Bulletin of Geography – physical geography series
No 2/2009: 19–33

https://www.doi.org/10.2478/bgeo-2009-0016

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DIRECT SOLAR RADIATION AND ATMOSPHERIC TURBIDITY IN MIKOŁAJKI IN THE YEARS 1971–1980 AND 1991–2000

Abstract: The present study deals with the changing amount of incoming direct solar radiation and the optical state of the atmosphere in Mikołajki in the years 1971–1980 and 1991–2000. The highest level of solar irradiance in these two decades occurred on 23rd June 1977 and amounted to 1043.9 $W \cdot m^{-2}$. Compared to the first decade analysed, the percentage of the solar constant reaching the Earth in the second decade was higher. The spectral structure of the radiation also changed – the share of the shortest waves (λ<525 nm) increased, whereas the amount of waves with a wavelength of 710 nm or more decreased. In both study periods the annual course of solar extinction (expressed in terms of Linke's turbidity factor) turned out to have been typical, with the highest values in summer and the lowest in winter. In the years 1991–2000, in all seasons, a lower atmospheric turbidity was observed in comparison with the years 1971–1980. The atmospheric turbidity was also analysed with relation to the air masses. In both decades in question the lowest turbidity occurred in arctic air masses and the highest in tropical air masses. An improved optical state of the atmosphere was observed in all considered air masses, though the biggest decrease in turbidity was found in polar air masses, particularly in the polar maritime old air (T_{LAM2} dropped by 0.75) and polar continental air (by 0.70).

Key words: direct solar radiation, Linke's turbidity factor, Mikołajki

Introduction

The direct solar radiation that reaches the Earth's surface is an important component of the radiation balance, thus influencing climatic and bioclimatic conditions of a given area. The water vapour and aerosols of various origins contained in the air cause the solar radiation to be more or less attenuated, as compared to the amount reaching the outer surface of the Earth's atmosphere. The changes are caused by both natural and anthropogenic factors. Studies of atmospheric extinction are usually conducted in cities, where the atmosphere is substantially polluted. As a result, it may be difficult to determine the share of natural and anthropogenic factors in the observed changes of the air transparency. Therefore, it seems reasonable to investigate the issue of the changing amount of direct solar radiation for an area that as little transformed by man as possible.

The purpose of this study is to present the changing amount of incoming direct solar irradiance and the changing optical state of the atmosphere in Mikołajki in the years 1971–1980 and 1991–2000. Since Mikołajki is situated in the Mazurian Lake District – i.e. in an area where the atmosphere is barely polluted – the changes observed in the incoming solar irradiance may be considered to have been clearly caused by natural factors, although some influence from anthropogenic factors cannot be ruled out.

So far, the problem of atmospheric extinction has been studied mainly for cities and large urban areas, e.g. Warsaw (Stenz 1919; Dziewulska-Łosiowa 1962; Krawczyk 1968; Michałowska-Smak 1981; Uscka-Kowalkowska 2007b), Bydgoszcz (Paszyński 1959), Kraków (Olecki 1992), Toruń (Wójcik et al. 1991) and Puławy (Uscka-Kowalkowska 2007a, 2008a). There are also some actinometric reference materials concerning areas where the anthropopressure has been rather limited, e.g. Belsk, Mount Kasprowy Wierch (Michałowska-Smak 1981) or Papowo Toruńskie (Uscka 2003; Uscka-Kowalkowska 2008a).

Materials and methods

The study makes use of the results of actinometric measurements taken in Mikołajki in the years 1971–1980 and 1991–2000. The data were collected and made available by the Institute of Meteorology and Water Management.

Mikołajki, as indicated above, is a small town situated in the Mazurian Lake District, though the actinometric station is located outside the built-up area, approximately 200 m from Lake Mikołajki, φ=53°47'N and λ=21°35'E, and 127 m a.s.l.

