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Comparison of the Linke turbidity factor in Warsaw and in Belsk

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Abstract. The paper describes the relationship between direct solar radiation in a city (Warsaw) and in its broadly-defined suburban area (Belsk). The analysis covers the days of 1969-2003 when observations were carried out at both sites. The degree of extinction of solar radiation was expressed by means of Linke's turbidity factor. Its mean annual value on the selected days of the period under consideration was 3.00± 0.10 in Warsaw and 2.87±0.11 in Belsk. Average atmospheric turbidity for individual seasons of the year as well as for the whole year was higher in Warsaw than in Belsk. In all cases, except for the summer, these differences were statistically significant. The period considered was divided into two sub-periods (1969-1993 and 1994-2003), in which atmospheric turbidity in Warsaw and in Belsk was compared by individual seasons and whole years. At both analysed sites Linke's atmospheric turbidity factor decreased in 1994-2003, compared to the values for the earlier sub-period (1969-1993). However, the average annual atmospheric turbidity in Warsaw in comparison to Belsk remained the same, i.e. greater turbidity occurred in the city in both sub-periods.

Key words:
direct solar radiation,
atmospheric turbidity,
Warsaw,
Belsk,
Poland

Introduction

Man's various activities cause changes in the natural environment. These include the use of land, and the chemical composition of water, soil and air (Landsberg 1981; Mohan et al. 2011; Sun et al. 2016). Such changes are the most evident in cities which are not only place where large populations live and work, but also where industries and transport cluster occurs. This leads to substantial atmospheric emissions of pollutants generated by communal, transport and industrial activities, which affects the climate conditions of urban areas (Landsberg 1981). A specific urban climate develops, best characterised by the Urban Heat Island phenomenon (Błażejczyk 2002; Fortuniak et al. 2006; Stewart and Oke 2012; Przybylak et al. 2017), but which also involves modified wind directions and restricted wind speeds (Landsberg 1981), decreased relative humidity (Ackerman 1986; Adebayo 1991; Unkašewić et al. 2001), increased cloudiness and a certain frequency of occurrence of hydrometeors, as well as a reduced amount of incoming solar radiation (Landsberg 1981; Abakumova et al. 1983; Kozłowska-Szczęsna et al. 1996). A changed amount of solar radiation reaching the earth's surface disturbs the energy balance, which in turn affects physical processes that

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occur in the atmospheric boundary layer, thus affecting the quality of life of urban communities.

The object of the present analysis was to determine the influence of a large urban area (agglomeration) on the amount of direct solar radiation reaching the earth's surface during clear sky conditions. The study used Warsaw – the largest city and capital of Poland, and the small village of Belsk, situated south of Warsaw in an area which had hardly undergone anthropogenic transformation. Based on available data, the paper shows the annual courses of Linke's turbidity factor. The differences in the value of the analysed parameter were worked out for individual seasons of the year and its frequency of occurrence in class intervals; the influence of air masses on the extent of differences in atmospheric extinction was considered and the differences in the degree of atmospheric turbidity were identified with regard to the direction of inflow and the backward trajectory of air masses.

Previous studies of aerosol impact on direct solar radiation, carried out by Zawadzka et al. (2013) in Warsaw and in Belsk, indicate that the Aerosol Optical Thickness (AOT) over the city was 10%-15% higher than at the background site. The results were obtained using sun photometers in the years 2005-2011. Similar results were obtained by Chubarova et al. (2011), in the area of the Moscow agglomeration. In that case, the differences in AOT in the city centre and on its outskirts were 0.02 for the 500 nm wavelength, which is equivalent to an approx. 10% difference. Although those results apply to the visible range of solar radiation, elevated amounts of aerosol over the city may lead to a reduction in broadband direct irradiance.

Geographical location and source data

The measurements of direct solar radiation used in this study were taken at two sites: Warsaw and Belsk (Fig. 1). Warsaw has a population of over 1.7 million and covers approx. 517 km^2 (www.stat.gov.pl, status as of 2014). The measurements were taken at the Institute of Meteorology and Water Management - National Research Institute (IMGW-PIB), located in the northern part of the city at φ=52°16'N, λ=20°59'E and at 130 m above sea level. This is a typically urban area, but it is not central, which means that it is not as densely developed as the city centre and that the emissions of pollutants are smaller, despite there being quite a lot of traffic on the streets. The measurement site is surrounded by buildings of diverse height. The weather station itself is situated in the northern part of the city, so that during the sun's culmination in winter, early spring and late autumn the route of direct solar radiation lies over the city. Belsk, on the other hand, is a small village situated 45 km south of Warsaw (approx. 50 km from the IMGW-PIB site) in a rural area, far from urban and industrial development. The measurements there were taken at the Central Geophysical Observatory of the Institute of Geophysics, Polish Academy of Sciences (coordinates: φ=51°50'N, λ=20°48'E, elevation 180 m above sea level).

