basis of the research was a long-term data series of daily sums of total solar radiation (*G*) from Kołobrzeg station, collected over the period from 1964 to 2013.

Kołobrzeg is a city of about 50 000 inhabitants, situated in the Pomerania region, on the coast of the Baltic Sea, in a SPA area covered by legal regulations ensuring environmental protection. In the nearest vicinity there are no large facilities that cause air pollution, except for small and medium-sized local boiler plants and home furnaces that burn solid fuel (mainly coal-fired). Air quality in the area is relatively good (WIOŚ 2014), mainly thanks to its location away from large industrial centres and the strong mixing of air due to the vicinity of a large water body – the Baltic Sea. Sulphur dioxide and nitrogen dioxide are the main air pollutants in Pomerania and their concentration is smaller than in the interior and the south of Poland (Kicińska 2001a, b).

The analysis was conducted on daily total solar radiation data obtained from the World Radiation Data Centre WRDC. The daily sums of *G* are expressed in $J cm^{-2}$. Monthly, seasonal and annual values of total solar radiation were calculated as the sums of diurnal values and expressed in $MJ m^{-2}$. The analysed WRDC data is a product of the actinometrical network of the Polish Institute of Meteorology and Water Management (IMGW). The initial data quality control is performed within the IMGW (Chwieduk, Bogdańska 2001) and the second step of this analysis is realised in the WRDC (https://www.wmo.int/pages/prog/arep/gaw/solar-radiation.html). However, additional quality control checks have also been applied in this study. These checks were performed on a daily data set in order to find and remove gross errors (Aguilar et al. 2003). The homogeneity of the *G* series in this study has been tested on a monthly basis by using the SNHT (Standard Normal Homogeneity Test) for single shifts (Alexandersson, Moberg 1997; Sanchez-Lorenzo 2013), and implemented using the AnClim software (Štěpánek 2008).

Total solar radiation at Kołobrzeg station is measured using the CM6B pyranometer by Kipp&Zonen (http://wrdc.mgo.rssi.ru/). More details about sensors used in the Polish actinometrical network is available in Bogdańska et al. (2002). For the analysis of G values in seasons, a 13-year Gaussian low-pass filter was applied to indicate periodical trends (Sanchez-Lorenzo 2013).

3. Results and discussion
3.1. Multiannual total solar radiation variability

The annual sums of total solar radiation in Kołobrzeg during the period from 1964 to 2013 ranged from $3 481 MJ m^{-2}$ (1966) to $4 190 MJ m^{-2}$ (1968) and the mean value for the whole analysed period was $3 841 MJ m^{-2}$. The values obtained are higher than those reported by Bogdańska and Podogrocki (2000) for the period from 1961 to 1995 in Kołobrzeg, where minimum, maximum and mean values were $3 428 MJ m^{-2}$, $4 138 MJ m^{-2}$ and $3 829 MJ m^{-2}$, respectively.

Analysis of total solar radiation trends indicates a statistically non-significant decrease in Kołobrzeg ($-2.9 MJ m^{-2}$ per year). The decrease in total solar radiation is evident from the beginning of the 1980s, with the minimum 5-year mean *G* value ($3 731 MJ m^{-2}$) occurring in the second half of the 1990s (Fig. 1). The biggest negative trend we have found was in the 1968-1987 period ($20.6 MJ m^{-2}$ per year) and it corresponds with results obtained for Kołobrzeg by Russak (1990). Total solar radiation studies conducted in Poland by other authors indicate varied trends. For example, an increase in total solar radiation in Wrocław within the years 1961-2012 (Bryś 2013) and a decrease in *G* in Krakow during the period from 1884 to 2010 (Matuszko 2014). From the early 2000s, *G* values in Kołobrzeg slightly increased.
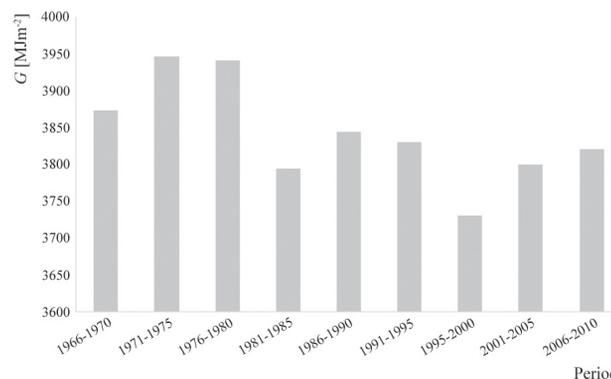

Fig. 1. The 5-year mean of total solar radiation sum (*G*) at Kołobrzeg station within the period 1964-2013 [$MJ m^{-2}$]

The year-to-year annual sums of *G* varied within the range of 10%. The highest increase in annual *G* values was recorded between 1967 and 1968 ($+ 432 MJ m^{-2}$), while the largest decrease was found between 1982 and 1983 ($-391 MJ m^{-2}$).