The measurements used in the study were taken using a Linke-Feussner actinometer at the culmination of the Sun or shortly before or after it (up to half an hour), both in the whole solar spectrum and in selected parts. A total of 811 days from both decades were considered, of which 541 days were taken from the first decade and the remaining 270 days, from the second (Table 1). Most of the measurement series come from spring months, while the fewest were registered in autumn (in the first decade) or winter (in the second one). The reason a greater number of measurements were taken in the years 1971–1980 was the human factor, connected with the functioning of actinometric stations. It is noteworthy that the problem concerns many other stations in Poland, as well. Different numbers of measurement series in individual seasons of the year result from cloudiness. In the years 1951–2000 the highest cloudiness in Poland was from November to February, and the lowest was in August (Żmudzka 2003). It is therefore natural, that there were more measurements taken in summer and spring than in winter and autumn.

Table 1. Number of measurement series taken in Mikołajki in 1971–1980 and 1991–2000, used in the study, by year and season

Period	MAM	JJA	SON	DJF	Year
1971–1980	185	163	88	105	541
1991–2000	79	72	60	59	270

The collected measurement data provided the basis for a comparison of the amount of direct solar radiation and its spectral composition for the years 1971–1980 and 1991–2000. Solar extinction was expressed by means of Linke's turbidity factor, calculated and reduced to the atmospheric optical mass of 2, using the methodology proposed by Grenier et al. (1994). The content of precipitable water in the atmosphere, required to normalize the turbidity factor to the atmospheric mass of 2, was determined on the basis of water vapour pressure measured at the ground surface (Averkiev, Evnevitch 1973). For both decades the changes in the atmospheric turbidity have been presented according to season. As the level of turbidity depends on the type of air masses, it was also calculated for the different air masses determined on the basis of weather charts published by the Institute of Meteorology and Water Management (formerly the National Institute of Hydrology and Meteorology).

Results

In the collected material the highest level of solar irradiance in Mikołajki in the years 1971–1980 occurred on 23rd June 1977 and amounted to 1043.9 $W \cdot m^{-2}$, whereas in the decade 1991–2000 the maximum value was lower, reaching only 989.8 $W \cdot m^{-2}$ and occurring on 18th May 1999 (Table 2). High irradiance levels coincide with high positions of the Sun over the horizon and a clear atmosphere. Obviously, the best time to expect record values is May and June. In winter months, despite a high level of air transparency, there is much less solar radiation, as the observed height of the Sun is much lower than in the warm period.

Table 2. Highest values of direct solar irradiance ($W \cdot m^{-2}$) measured in Mikołajki in the periods 1971–1980 and 1991–2000

Period	MAM	JJA	SON	DJF	Year	Date
1971–1980	1018.1	1043.9	956.7	895.3	1043.9	23 June 1977
1991–2000	989.8	962.5	936.3	919.0	989.8	18 May 1999

The amount of solar energy reaching the Earth's surface, as compared to the amount of solar energy found in the outer surface of the atmosphere, depends on the distance covered by solar rays in the atmosphere. For each of the optical masses of the atmosphere distinguished, more energy reached the ground in the second of the two decades. The biggest difference (amounting to 6.3%) occurred when the sun rays took the shortest time to travel through the atmosphere, i.e. when the atmospheric mass was less than 1.3 (Fig. 1.).

When the value of atmospheric optical mass rises (i.e. when the height of the Sun over the horizon lowers) the spectral composition of direct solar radiation changes, so the spectrum has a higher percentage of waves with wavelengths of $\lambda>710$ nm. On the other hand the share of the shortest waves ($\lambda<525$ nm) falls. In both decades studied the highest amounts of energy

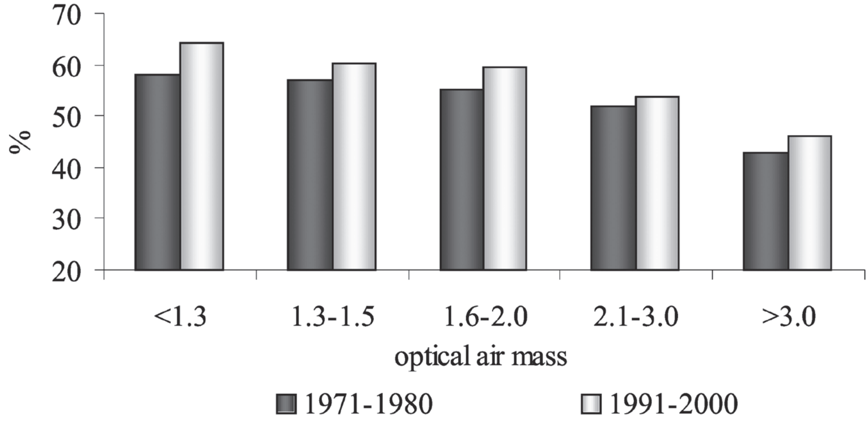

Fig. 1. The percentage of incoming direct solar radiation, compared to the solar constant in Mikołajki in the periods 1971–1980 and 1991–2000

