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Solar radiation variability at Koniczynka near Toruń (Central Poland) in the years 2003–2016

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Abstract. The paper presents the variability of global solar radiation (K↓) in the agriculture area (Koniczynka near Toruń) in the years 2003–2016. The variability of K↓ has been analysed with reference to atmospheric circulation. The mean yearly sum of K↓ in the analysed period was 3,816.0 MJ·m^{-2}. In an annual course the highest mean values of K↓ occurred in June (608.3 MJ·m^{-2}) and the smallest in December (69.0 MJ·m^{-2}). The diurnal course of K↓ was symmetrical with respect to the solar noon. Only 44.7% of the solar energy on the top of atmosphere reaches the ground. The highest transmittance occurred in spring and summer, and the lowest in December. The observations revealed an increase in the amount of K↓ (trend 13.6 MJ·m^{-2}·year^{1}) and its considerable day-to-day and year-to-year variability. Its increase has been attributed to reduced emissions of aerosols in Poland and Europe (global brightening). The changes of K↓ depend on atmospheric circulation (cyclonic and anticyclonic situations), cloudiness and the optical characteristics of incoming air masses.

Key words:
global solar radiation,
clearness index,
global brightening,
atmospheric circulation,
Koniczynka,
Integrated Monitoring of Environment

Introduction

The radiation the Sun emits in the form of electromagnetic waves reaches the atmospheric boundary layer of our planet. Its irradiance is defined by the solar constant of 1,367 W·m^{-2} (Iqbal 1983). In the atmosphere, solar radiation is partially absorbed and partially reflected by atmospheric gases, clouds and aerosols. Solar energy reaches the Earth's surface as direct solar radiation (straight from the solar disk) and as diffuse radiation, both of them making up what is known as global solar radiation (K↓). This occurs during the day and its flux density is expressed in Wm^{-2}, whereas the amount of energy it brings is measured in J·m^{-2} (Niedźwiedź 2003).

The amount of incoming solar radiation, K↓, reaching the Earth's surface depends on the elevation of the Sun relative to the horizon, i.e. the solar elevation angle. The angle changes as the day progresses (from sunrise through the culmination to sunset) and also during the year with the variable declination of the Sun. When the position of the Sun over the horizon changes, the path of sun rays in the atmosphere changes, and so does the optical atmospheric mass the rays have to penetrate. Another major astronomical factor which affects K↓ is the length of day, which also changes regularly throughout the year. The solar radiation which passes through the atmosphere may be absorbed or dispersed by clouds, gases and aerosols. The gases and other air pollutants originate from natural processes or human activity. The amount of incoming solar radiation at a specific area may be limited by terrain obstacles, such as hills, trees, buildings, etc.

In Poland, regular actinometric measurements were initiated by Gorczyński in Warsaw in 1900 and later undertaken in other places as well. A detailed inventory of the history of Polish actinometric observations was provided by Uscka-Kowalkowska in an article from 2010. Long-term actinometric observations have been carried out in Kraków (Hess et al. 1980) and its suburban zone (Bokwa and Matuszyk 2007), in Wrocław (Dubicka 1994; Bryś and Bryś 2007; Bryś 2013) and in Łódź (Podstawczyńska 2007; Fortuniak 2010). In Toruń, transmittance of solar radiation through the atmosphere has been studied by Wójcik (1996), Uscka (2004), Kejna et al. (2014a, b), Kejna and Uscka-Kowalkowska (2018) in the suburbs of Toruń.

Spatial analyses of incoming solar radiation in Poland demonstrate that it is not consistent with latitude. The greatest annual sums of K↓ occur in the north (on the Baltic coast), in central Poland, in the south east and on mountain tops (>3,800 MJ·m^{-2}) according to, for example: Kozłowska-Szczęsna (1973), Podogrocki (1978), Miara et al. (1987), Bogdańska and Podogrocki (2000) and Lorenc (2005). This is an effect of the changeable length of day, the absolute height (reducing the optical mass of the atmosphere), cloudiness and air pollution.

The amount of K↓ varies each year; there are long-term trends connected with climate changes and emission of pollution to the atmosphere. Globally, in the years 1950–1980 the amount of solar radiation reaching the Earth's surface was seen to fall. This so-called 'global dimming' was interpreted as a result of increased anthropogenic pollution of the atmosphere. In recent years the trend has reversed and a 'global brightening' is being observed (Petrenz et al. 2007; Wild 2009). The decreased influx of K↓ was attributed to substantial emissions of pollution (dimming), and its recent increase has been attributed to reduced emissions of particulate matter and changes in cloudiness (Stjern et al. 2009).

In Poland, incoming solar radiation has a variable tendency. Bogdańska and Podogrocki (2000) found that in the years 1961–1995 at 5 of 7 analysed sites the amount of K↓ increased, although in Wrocław the trend was negative (-2.7 MJ·m^{-2} per year in 1875–2004) (Bryś and Bryś 2007). Similarly, in Kraków in 1861–1990 the sunshine duration (and thus the amount of K↓) was observed to have decreased while the cloud amount increased (Morawska-Horawska 1990). In recent years, due to reduced air pollution, the insolation conditions in the city have improved (Matuszko 2007). Similar trends have been observed in Warsaw (Klleniewska and Chojnicki 2016; Uscka-Kowalkowska et al. 2016).

The influx of K↓ is affected by cloudiness and the optical properties of incoming air masses. The influence of atmospheric circulation on K↓ has been analysed by a number of authors in Poland (Niedziałek 1981; Dubicka 1994; Więcław 2011; Nelken 2016) and in Europe related studies have been carried out by Stjern et al. (2009), Chiacchio and Vitolo (2012), Panziera et al. (2015), Parding et al. (2016). It has also been found that there were substantial differences between the amount of incoming solar radiation in urban areas, suburbs and rural areas. These were connected with the degree of horizon obstruction (typical for urban areas), the amount of dust in the air, cloudiness and the frequency of fog. For example, in the centre of Łódź K↓ is 5% lower than at an extra-urban site. The difference increases in winter, reaching 25% for diurnal sums (Podstawczyńska 2007). Also in Kraków, as compared with its suburban zone, the mean values of K↓ were lower, especially around noon (7%), and in winter (25%) (Matuszko and Struś 2007). In Toruń the amount of K↓ in the centre of the city is as much as 30% lower (Kejna et al. 2014b). Nelken and Leziak (2017) stated that on clear days in spring and summer more energy reaches agricultural areas (Belsk), whereas in autumn more K↓ was observed at the urban site (Warsaw).