Direct solar radiation was measured by means of a Linke-Feussner actinometer in 1969-2003. Only the results of the direct solar radiation measurements performed in Warsaw and Belsk during the same day were used for data processing. Only data gathered during the noon periods (within more or less half an hour before and after the time of the solar noon) and the periods when the sun shield was not covered by clouds were selected for further analysis.

Direct solar radiation during clear sky condition depends mostly on the total water vapour content and AOT, both of which change with the air mass. The air masses have been defined and presented in maps published by the IMGW-PIB in the Synoptic

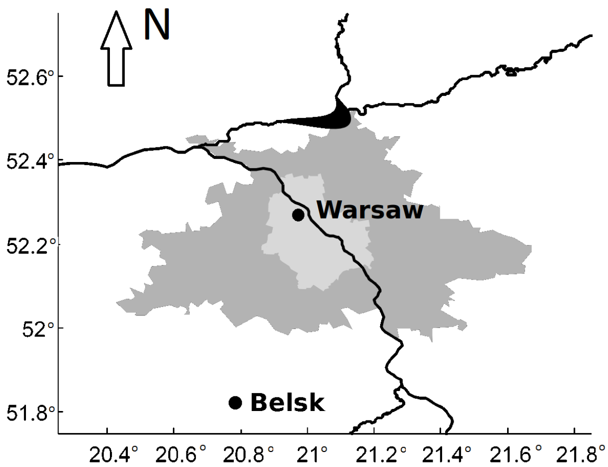

Fig. 1. Location of the measurement sites

Bulletins (until 1978), and in the Daily Meteorological Bulletins (from 1979 onwards). The air masses occurring over the area of observations were identified and divided into 5 groups: arctic, polar continental, polar maritime, polar maritime old and tropical. For each type of air mass, Linke's turbidity factor was determined, with its differences depending on the measurement site location and changes over time.

In addition, the HYbrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model (Stein et al. 2015) was used for determination of the backward trajectories of air masses flowing over each measurement site. As an input to HYSPLIT model NCEP/NCAR Reanalysis Project meteorological data were used (Kalnay et al. 1996) with a 2.5 degree spatial and 6 hours temporal resolution. The presented air masses trajectories were computed for 72 hours backwards.. Computations of trajectories were made for levels ending at 0.5, 1, 1.5, 2, 3 and 5 km above ground level.

Data processing methodology

Linke's turbidity factor (T_L) was applied to determine the extent of atmospheric extinction of direct solar radiation in the urban and nonurban areas. It was calculated from the results of measurements of direct solar radiation. Linke's factor indicates the influence of all components contributing to the atmospheric extinction. It represents the number of clean dry atmospheres required to achieve the same attenuation of solar radiation as is caused by the actual atmosphere.

The calculation methodology used in this study has been described in detail in a previous work (Uscka-Kowalkowska 2013). Linke's turbidity factor (1922, 1929) was calculated using the method proposed by Grenier et al. (1994):

$$T_L = (1/\delta_R m)\ln(E_0 I_{SC}/I_N)$$

where: δ_R is the optical thickness of clean dry atmosphere; m is the relative optical air mass corrected for atmospheric pressure; $E_0 I_{SC}$ is the solar constant corrected by the eccentricity factor, and I_N is the direct solar irradiance at the surface.

The relative optical air mass of the atmosphere was determined using Gueymard's formula (1993) making allowance for atmospheric pressure:

$$m = (P/1013.25\ \text{hPa})\cdot 1/[\sinh + a(90 - h)(b + h)^{-c}]$$

where: P is the actual pressure at the site (hPa, h is the solar elevation (in degrees), $a=1.76759\cdot 10^{-3}$, $b=4.37515°$, and $c=1.21563$.

Optical thickness of the clean dry atmosphere is obtained from a formula by Grenier et al. (1994):

$$\delta_R = (5.4729 + 3.0312m - 0.6329m^2 + 0.0910m^3 - 0.00512m^4)^{-1}$$

In order to eliminate a diurnal cycle of the Linke's turbidity factor related to Forbes effect, the above model, proposed by Grenier et al. (1994) was applied. This consists in a standardisation of values of Linke's turbidity factor, to obtain the value that the factor would have if the solar elevation angle was 30°.