were found in the range of λ>710 nm (60.5% in the years 1971–1980 and 54.3% in 1991–2000), and the lowest – depending on the period – in either the range of 525 nm<λ<710 nm (in 1971–1980 – 19.5%) or in the shortest waves range, i.e. λ<525 nm (in the period 1991–2000 – 21.2%) (Table 3). In the period 1991–2000, in comparison to the decade of 1971–1980, the percentage of the shortest waves (λ<525 nm) increased, whereas the share of waves with wavelengths of 710 nm and more decreased (Fig. 2). The increase observed in the shortest waves probably resulted from a decrease in aerosol scattering, which plays a substantial role in the extinction of this segment of the solar spectrum. The decreased share of waves with wavelengths of λ>710 nm in the spectrum is connected with an increased content of precipitable water in the atmosphere during the second decade analysed. The more precipitable water in the atmosphere, the higher the extinction of the longest wavelength waves. Therefore, the decrease in the percentage of longer waves (λ>710 nm) is on the one hand caused by their increased extinction, and on the other hand by a lower scattering of the shortest waves.

A popular measure to determine the extent of attenuation of solar radiation in the Earth's atmosphere is Linke's turbidity factor. Since the value of this factor depends on the changing spectral composition of the radiation passing through the atmosphere, it must be reduced to a selected atmos-

Table 3. The spectral composition (%) of direct solar radiation (nm), depending on the optical air mass in Mikołajki in the periods of 1971–1980 and 1991–2000

Optical air mass	1971–1980			1991–2000		
	λ<525	525<λ<710	λ>710	λ<525	525<λ<710	λ>710
<1.3	23.0	20.3	56.7	24.7	25.1	50.3
1.3–1.5	21.0	19.9	59.1	23.1	25.1	51.9
1.6–2.0	20.1	19.5	60.4	21.4	24.7	53.9
2.1–3.0	17.3	19.2	63.5	19.2	23.8	56.9
>3.0	13.5	17.0	69.5	14.9	23.0	62.1
mean	20.0	19.5	60.5	21.2	24.5	54.3

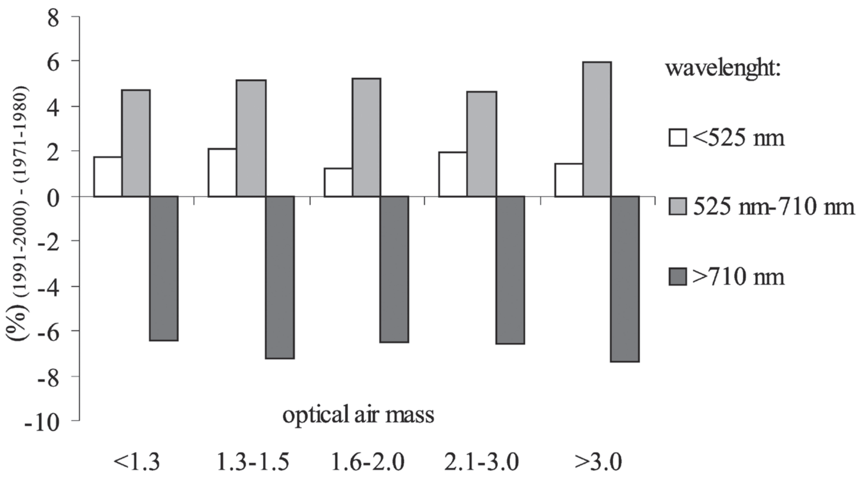

Fig. 2. Differences in the spectral composition (%) of direct solar radiation in Mikołajki in the period 1991–2000 as compared to the period 1971–1980

pheric optical mass – usually of 2, which corresponds to the position of the Sun over the horizon at 30°. The values of Linke's turbidity factor presented below have been reduced to an optical mass of 2 using the method developed by Grenier et al. (1994). The turbidity factor for the optical mass of 2 is expressed as T_{LAM2}.