3.2. Seasonal analysis

The analysis of seasonal *G* patterns (Fig. 2) shows that the dynamics of *G* in summer is most similar to the annual pattern. The correlation coefficient between mean annual and seasonal series ranges between 0.05 in winter to 0.74 in summer.

Regarding linear trends for seasons, only the summer series shows a statistically significant decrease in *G* dur-
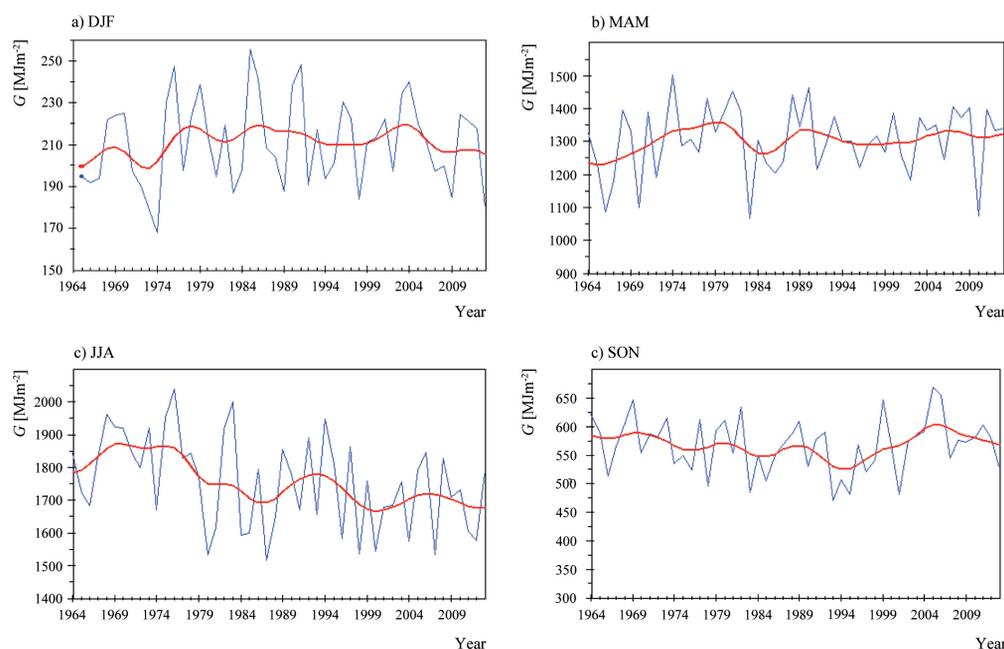
Fig. 2. Seasonal total solar radiation runs (blue line) filtered with 13-year Gaussian low-pass filter (red line) for the 1964-2013 period in Kołobrzeg

ing the 1964-2013 period (3.7 MJ m^{-2} per year), while during the other seasons the rates of change were fairly small (max 0.8 MJm^{-2} per year) and statistically non-significant.

3.3. Annual course of total solar radiation

The analysis of monthly values of total solar radiation is very useful for long-term studies of mass and energy exchange between ecosystems and the atmosphere (Baldocchi 2000). For this reason the next step of the study consisted of analysing the variation and trends in mean monthly G values in the years from 1964 to 2013 (Fig. 3, Table 1).

The greatest mean monthly G values during each year were found in June (19 cases), May (18 cases) and July (13 cases), while the highest mean monthly value in the whole period 1964-2013 was found in June (628.0 MJ m^{-2}).

The G values in June contributed the most to annual G sums in the decades 1971-1980 (16.6%) and 2001-2010 (16.5%, Table 1). The two decades 1981-1990 and 1991-2000 were dimmed and the contribution of June G values during these periods was reduced. This resulted in the
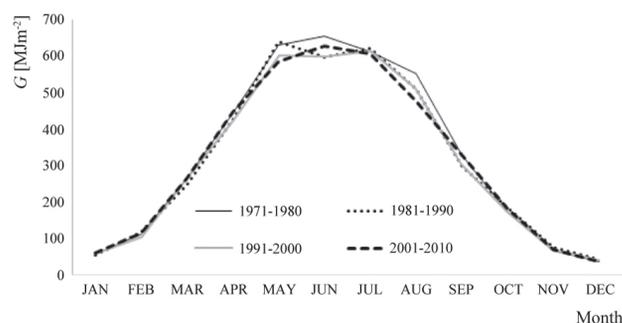

Fig. 3. The annual runs of G in Kołobrzeg – binned in decades

dominance of July and May G values during these periods (Fig. 3, Table 1). The decrease in the contribution of August G values to the annual sum is persistent during the whole study period.