Linke's turbidity factor was also presented in class intervals developed on the basis of the method proposed by Sivkov (1968) and Evnevich and Savikovskij (Ohvril et al. 1999). The atmospheric transparency coefficient corresponding with normal values was 0.736 and 0.770 (Ohvril et al. 1999), which translated into respective turbidity factors of 2.61 and 3.06. The class intervals corresponding to normal turbidity in this paper comprise T_{L2} values ranging from 2.6 to 3.0. Other classes are set every 0.5 of T_{L2}.

In order to estimate uncertainty of Linke's turbidity factor, it was assumed that the measurement error for direct solar radiation is 2.5%, of which 1% is the statistical error and 1.5% the systematic error (Markowicz and Uscka-Kowalkowska 2015). The uncertainty of Linke's turbidity factor, calculated using the above-mentioned method, ranges from 0.07 (Warsaw) and 0.08 (Belsk) to 0.18, which constitutes from more than 1% (Belsk) and more than 2% (Warsaw) to almost 8% of the obtained values of Linke's turbidity factor.

In all analysed differences between both sites, the applied level of statistical significance was 0.05. In addition, standard deviation for the values of monthly, seasonal and annual means are shown in the diagrams and tables. The statistical significance was calculated by the Statistica sotware using the t test.

Results

Based on the selected days, mean monthly and annual values of Linke's turbidity factor were calculated for Warsaw and Belsk (Table 1). The average value of Linke's turbidity factor in the analyzed period was 3.00 in Warsaw and 2.87 in Belsk. The annual course of atmospheric turbidity was similar at both sites. In the analysed data set, the atmosphere was the most turbid in April, with the second peak in summer months: August in Warsaw and July in Belsk. The minimum value for the annual course was observed in December at both sites. The annual course with its summer maximum and winter minimum is consistent with the pattern of Aerosol Optical Thickness (AOT) and the total water vapour content in the atmospheric column typically observed in Central Europe. Mainly these values affect Linke's turbidity factor. Previous studies based on measurements taken in Belsk (Jarosławski and Pietruczuk 2010; Zawadzka et al. 2013; Posyniak et al. 2016), on Mt. Kasprowy Wierch (Markowicz and Uscka-Kowalkowska 2015), as well as the results of numerical simulations of aerosol transport for Central Europe (Maciszewska et al. 2010), indicate that a typical pattern of AOT has its peaks in spring and summer. The spring maximum is connected with grassland fires and the inflow of Saharan dust, whereas the second maximum results from frequent forest and peatland fires in Eastern Europe (Jarosławski and Pietruczuk 2010; Zawadzka et al. 2013).

Nine months of the year were marked by higher values of T_{L2} in Warsaw when compared with Belsk, with October and February particularly standing out. In the other three months, the atmosphere was more turbid in Belsk, especially in July. The greatest standard deviation can be observed in the atmospheric turbidity values for spring (April and March) and summer months (August in Warsaw and July in Belsk). The smallest standard deviation was found for winter months, and December in particular (Table 1).

The data from both investigated sites show a similar seasonal variability of atmospheric turbidity. In terms of seasons, with each one comprising 3 months, the greatest atmospheric turbidity in both sites occurred in summer (June-August) and the smallest in winter (December-February) (Fig. 2). Nevertheless, only the winter minimum for each site is statistically significant (apart from winter and autumn in Belsk), as the increased turbidity in summer, compared with spring and autumn, showed no statistical significance. The difference in the value of atmospheric turbidity between summer and winter at both sites largely exceeds the determined uncertainty for Linke's factor. For both sites in spring (March-May), the atmospheric turbidity was great-

Table 1. Monthly means and uncertainty of Linke's turbidity factor (T_{L2}) as well as its standard deviation (σ) on selected days in Warsaw and Belsk in 1969-2003

Month/Year	Warsaw		Belsk	
	T_{L2}	σ	T_{L2}	σ
Jan	2.48 ± 0.06	0.46	2.51 ± 0.06	0.53
Feb	3.00 ± 0.08	0.64	2.76 ± 0.08	0.52
Mar	3.06 ± 0.10	0.70	2.86 ± 0.10	0.62
Apr	3.38 ± 0.12	0.71	3.32 ± 0.12	0.82
May	3.12 ± 0.13	0.60	2.92 ± 0.13	0.59
Jun	3.27 ± 0.13	0.50	3.03 ± 0.13	0.44
Jul	2.98 ± 0.13	0.67	3.27 ± 0.13	0.86
Aug	3.36 ± 0.12	0.80	3.16 ± 0.12	0.69
Sep	3.24 ± 0.11	0.60	3.00 ± 0.11	0.54
Oct	3.18 ± 0.08	0.50	2.89 ± 0.09	0.48
Nov	2.48 ± 0.07	0.35	2.49 ± 0.07	0.40
Dec	2.40 ± 0.06	0.32	2.25 ± 0.06	0.17
Year	3.00 ± 0.10	0.66	2.87 ± 0.11	0.63