The purpose of this article is to analyse the variability of K↓ in the diurnal and annual course in the years 2003–2016 for the weather station located in the agricultural environment of Koniczynka near Toruń. The variability has been analysed with reference to atmospheric circulation, which determines the type of air masses and cloudiness.

Location, source data and methodology

Source data was obtained from the station of Integrated Monitoring of Natural Environment at Koniczynka situated in the Chełmno Lakeland to the north east of Toruń (53.08°N, 18.68°E, 84 m a.s.l.). The measurements were performed using a Class 1 Kipp&Zonen CMP6B pyranometer (Fig. 1). The CMP6 measures solar radiation with a high-quality blackened thermopile protected by two glass domes. Its flat spectral sensitivity is from 285 nm to 2800 nm. The instrument was not ventilated, but its domes were cleaned every day, so atmospheric deposits, dust and precipitation were removed.

Koniczynka is an extra-urban station where local conditions did not change throughout the period of observations, which is essential when analysing factors affecting the influx of K↓. The view of the horizon at Koniczynka was clear, except for the north east where the trees of a nearby park obstructed the sun at low solar elevation angles (Fig. 2). The sky view factor (SVF) of the measurement site was 0.97 (Kejna et al. 2014b).


Fig. 1. Meteorological station with pyranometer SMP6B at Koniczynka

The study uses mean values of K↓ flux density (W·m^{-2}) for hourly intervals in the years 2003–2016. When recording the K↓, Central European Time was used (referenced to the 15th meridian east). The data set was almost complete: K↓ was not recorded on 15 out of 5114 days of observation. The missing data was sourced from another pyranometer (used in a set with a CNR4 net radiometer from 2011) or on the basis of correlation with sunshine duration. The obtained data was compared with corresponding data from another sensor (CNR4) and no significant discrepancies were found (Kejna et al. 2014b).

The amount of solar radiation at the upper boundary of the atmosphere on the parallel 53.08°N (latitude of the Koniczynka station) was determined using the following formula Hartmann (1994) and Kędziora (1999), (Keina et al. 2014b):

$$Q_d = \frac{E_0 I_{SC} \cdot \varsigma}{\pi}(h_0 sin\varphi sin\delta + cos\varphi cos\delta sinh_0)$$

where:
Q_d – diurnal sum of radiant energy reaching a horizontal surface at the upper atmospheric boundary (MJ·m^{-2}),
$E_0 I_{SC}$ – solar constant calculated for each day of the year (I_{SC}=1367 W·m^{-2}),
ς – number of seconds in 24 hours (86,400),
h_0 – solar hour angle (rad),
φ – latitude at the point of observation (rad),
δ – declination of the sun on a given day (rad).

The solar constant for each day and the declination of the sun were determined using Aydinli's formulas (Podogrocki et al. 1998):

$$E_0 I_{SC} = I_{SC} \cdot [1 + 0.0334 \cdot cos(N_d \cdot J - 3{,}5°) + 0.000721 \cdot cos(2N_d \cdot J - 6.9°) - 0.000023 \cdot cos(3N_d \cdot J - 10.15°)]$$

$$\delta = 0.3948 - 23.25596 \cdot cos(N_d \cdot J + 8.87°) - 0.3915 \cdot cos(2N_d \cdot J + 5.35°) - 0.1764 \cdot cos(3N_d \cdot J + 26.01°)$$

where:
N_d = 360°/365 = 0.9863 [°] for a regular year and 360°/366 = 0.9836 [°] for a leap year;
J – number of the day in a year.

The solar hour angle was calculated using the formula (Hartmann 1994; Kędziora 1999):

$$cosh_0 = -tan\varphi \cdot tan\delta$$

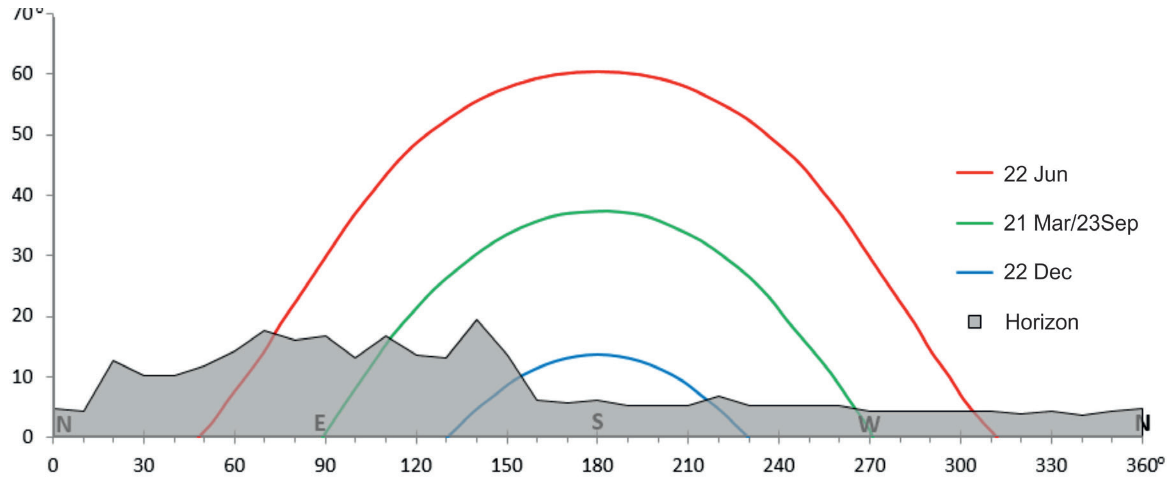

Fig. 2. The obstruction of the horizon and the sun's path on 21 March/23 September and 22 June and 22 December in Koniczynka (according to Kejna et al. 2015)

For the purpose of analysis a calendar of synoptic situations for the years 2003–2016 at Koniczynka was developed based on the classification proposed by T. Niedźwiedź (1981). For each day, using maps made available by the Institute of Meteorology and Water Management National Research Institute (http://www.pogodynka.pl/polska/mapa_synoptyczna), the relevant types of synoptic situations were determined, identifying the kind of barometric centre ('a' for anticyclonic and 'c' for cyclonic weather) and the advection direction according to the 8-point wind rose. Furthermore, the classification enables the determination of an anticyclonic centre (Ca), anticyclonic wedge (Ka), cyclonic centre (Cc) and cyclonic trough (Bc), and the other situations are denominated by 'X'. The following atmospheric circulation indices proposed by Niedźwiedź (2003) were also determined:

C – Cyclonicity index – Cc and Bc situations were assigned +2 points, the other cyclonic situations were assigned +1 point, Ca and Ka -2 points, other anticyclonic situations -1 point each, and X was assigned 0 points. Positive values of C indicate that cyclonic situations prevailed.