The mean value of T_{LAM2} in Mikołajki, in the first of the two decades analysed amounted to 3.43, but then dropped to 2.90. The extreme values

Table 4. Mean, highest and lowest values of Linke's turbidity factor (T_{LAM2}) in Mikołajki in the periods 1971–1980 and 1991–2000

Periods	Parameter	MAM	JJA	SON	DJF	Year
1971–1980	mean	3.65	3.89	2.92	2.73	3.43
	max	7.86	6.99	5.42	5.58	7.86
	min	1.52	1.56	1.79	1.94	1.52
1991–2000	mean	2.95	3.30	2.80	2.42	2.90
	max	4.85	6.54	4.91	4.13	6.54
	min	1.88	2.08	1.73	1.71	1.71

of T_{LAM2} were 7.86 (on 27 March 1973) and 1.52 (on 7 March 1977) (Table 4.).

The annual course of atmospheric turbidity in Mikołajki reveals its highest values in summer and lowest in winter (Fig. 3). A similar pattern has been observed in many other places in Poland, e.g. in Warsaw (Dziewulska-Łosiowa 1962; Michałowska-Smak 1981; Uscka-Kowalkowska 2007b), Belsk and at the top of Mt. Kasprowy (Michałowska-Smak 1981), in Papowo Toruńskie (Uscka 2003, Uscka-Kowalkowska 2008a), Puławy (Uscka-Kowalkowska 2007a, 2008a) and Kołobrzeg (Uscka-Kowalkowska 2008b). For all seasons in Mikołajki the atmospheric turbidity was lower in the second decade than in the first. The decrease ranged from 0.12 in autumn to 0.70 in spring. The observed lower turbidity must have been caused by a reduced aerosol content in the atmosphere, as the content of precipitable water in the second of the analysed periods was higher (in spring and summer), almost the same (in winter) or slightly lower (in autumn) (Fig. 4).

All observations were divided into classes according to their value of T_{LAM2}, on the basis of the turbidity classes proposed by S.I. Sivkov (1968). The following six classes of T_{LAM2} were distinguished:

Very low	<2.1
Low	2.1–2.5
Normal	2.6–3.0
Elevated	3.1–3.5
Strongly elevated	3.6–4.0
High	>4.0

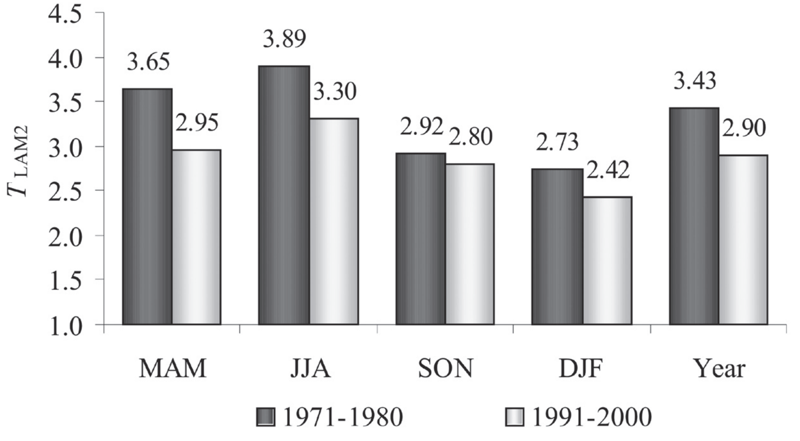

Fig. 3. Seasonal atmospheric turbidity (T_{LAM2}) and its mean annual value in Mikołajki in the periods 1971–1980 and 1991–2000