The relatively high contribution of total solar radiation during May to the annual sums of G can be explained by the frequent presence of Arctic air masses over Poland during this month, when the enhanced clearness of the air during these events causes an increase in the amount of direct solar radiation (the prevailing part of total solar radiation) that reaches the Earth's surface (Bryś 2013).

The large contribution of summer monthly values to the annual sums (Table 1) and their variability (Fig. 3) indicates that the warmer part of the year is crucial for annual G values.

Emissions of air pollutants in Poland are higher during the cooler part of the year (Bokwa 2008; Kleniewska, Rozbicka 2008; Majewski et al. 2011; Rozbicka et al. 2014; Żyromski et al. 2014) mainly because of heating needs, however these loads have been reduced since 1990 (Smith et al. 2011) due to the conversion of industrial activity. The decadal anomalies in monthly G value trends over the cooler months do not reflect this fact (Fig. 4) as relative changes in G during the studied periods show the same range over the whole year (Fig. 5). There are only two noticeable tendencies in monthly G over the studied decades. These are negative trends in May and August. The August depletion corresponds with the summer negative trend (Fig. 1c). The negative tendency in May appears to have less impact on the trend observed during the spring (Fig. 1b). Both negative trends correspond with the decreasing

Table 1. The mean monthly G sums [MJm^{-2}] and its contribution in annual sums [in brackets, %] in Kołobrzeg

Month	Period				
	1971-1980	1981-1990	1991-2000	2001-2010	1964-2013
January	57.3 (1.5)	53.7 (1.4)	60.9 (1.6)	60.3 (1.6)	57.4 (1.5)
February	113.7 (2.9)	117.6 (3.1)	106.5 (2.8)	114.6 (3.0)	113.8 (3.0)
March	267.1 (6.8)	247. 5 (6.5)	268.3 (7.1)	266.3 (7.0)	264. 8 (6.9)
April	444.3 (11.3)	426.8 (11.2)	424.2 (11.2)	446.1 (11.7)	429.4 (11.2)
May	631.6 (16.0)	640.3 (16.8)	604.3 (16.0)	587.4 (15.4)	611.1 (15.9)
June	654.8 (16.6)	597.6 (15.6)	599.4 (15.9)	627.9 (16.5)	628.5 (16.4)
July	613.0 (15.5)	622.8 (16.3)	614.4 (16.3)	628.0 (16.5)	611.0 (15.9)
August	553.5 (14.0)	512.2 (13.4)	512.8 (13.6)	478.9 (12.6)	516.5 (13.4)
September	330.0 (8.4)	298.2 (7.8)	303.8 (8.0)	330.6 (8.7)	319.0 (8.3)
October	173.8 (4.4)	184.1 (4.8)	174. 9 (4.6)	182.4 (4.8)	178.9 (4.7)
November	66.7 (1.7)	75.0 (2.0)	68.3 (1.8)	69.9 (1.8)	69.8 (1.8)
December	37.6 (1.0)	43.6 (1.1)	42.9 (1.1)	38.1 (1.0)	40.3 (1.0)

role of May and August in annual sums of G (Table 1). The lack of clear tendencies in Kołobrzeg in the rest of the months suggests that the source of monthly G variability was not related to the emission of air pollutants. Since Kołobrzeg station is located far away from significant sources of industrial pollution, it is a site that is ideal for studying the influence of other environmental factors on monthly variability in G. Factors which influence decreasing solar radiation, according to different authors, might be as follows: an increase in the amount of low clouds and atmospheric transparency coefficient decrease (Russak (1990) or changes in the cloud type (Liepert 1997).