W – Zonal circulation index – Wa and Wc situations were assigned +2 points, NWa, NWc, SWa and SWc +1 point, Ea and Ec -2 points, NEa, NEc, SEa and SWc -1 point, and the others were assigned 0 points. Positive values of W indicate that westerly circulation prevailed.

S – Meridional circulation index – Sa and Sc situations were assigned +2 points, SWa, SWc, SEa and SEc +1 point, Na and Nc -2 points, NEa, NEc, SEa and SWc -1 point, and the others 0 points. Positive values of S indicate that southerly circulation prevailed.

Annual course of solar radiation

The mean annual sum of K↓ at Koniczynka in the years 2003–2016 was 3816.0 MJ·m^{-2} (Table 1). In the annual course, the highest monthly sums were obtained for June (608.3 MJ·m^{-2}), and the smallest in December (44.8 MJ·m^{-2}), which results from the solar elevation angle and changes in the length of day throughout the year. Looking into monthly sums, it was found that in individual years the most energy reached the surface in July (8 times), June (4) and May (in 2007 and 2012). This is the result of changeable cloud cover in the warm part of the year. In July, the difference between the biggest and the smallest sum of K↓ was 249.6 MJ·m^{-2} (from 718.4 MJ·m^{-2} in 2006 to 424.3 MJ·m^{-2} in 2011). The standard deviation of K↓ in July was 82.3 MJ·m^{-2}.

An even more distinct influence of cloudiness on K↓ was observed on individual days. The annual course, despite being averaged for the years 2003–2016, still reveals substantial day-on-day changes in K↓ (Fig. 3). Maximum sums of K↓ exceeded 30 MJ ·m^{-2} in June and July, but in winter they dropped to <1 MJ·m^{-2}. In summer, the difference in the value of K↓ between cloudy and clear days reached as much as 20–25 MJ·m^{-2}.

Table 1. Monthly and yearly sums of global solar radiation (w MJ·m^{-2}) at Koniczynka in the period 2003-2016

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
2003	54.1	140.6	266.7	389.9	501.6	611.9	466.6	459.9	334.7	167.0	64.7	30.1	3487.6
2004	51.7	107.5	219.5	424.8	537.8	574.5	583.4	501.4	343.4	179.6	70.3	41.4	3635.3
2005	69.7	37.1	211.5	481.1	561.1	628.5	652.7	517.1	383.1	238.1	64.9	39.3	3884.2
2006	90.4	140.2	360.1	378.1	580.2	649.1	718.4	361.7	402.3	190.4	77.2	49.8	3998.1
2007	65.4	101.9	284.1	507.4	623.1	577.9	496.8	503.3	319.3	192.5	68.7	35.1	3775.3
2008	69.3	112.3	241.7	363.2	645.0	697.5	656.2	440.9	270.3	177.3	76.0	43.4	3793.2
2009	72.5	111.7	228.8	590.9	578.9	513.8	579.1	552.0	374.4	141.8	84.0	41.0	3868.9
2010	85.9	141.8	290.5	439.8	414.7	632.9	612.3	458.6	323.6	250.0	50.9	53.7	3754.8
2011	54.4	168.1	325.8	469.1	627.3	675.5	424.3	499.3	377.0	207.7	95.1	44.4	3967.9
2012	75.1	153.2	342.0	441.6	639.3	503.5	597.7	478.6	346.8	189.3	61.3	47.8	3876.1
2013	68.7	115.0	351.9	420.1	522.1	586.7	598.9	527.4	300.1	210.4	62.3	49.5	3813.1
2014	75.1	160.6	287.8	462.7	529.1	616.8	645.2	495.6	367.2	193.0	65.6	45.3	3943.9
2015	57.1	135.3	261.6	460.7	564.4	592.9	574.3	611.3	326.9	184.6	64.9	55.9	3890.0
2016	76.3	122.4	231.1	437.7	619.2	654.7	492.2	474.0	393.0	110.3	74.4	50.3	3735.6
2003-2016	69.0	124.8	278.8	447.7	567.4	608.3	578.4	491.5	347.3	188.0	70.0	44.8	3816.0
Max	90.4	168.1	360.1	590.9	645.0	697.5	718.4	611.3	402.3	250.0	95.1	55.9	3998.1
Min	51.7	37.1	211.5	363.2	414.7	503.5	424.3	361.7	270.3	110.3	50.9	30.1	3487.6
Max-Min	38.8	131.0	148.6	227.7	230.4	194.0	294.2	249.6	132.0	139.7	44.2	25.8	510.5
Std	11.7	32.6	50.4	57.4	63.8	55.5	82.3	57.0	37.7	35.2	10.9	7.1	136.4

Std – standard deviation

On the upper limit of the atmosphere (for 53°9'N) the annual sum of K↓ is 8,530.6 MJ·m^{-2}, and follows an annual course which is consistent with solar declination. At Koniczynka, only a portion of K↓ (44.7%) reaches the ground, depending on the optical state of the atmosphere and the distance sun rays have to travel through the atmosphere.