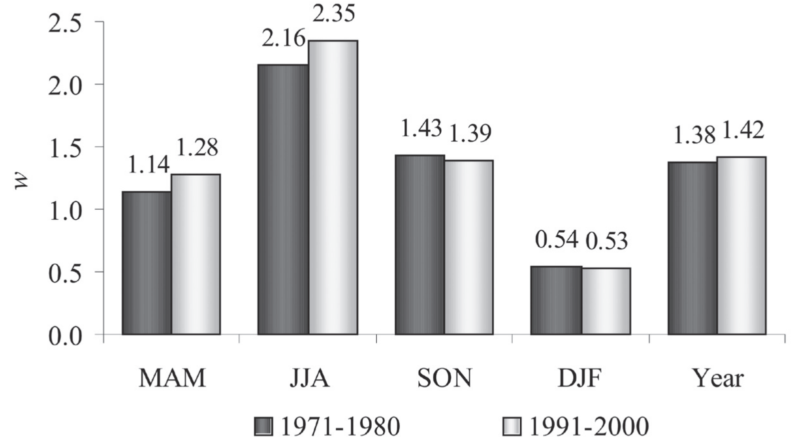

Fig. 4. Precipitable water content (w in cm) according to season and its mean annual value in Mikołajki in the periods 1971–1980 and 1991–2000

The frequency of individual classes of T_{LAM2} in both decades has been shown in Fig. 5. In the years 1971–1980 the high turbidity class was the most frequent, occurring in as much as 24.4% of all observations. In the decade 1991–2000 the low turbidity class was the most common. It seems that in the second period analysed the frequency structure of T_{LAM2} was inverted to a certain degree as compared to the first decade. This inversion translates into a substantial improvement of the optical state of the atmosphere in the years 1991–2000, as compared to the decade 1971–1980.

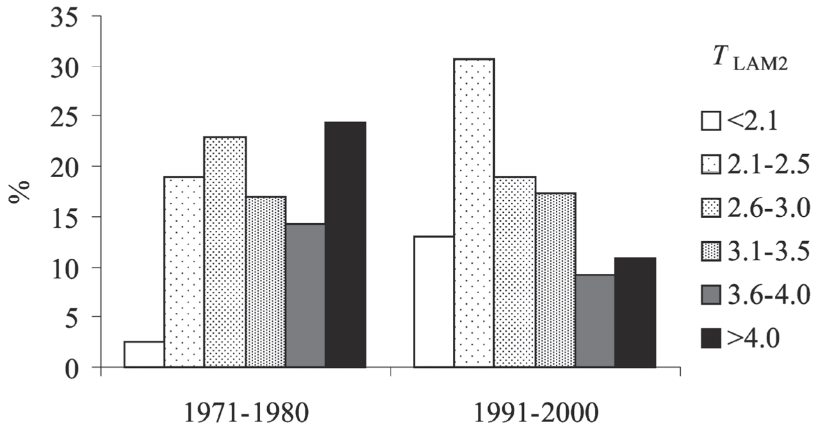

Fig. 5. Relative (%) frequency of atmospheric turbidity (T_{LAM2}) in selected classes in the periods 1971–1980 and 1991–2000

The level of atmospheric turbidity depends on the type of air masses occurring in the area. Using weather charts published by the Institute of Meteorology and Water Management (IMGW, formerly PIHM, 1971–1980, 1991–2000) the types of air masses over Mikołajki were determined for the days when the actinometric measurements were taken. The decades analysed are quite different when as regards the occurrence of various types of air masses (Fig. 6). In the years 1971–1980 polar continental air was predominant, noted in 37.5% of observations. The second most common air type was polar maritime old air (24.2% of the days). In 1991–2000 the distribution is more even, with the highest values being noted for arctic and polar continental air masses (27.8% and 27.0% of days respectively). In the second decade there was a decrease in the occurrence frequency of polar