3.4. Daily sum of total solar radiation

The daily amounts of total solar radiation vary strongly with time and this is mainly determined by meteorological conditions (Bogdańska, Podogrocki 2000). Daily G values lower than 10 MJm^{-2} were the most frequently observed values (55.8%) and the contribution of this value class increased from 54.7% in the 1971-1980 decade to 56.5% in the 1991-2000 decade. Simultaneously, the contribution

of G values in the range 10.1-20.0 MJm^{-2} increased from 25.3% to 26.9% (Fig. 6). The observed daily G values higher than 30 MJm^{-2} decreased from 1.9% (the 1970s) to 0.05% (the 2000s). The shape of the decadal daily G histogram remained unchanged during the analysed decades. Such stability was not found in the Warsaw agglomeration (Kleniewska, Chojnicki 2016), where the distribution of daily sums of G has changed since 1980, and the frequency of values above 20,0 MJm^{-2} have increased and values below 5,0 MJm^{-2} have decreased.

4. Concluding remarks

A statistically non-significant decrease in G (-2.9 MJm^{-2} per year) was found in Kołobrzeg for the period from 1964 to 2013. However, the largest, statistically significant, negative trend (20.6 MJm^{-2} per year) was observed in the 1968-1987 period. A decrease in the 5-year total solar radiation from the beginning of the 1980s is evident. The minimum 5-year total solar radiation value occurred in the second half of the 1990s (3731 MJm^{-2}), while this value slightly increased from the early 2000s.
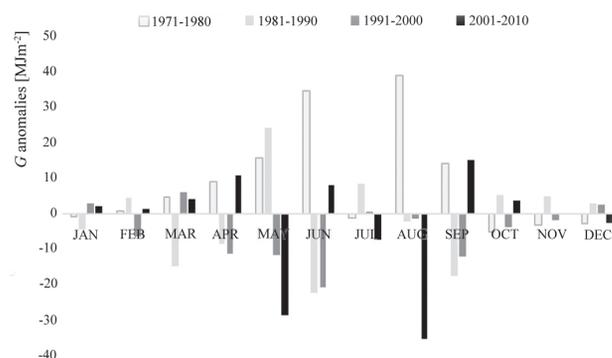

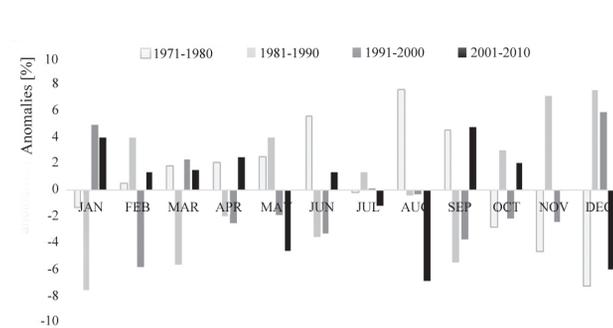Fig. 4. Absolute monthly solar radiation anomalies from the 1971-2010 mean [MJm^{-2}] – binned in decades

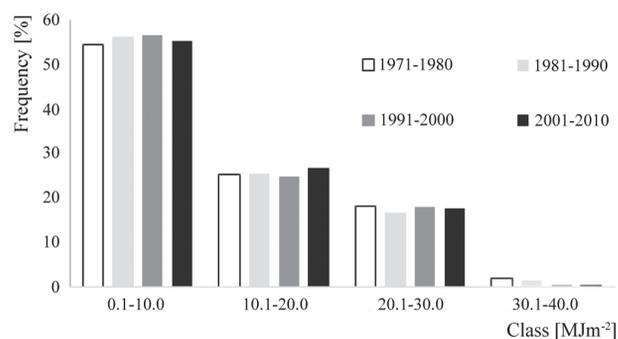Fig. 5. Total monthly solar radiation relative anomalies from the 1971-2010 mean [MJm^{-2}] – binned in decades

Fig. 6. The histogram of daily *G* values [MJm⁻²] for Kołobrzeg – binned in decades

The analysis of seasonal *G* patterns showed that the dynamics of *G* in summer is the most similar to the annual pattern ($R = 0.74$) and only the summer series trend shows a statistically significant decrease (3.7 MJ m⁻² per year). This corresponds with the negative trend observed within the studied period. There are only two noticeable tendencies in monthly anomalies of *G* over the studied decades and they are negative trends in May and August. The rest of the months in the analysed decades do not show clear tendencies.

The daily values of *G* have not changed substantially during the analysed decades. The most frequently observed values of daily *G* lower than 10 MJ m⁻² increased between the 1970s and 2000s from 54.7% to 56.5%, respectively. Simultaneously, the contribution of *G* values higher than 30 MJ m⁻² decreased between the 1970s to the 2000s from 1.9% to 0.05%, respectively.

Analysis of the monthly and daily *G* values during the studied decades show that the Kołobrzeg station is largely unaffected by the impact of industrial emissions and it is expected that the long-term trends observed at this station are the result of regional and/or global changes observed in the atmosphere.

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