Transmittance of K↓ was particularly restricted in November and December, with a clearness index of 25.9% and 24.3%, respectively (Table 2). The atmosphere was very clear from April to September, with peaks in April and June (49.0% in both cases). In individual months, the clearness index ranged from 10.2% in February 2005 to 64.7% in April 2009. In the analysed years, considerable dif-

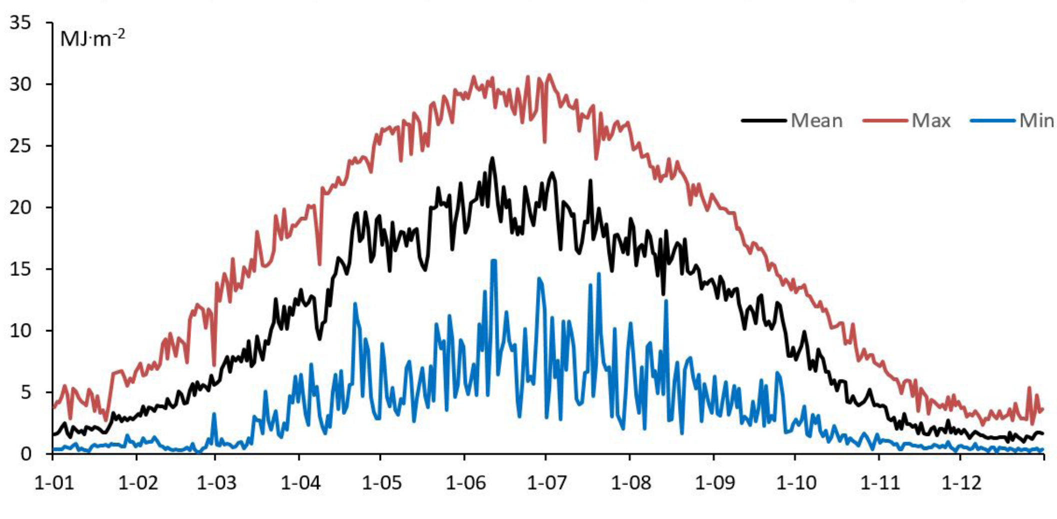

Fig. 3. Annual course of global solar radiation in Koniczynka, 2003-2016 (according to Kejna and Uscka-Kowalkowska 2018)

Table 2. Global solar radiation (MJm^{-2}) at the top of the atmosphere and the clearness index (%) at Koniczynka in the period 2003-2016

Months	Top of the atmosphere ($MJ·m^{-2}$)	Koniczynka ($MJ·m^{-2}$)	Clearness index (%)				
			Mean	Max	Year	Min	Year
Jan	215.7	69.0	32.0	41.9	2006	24.0	2004
Feb	364.3	124.8	34.3	46.1	2011	10.2	2005
Mar	655.3	278.8	42.5	54.9	2006	32.3	2005
Apr	913.4	447.7	49.0	64.7	2009	39.8	2008
May	1172.2	567.4	48.4	55.0	2008	35.4	2010
Jun	1240.2	608.3	49.0	56.2	2008	40.6	2012
Jul	1234.1	578.4	46.9	58.2	2006	34.4	2011
Aug	1041.8	491.5	47.2	58.7	2015	34.7	2006
Sep	745.9	347.3	46.6	53.9	2006	36.2	2008
Oct	492.5	188.0	38.2	50.8	2010	22.4	2016
Nov	270.6	70.0	25.9	35.1	2011	18.8	2010
Dec	184.7	44.8	24.3	30.3	2015	16.3	2003
Year	8530.6	3816.0	44.7	46.9	2006	40.9	2003

ferences in the clearness index were observed: for example, it ranged from 10.2% to 46.1% in February, from 16.3% to 30.3% in December, and from 22.4% to 50.8% in October.

Diurnal course of solar radiation

The diurnal course of K↓ corresponds to the solar elevation angle and the greatest values of K↓ concur with the Sun's culmination (Fig. 4). The astronomically-determined regular course of K↓ is disturbed by clouds and other atmospheric phenomena which restrict solar radiation, such as fog, blizzard or aerosols and pollutants in the air. The mean values of irradiance in the afternoon reached 600 $W·m^{-2}$ (June), whereas in winter months they did not exceed 100 $W·m^{-2}$ (December). Averaged diurnal courses of K↓ are symmetrical with respect to solar noon.

Solar radiation trend

In the years 2003–2016, the annual sums of K↓ changed from 3,487.6 $MJ·m^{-2}$ in 2003 to 3,998.1 $MJ·m^{-2}$ in 2006 (Table 1). The difference between the values is 136.4 $MJ·m^{-2}$, or 3.6% of the mean sum of K↓ in the analysed period. At Koniczynka, K↓ changed every year. A statistically-significant ($p \leq 0.05$) positive trend of K↓ was observed, reaching 13.6 $MJ·m^{-2}·year^{-1}$ (Fig. 5). The positive trend occurred particularly in winter ($r = 0.60$) and spring ($r = 0.31$).

Radiation–atmospheric circulation relationship

Atmospheric circulation in Poland is regulated by constant barometric centres: the Icelandic Low, the Azores High and Mediterranean lows. It is also affected by seasonal anticyclonic centres from Eastern Europe (winter), Scandinavia (usually in spring) and Southern Europe (usually in autumn). Westerly zonal flow prevails (Kożuchowski 2001). Its characteristic feature in this region is the substantial variability of synoptic situations.

In the years 2003–2016, a balanced share of cyclonic situations (49.2%) and anticyclonic ones (49.0%) was observed. Indefinite situations (X) accounted for only 1.8% (Table 3, Fig. 6).

In the case of cyclonic situations the most frequent types were those associated with the western