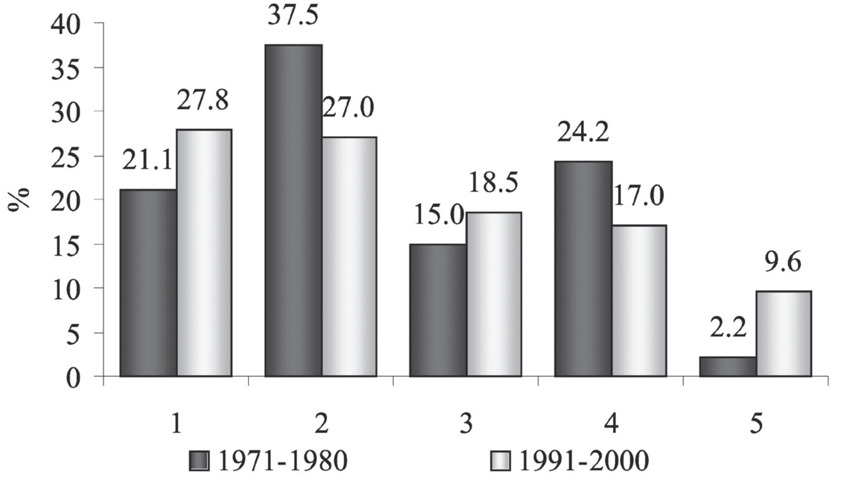

Fig. 6. Occurrence frequency (%) of various types of air masses (1–5) over Mikołajki in the periods 1971–1980 and 1991–2000
Air masses: 1 – Arctic (A, Ao, Am, Amo), 2 – Polar continental (Pc, Pco), 3 – Polar maritime (Pm, Pmw), 4 – Polar maritime old (Pmo), 5 – Tropical (T, Tm, Tmo, Tc, To)

continental and polar maritime old masses, though other types of air masses increased their share.

In both periods analysed the lowest turbidity occurred in arctic air masses (in the first decade T_{LAM2} was 2.71, and in the second it was 2.42) and the highest turbidity was observed in tropical air masses (where T_{LAM2} was 4.27 and 4.05, respectively). Similar patterns have been observed in Papowo Toruńskie (Uscka 2003, Uscka-Kowalkowska 2008a), Puławy (Uscka-Kowalkowska 2007a, 2008a), Kołobrzeg (Uscka-Kowalkowska 2008b) and Warsaw (Dziewulska-Łosiowa 1962; Uscka-Kowalkowska 2007b). All polar air masses are characterised by similar values of turbidity coefficients in each of the decades analysed. In the first decade the difference between the most turbid polar maritime old air (T_{LAM2}=3.63) and the cleanest polar maritime air masses (T_{LAM2}=3.53) amounted to only 0.10. In the second decade, there also were small differences between the levels of turbidity of polar air masses. The highest turbidity occurred in polar maritime air (T_{LAM2}=3.01). Polar maritime old air and polar continental air masses affected the level of

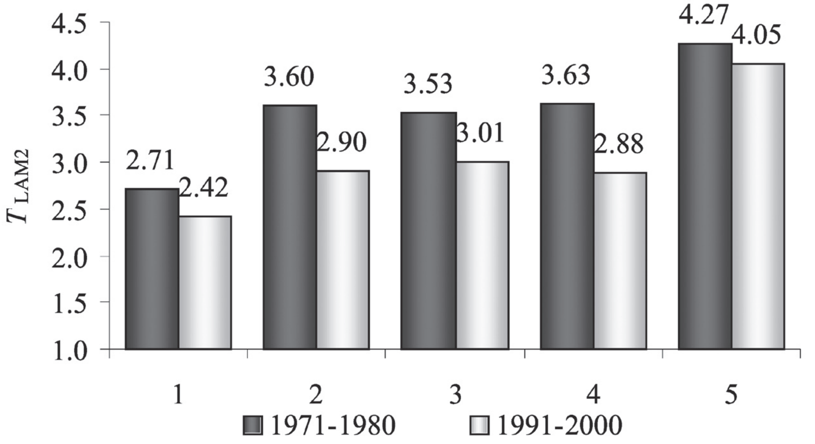

Fig. 7. Atmospheric turbidity (T_{LAM2}) in the air masses over Mikołajki in the periods 1971–1980 and 1991–2000
Air masses: 1 – Arctic (A, Ao, Am, Amo), 2 – Polar continental (Pc, Pco), 3 – Polar maritime (Pm, Pmw), 4 – Polar maritime old (Pmo), 5 – Tropical (T, Tm, Tmo, Tc, To)

atmospheric turbidity almost to the same extent, resulting in T_{LAM2} values of 2.88 and 2.90, respectively (Fig. 7).

Considering the frequency of occurrence of the turbidity classes with various Linke's factor values in individual types of air masses in both periods analysed, the lowest turbidity class appears to be most frequent in arctic air masses, while the highest turbidity class dominates in tropical air masses (Table 5). In the first of the two decades analysed – in all air masses, except for arctic masses – the maximum frequency is found in the high turbidity class, whereas in the second decade the optical state of the atmosphere was improved, as demonstrated in the shift of the maximum frequency to classes of lower turbidity (except for the arctic and tropical air masses).