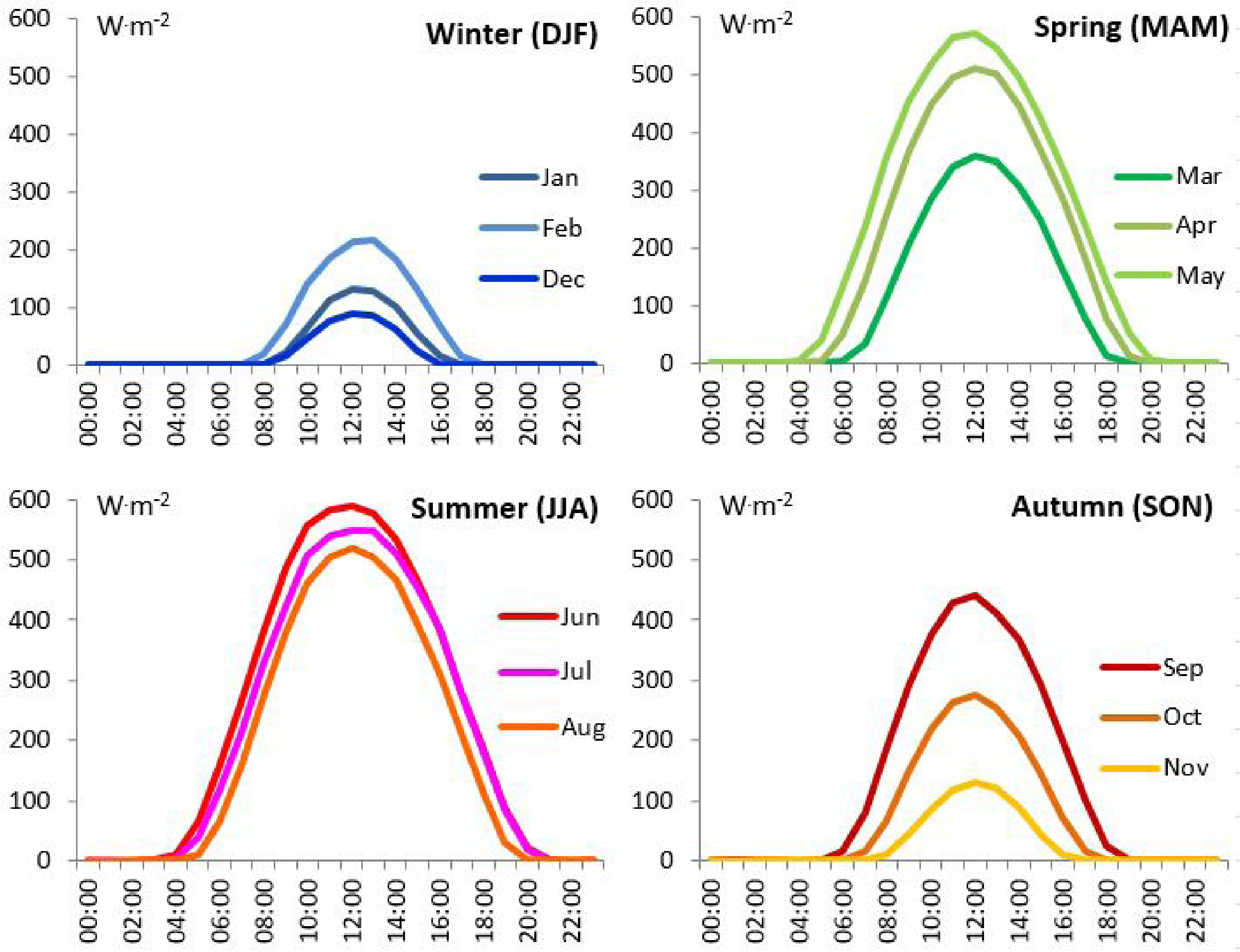

Fig. 4. Daily course of global solar radiation in Koniczynka, 2003-2016 (according to Kejna and Uscka-Kowalkowska 2018)

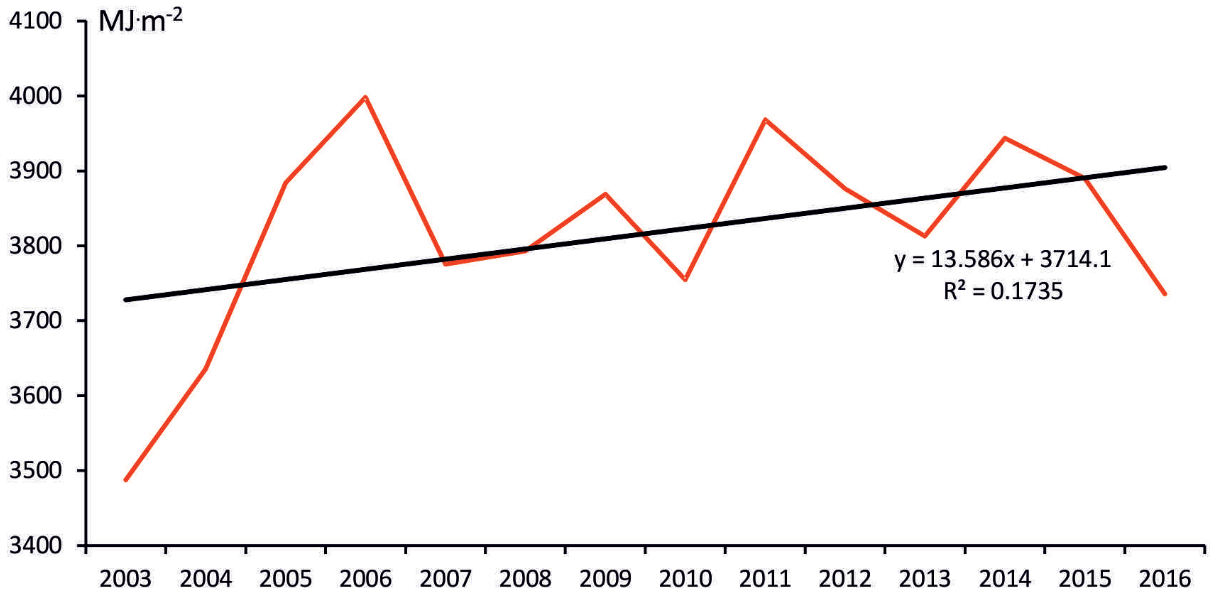

Fig. 5. Course of global solar radiation and its trend at Koniczynka in the period 2003-2016

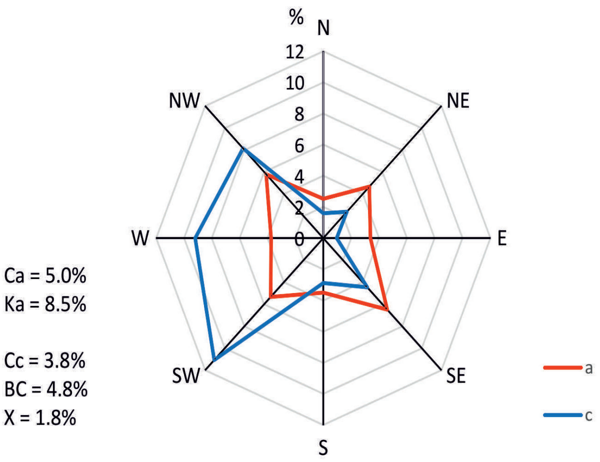

Fig. 6. Frequency of types of atmospheric situations at Koniczynka in the period 2003-2016. Explanations – see text.

sector: SWc (11.1%), Wc (9.2%) and NWc (8.2%), whereas in the anticyclonic situations Ka (8.5%), SEa (6.5%) and NWa (5.8%) types prevailed. These values are different from the frequencies observed in the years 1921–2000 (Przybylak and Maszewski 2009). In the analysed period more southerly advection types occurred and Ka and Bc were less frequent.

The frequency of synoptic situation types influences the type of air masses and cloudiness which in turn affects the amount of incoming solar radiation. In the years 2003–2016 at Koniczynka a smaller influx of K↓ was observed for cyclonic situations (8.4 MJ·m^{-2} on average), whereas for anticyclonic situations it reached 12.3 MJ·m^{-2}. The highest values of K↓ coincided with the centre of anticyclone (16.0 MJ·m^{-2}), and the lowest in a cyclonic situation with easterly advection (Ec 6.7 MJ·m^{-2}) – Table 3. In the analysed period, the advection direction evidently affected K↓: in the case of both anticyclonic and cyclonic situations higher values of K↓ occurred with northerly advection (NEa 13.8 MJ·m^{-2}, NWa 12.2 MJ·m^{-2}, NEc 10.3 MJ·m^{-2}), but anticyclonic easterly advection also favoured a considerable influx of K↓ (Ea 13.6 MJ·m^{-2}). On the other hand, westerly and southerly advection decreased K↓. For example, in the case of anticyclones: Sa 10.3 MJ·m^{-2}, SWa 10.2 MJ·m^{-2}, Wa 10.4 MJ·m^{-2}, and cyclones: SWc 7.7 MJ·m^{-2} and Sc 8.0 MJ·m^{-2}. Low values also occurred for Cc and Bc types (8.1 MJ·m^{-2} and 8.0 MJ·m^{-2}, respectively).

The correlation of incoming solar radiation and atmospheric circulation was also analysed by comparing monthly values of K↓ with circulation indices (cyclonicity index, zonal circulation index and meridional circulation index).

In the years 2003–2016 at Koniczynka the cyclonicity index was -1.4. It varied in individual years from -10.7 (2003), when anticyclonic situations prevailed, to 5.8 (2010), when cyclonic types were more frequent (Fig. 7).

Table 3. Mean values of global solar radiation according to type of synoptic situations at Koniczynka in the period 2003-2016

Circulation types	Frequency (%)	Mean solar radiation (MJ·m^{-2})	Circulation types	Frequency (%)	Mean solar radiation (MJ·m^{-2})
Na	2.5	11.7	Nc	1.6	9.8
NEa	4.7	13.8	NEc	2.4	10.3
Ea	3.4	13.6	Ec	1.0	6.7
SEa	6.5	10.8	SEc	4.4	9.6
Sa	3.5	10.3	Sc	2.9	8.0
SWa	5.3	10.2	SWc	11.1	7.7
Wa	3.7	10.4	Wc	9.2	8.3
NWa	5.8	12.2	NWc	8.2	8.9
Ca	5.1	16.0	Cc	3.7	8.1
Ka	8.5	13.5	Bc	4.8	8.0
Anticyclonic	49.0	12.3	Cyclonic	49.2	8.4
X	1.8	13.7			

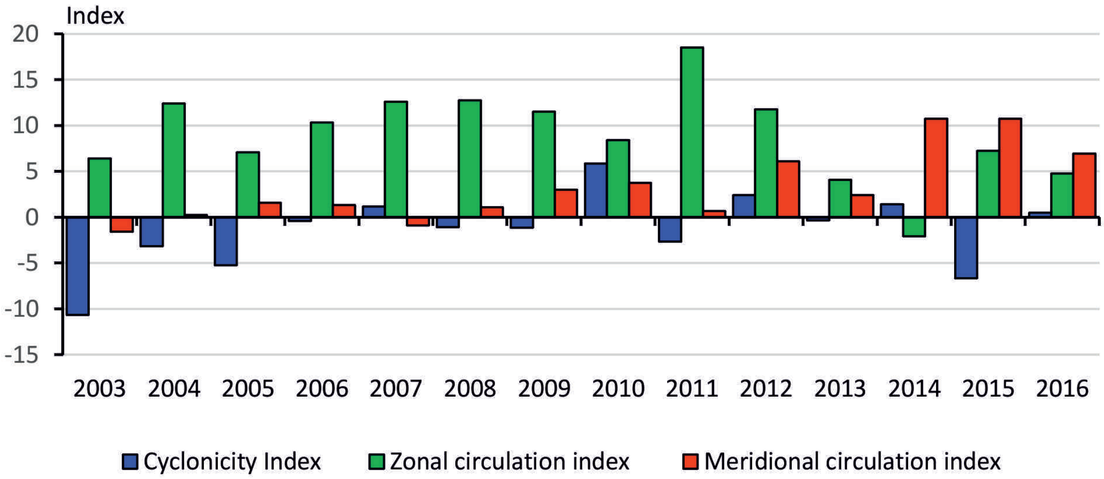

Fig. 7. Course of atmospheric circulation indices for Koniczynka, 2003-2016

In the annual course cyclones predominated from November to February (5.1 in January) but in the other months more anticyclonic situations were observed (-7.2 in September) – Table 4.

Easterly advection prevailed at Koniczynka and the mean zonal circulation index was 9.0. It was positive in all analysed years (up to 18.5 in 2011) except for 2014 when it dropped to -2.1. Westerly advection becomes more frequent in winter (19.3 in December) and summer (12.5 in August) but declines in spring (1.3 in April) and autumn (5.8 in September).

The meridional circulation index was 3.3, which indicates a prevalence of southerly advection, which was particularly evident in 2014 and 2015 (10.8). Northerly circulation types were the most frequent in 2003 (-1.6) and 2007 (-0.9). In the annual course, negative values of the index were recorded in March, April and June (-3.1) and were the highest in November (11.1), indicating that southerly advection prevailed.