Table 5. Relative frequency (%) of atmospheric turbidity (T_{LAM2}) in selected classes in various air masses over Mikołajki in the periods 1971–1980 (A) and 1991–2000 (B)

T_{LAM2}	Air masses									
	arctic[1]		polar-continental[2]		polar-maritime[3]		polar maritime old[4]		tropical[5]	
	A	B	A	B	A	B	A	B	A	B
<2.1	5.3	25.3	1.5	15.1	2.5	8.0	2.3	2.2	0.0	0.0
2.1–2.5	40.4	44.0	17.2	19.2	13.6	28.0	7.6	41.3	0.0	11.5
2.6–3.0	28.9	20.0	20.7	24.7	24.7	16.0	20.6	21.7	16.7	0.0
3.1–3.5	16.7	6.7	15.3	24.7	16.0	22.0	21.4	17.4	8.3	19.2
3.6–4.0	5.3	2.7	13.8	11.0	14.8	12.0	21.4	6.5	25.0	23.1
>4.0	3.5	1.3	31.5	5.5	28.4	14.0	26.7	10.9	50.0	46.2

[1] –arctic (A, Ao, Am, Amo), [2] – polar continental (Pc, Pco), [3] – polar maritime (Pm, Pmw), [4] – polar maritime old (Pmo), [5] – tropical (T, Tm, Tmo, Tc, To)

Summary and discussion

The study of direct solar radiation and atmospheric turbidity in Mikołajki in the years 1971–1980 and 1991–2000 revealed an improvement in the optical state of the atmosphere. This is evident, for example, in the increased percentage of the solar constant reaching the Earth's surface in the second decade analysed. This increase is noticeable for all atmospheric masses, and especially for the highest positions of the Sun over the horizon (atmospheric mass below 1.3). The spectral composition of the radiation was also changed. A greater share of the shortest waves (λ<525 nm) and a lower share of the longest waves (710 nm and more) were observed.

The annual course of solar extinction occurred in both decades analysed, with its highest values in summer and lowest in winter. In all seasons the atmospheric turbidity was lower in the second of the analysed decades. Most probably this was caused by a lower aerosol content in the atmosphere, as the average content of precipitable water slightly increased in the second decade. The decrease in aerosol scattering may be connected with the considerably reduced emission of pollutants into the atmosphere after 1989.

Although the town of Mikołajki is situated in a relatively clean area, pollution released in industrial areas can still be found there. In the second of the analysed decades a number of environmentally arduous industrial facilities were shut down as a result of economic transformations. At the same time, more restrictive pollution emission standards were introduced, which also contributed to the improvement of the optical state of the atmosphere. As proof of this development in Mikołajki, the frequency of days with specific T_{LAM2} values changed. The maximum frequency shifted from the high turbidity class (T_{LAM2}>4.0) in the first decade, to the low turbidity class (2.1<T_{LAM2}<2.5) in the second decade.

An improvement in the optical state of the atmosphere was observed for all air masses which were considered, though the biggest decrease was found in polar air masses, especially in the polar maritime old air (where T_{LAM2} dropped by 0.75) and polar continental air (by 0.70). A smaller decrease was observed in polar maritime air, and thus this type of air mass revealed the highest value of T_{LAM2} in the second decade, as compared to other polar air masses. As far as arctic and polar continental air masses are concerned, the lower turbidity might have been caused not only by a reduced aerosol scattering, but also by a small decrease in the content of precipitable water in the atmosphere. In other air masses the precipitable water content did not decrease, therefore the improvement of the optical state must have been caused mainly by reduced pollutant emissions.

It is also noteworthy that the two decades analysed are characterised by different frequencies of occurrence of air masses over Mikołajki. In the second decade the percentage of clean arctic masses was higher, which contributed to the improvement in the optical state of the atmosphere; however tropical air masses occurred more frequently too, resulting in a high extinction of solar radiation. Nevertheless, despite the higher occurrence frequency of tropical air masses in the second decade, they were still the least frequent type of air masses, and thus their influence on the mean value of T_{LAM2} in the whole period analysed was limited.

Acknowledgements

The research was funded by a grant obtained from the State Committee for Scientific Research for 2005–2008 (grant no. 2 P04E 012 28).

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