An analysis of the relationship between K↓ and the circulation indices revealed no correlation with zonal or meridional circulation; however, a statistically significant correlation was found with the cyclonicity index (Pearson correlation coefficient was -0.43) – Figure 8. Cloudiness increases in cyclonic situations, particularly in atmospheric front zones, whereas in anticyclonic situations cloudiness is little or the clouds are convective. When cyclonicity develops, the amount of solar radiation reaching the ground is decreased. For example, in November 2010 the sum of K↓ was 50.9 MJ·m^{-2} (72.8% of the mean value for the month), while the cyclonicity index reached 33. On the other hand, in April 2009, when anticyclonic situations prevailed (C = -38) K↓ at Koniczynka was recorded at 590.9 MJ·m^{-2} (132.0% of the mean value).

The influence of atmospheric circulation was evident in 2015 and 2016 (Fig. 9). In 2015, the amount of solar energy which reached the ground at Koniczynka was 3,890.0 MJ·m^{-2}, and 3,735.6 MJ·m^{-2} the following year. The two years differed in terms of the frequency of circulation types: in 2015 anticyclonic types prevailed (209 days) whereas in 2016 cyclonic types were more frequent (189 days). In

Table 4. Mean values of circulation indices at Koniczynka in the years 2003-2016

Indices	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Cyclonicity	5.1	2.6	-1.1	-5.3	-1.6	-4.4	-4.4	-4.4	-7.2	-4.9	4.2	4.3	-1.4
Zonal circulation	11.9	6.7	8.7	1.3	2.3	9.4	9.1	12.5	5.8	8.1	12.8	19.3	9.0
Meridional circulation	3.6	5.4	-1.7	-0.7	1.4	-3.1	0.3	4.6	3.6	6.1	11.1	8.9	3.3

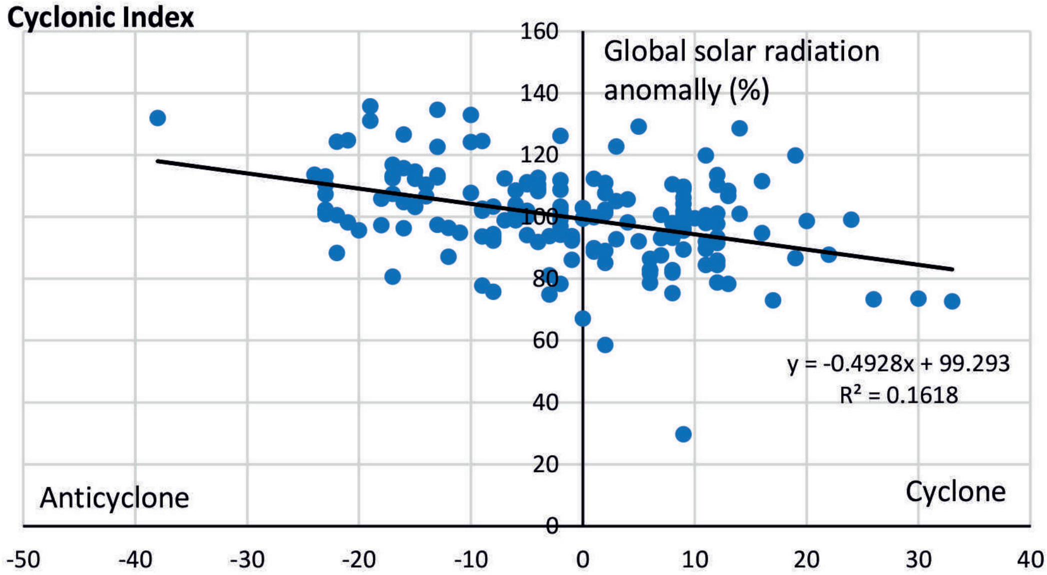

Fig. 8. Correlation between anomalies of global solar radiation at Koniczynka and cyclonic index of atmospheric circulation and in the period 2003-2016

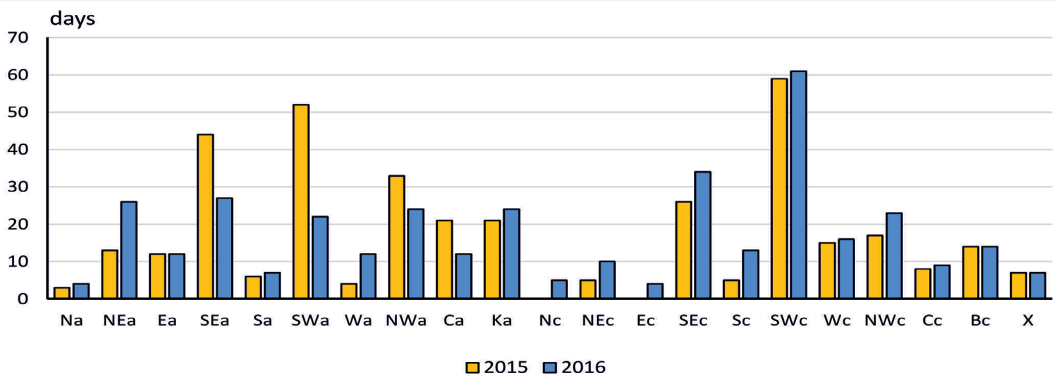

Fig. 9. Frequency of synoptic types in the year of large (2015) and small (2016) amount of global solar radiation at Koniczynka

2015 such types as SWa (52 days), SEa (44 days) and Ca (22 days) were observed more often, whereas in 2016 the more frequent types included SEc (34 days), NWc (23 days) and Sc (12 days).

Summary and conclusions

The measurements of K↓ carried out at Koniczynka in the suburban zone of Toruń were less disturbed by anthropogenic factors connected with local emissions of atmospheric pollution. The observed changes in K↓ were due to changeable atmospheric circulation.

The mean sum of K↓ at Koniczynka in the years 2003–2016 was 3,816.0 MJ·m^{-2}, which is similar to results obtained in Toruń in previous observations, e.g. in 1956–1975 mean K↓ was 3,689.3 MJ·m^{-2} (Miara et al. 1987), and in 1983–1991 it was 3,823.6 MJ·m^{-2} (Wójcik 1996) (Table 5). Concurrent measurements taken in 2012 revealed that the sum of K↓ in the city was 7% smaller, amounting to 3,570.1 MJ·m^{-2} in Toruń, whereas at Koniczynka it was 3,840.1 MJ·m^{-2} (Kejna et al. 2014a,b).

In an annual course the biggest mean values of K↓ occurred in June (608.3 MJ·m^{-2}) and the smallest in December (69.0 MJ·m^{-2}). However, changeable cloud cover resulted in substantial fluctuations in the K↓ sums in summer and the greatest influx

Table. 5. Mean monthly and yearly values of global solar radiation in Toruń and Koniczynka

Month	Toruń-Wrzosy (1956-1975)*	Toruń-Wrzosy (1983-1991)**	Toruń-UMK (2012)***	Koniczynka (2012)***	Koniczynka (2003-2016)
Jan	71.0	70.7	54.2	68.0	69.0
Feb	120.6	143.6	115.1	145.2	124.8
Mar	268.5	275.6	316.6	329.4	278.8
Apr	379.2	418.5	422.1	436.6	447.7
May	535.1	595.2	599.5	639.3	567.4
Jun	591.6	548.7	450.6	502.6	608.3
Jul	566.7	607.3	563.1	599.1	578.4
Aug	494.5	499.7	443.4	476.3	491.5
Sep	345.9	314.4	321.7	347.3	347.3
Oct	183.8	209.6	177.1	189.3	188.0
Nov	79.8	86.4	56.8	60.5	70.0
Dec	52.7	53.9	49.9	46.5	44.8
Mean	3689.3	3823.6	3570.1	3840.1	3816.0

* - Miara et al. 1987, ** - Wójcik 1996, *** - Kejna et al. 2014a,b

of solar radiation occurred between May and July. Diurnal sums of K↓ ranged from 0.1 MJ·m^{-2} (23 February 2005) to 30.8 MJ·m^{-2} (2 July 2010). Huge differences in K↓ were observed from one day to another, due to the degree of cloudiness.

The amount of solar energy reaching the upper limit of the atmosphere (at 53°9'N it was 8,530.6 MJ·m^{-2}) could be used to determine the clearness index. At Koniczynka, 44.7% of the solar energy reaches the ground and most of it is transmitted through the atmosphere in spring and summer (April and June: 49.0% each). The transmittance is the weakest in November and December (25.9% and 24.3%, respectively), which is due to the low solar elevation angle, the great optical mass of the atmosphere and substantial cloudiness. The diurnal course of K↓ is symmetrical with respect to the solar noon (Kejna and Uscka-Kowalkowska 2018).

The year-on-year variability of K↓ is not great – its annual sums in the analysed period ranged from 3,487.6 MJ·m^{-2} in 2003 to 3,998.1 MJ·m^{-2} in 2006. These small changes (3.6% of the mean sum of K↓) are nonetheless important for the functions of atmosphere and environment. A statistically-significant positive trend was found, reaching 13.6 MJ·m^{-2}·year^{-1}, which is consistent with global trends. In the years 1950–1980 in a number of areas around the globe there was a decrease in global solar radiation reaching the Earth's surface (global dimming), followed by an increase in more recent times (global brightening) (Wild 2009). In the years 1961–1995 in Poland at most stations an increase was observed (Bogdańska and Podogrocki 2000). Similarly, in Wrocław K↓ increased in the last few decades (Bryś 2013). The trend continues and in Warsaw, for example, it reached 11.4 MJ·m^{-2} per year in 1964–2013 (Kleniewska and Chojnicki 2016).

Changes in solar conditions are influenced by cloudiness, which is affected by processes occurring in the troposphere, and particularly by the type of barometric pressure centre and air masses connected with the direction of advection. According to Kirschenstein (2003) the greatest amount of clouds occurs in westerly cyclonic situations and the smallest with easterly advection types. The type of incoming air masses is also significant (Niedziałek 1981).

The results of our analysis demonstrate that at Koniczynka the mean diurnal sum of K↓ in cyclonic situations was 8.4 MJ·m^{-2} and 12.3 MJ·m^{-2} in anticyclonic weather. The highest values of K↓ were observed at the centre of an anticyclone (Ca 16.0 MJ·m^{-2}) and in an anticyclonic wedge, with northerly advection (NEa 13.8 MJ·m^{-2}, NWa 12.2 MJ·m^{-2}, NEc 10.3 MJ·m^{-2}) and with easterly advection (Ea 13.6 MJ·m^{-2}). Cyclonic situations are accompanied by atmospheric fronts bringing in clouds and low value of K↓ (Ec 6.7 MJ·m^{-2}, SWc 7.7 MJ·m^{-2}, Sc 8.0 MJ·m^{-2}, Cc

8.1 MJ·m^{-2} and Bc 8.0 MJ·m^{-2}). This is validated by the correlation of K↓ and the cyclonicity index, being -0.43. The influx of solar radiation decreases in cyclonic weather, so in November 2010, for example, the cyclonicity index was 33, and the total sum of radiation reached 72.8% of its monthly mean. In April 2009, the index dropped to -38 (prevalence of anticyclones) and K↓ was just 32.0% of the mean value.

The share of various types of synoptic situations also affects K↓. In the years when anticyclonic situations prevailed (e.g. for 209 days in 2015) the sum of K↓ was high (3,890.0 MJ·m^{-2}). When cyclonic weather was more frequent (189 days in 2016) K↓ clearly decreased (3,735.6 MJ·m^{-2}).

The importance of barometric centre and advection direction was corroborated in research conducted at Belsk near Warsaw, where in 1971–2014 the highest values of K↓ were observed with northerly and easterly anticyclonic situations (according to the circulation types proposed by Lityński), whereas in cyclonic weather and with westerly and northerly advection they were the lowest (Nelken 2016). When westerly circulation increases and the North Atlantic Oscillation is in a positive phase, cloudiness increases and thus the amount of solar radiation reaching the ground decreases. In Southern Europe, the influence of the NAO on K↓ is evident in autumn and winter, but in Northern Europe it is clear in spring and summer (Chiacchio and Wild 2010). Incoming air masses carry different quantities of aerosols and water vapour. As demonstrated by Niedziałek (1981), the highest levels of K↓ reach the Earth's surface when continental polar air masses and maritime polar old air masses prevail.

The observations carried out at Koniczynka revealed an increase in the amount of K↓ and its considerable day-to-day and year-to-year variability. The changes depend on atmospheric circulation, cloudiness and the characteristics of incoming air masses.

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