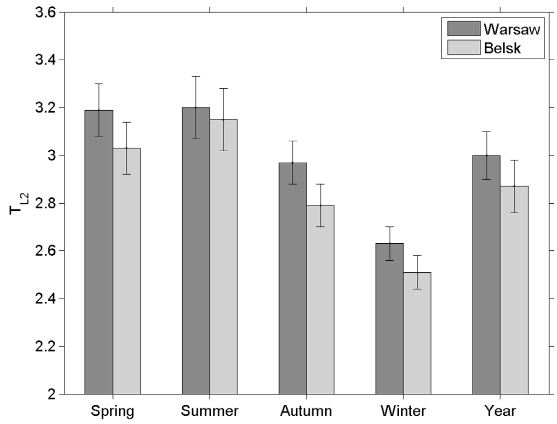

Fig. 2. Annual course of Linke's turbidity factor (by season) in Warsaw and Belsk in 1969-2003. The error bars show uncertainty of Linke's turbidity factor

er than in autumn (September-November), however the difference between these seasons is not statistically significant. In spring and summer, the analysed data set for both sites shows a greater standard deviation than in autumn and winter. In summary, the year can be divided into a cold part (winter) with low atmospheric turbidity, and a warm part (the other seasons) with increased turbidity.

Comparing the degree of turbidity in corresponding seasons in Warsaw and Belsk, smaller average values noted in Belsk than in Warsaw were observed in all seasons (Fig. 2). All these relations are statistically significant except the summer, when differences in the atmospheric turbidity in Warsaw and Belsk are small.

All of the measurements of atmospheric turbidity (T_{L2}) in Warsaw and Belsk were divided into classes (Table 2). The classes representing normal turbidity (2.6 – 3.0) comprise the same number of cases in both sites. During the year, Warsaw has fewer cases with a lower-than-usual degree of turbidity, and more cases with greater turbidity. The lower share of cases with low turbidity in Warsaw compared with Belsk is particularly marked in the cool season (October - March), while the prevalence of the higher turbidity classes in Warsaw compared with Belsk is similar in both parts of the year.

For each analysed day the difference in the value of Linke's turbidity factor between the two sites was calculated. The differences were then divided into classes shown in Table 3. Small differences were found to be the most frequent, indicating greater atmospheric turbidity in Warsaw (36.2%). Quite frequent were also the classes representing slightly greater turbidity in Belsk (20.1%). Overall, the classes indicating greater turbidity in Warsaw are more frequent (68.5%) than those indicating greater turbidity in Belsk (31.5%).

The frequency of occurrence of differences in the value of Linke's turbidity factor between Warsaw and Belsk varies in small extent depending on the part of the year (Table 3). In the warm (April - September) and in the cold (October - March) season the share of classes indicating greater turbidity in Warsaw compared with Belsk is similar, at 66.7% and 70.1%, respectively.

The atmospheric turbidity shows also long-term variability. The entire studied period of observations was divided into two sub-periods: an earlier (from 1969 to 1993) and a later period (from 1994 to 2003) (Uscka-Kowalkowska 2013; Posyniak et al. 2016). During the first sub-period both substantial atmospheric emissions of pollution and substantial volcanic activity were observed. The second sub-period was a time of decreased influence of anthropogenic factors, among which the decrease of industrial emissions to the atmosphere is the most important.

Following the social and economic transformations in Central Europe at the end of the 1980s, a great number of industrial plants were shut down and the new plants switched to new, cleaner technologies. After 1993, no major volcanic eruptions were observed which could be relevant to the study of atmospheric extinction. In the case of Warsaw and Belsk, Linke's atmospheric turbidity factor decreased in 1994-2003, compared to the values for the earlier sub-period (1969-1993) at both analysed sites (Table 4). This decrease is statistically significant for individual seasons and for the whole year.

In the first of the analysed sub-periods, greater atmospheric turbidity was observed in Warsaw

Table 2. Frequency classes of Linke's turbidity factor in Warsaw and Belsk in 1969-2003

Class	April - September				October - March				Year			
	Warsaw		Belsk		Warsaw		Belsk		Warsaw		Belsk	
	n	%	n	%	n	%	n	%	n	%	n	%
<2.1	0	0.0	0	0.0	6	7.8	5	6.5	6	4.0	5	3.4
2.1-2.5	11	15.3	17	23.6	22	28.6	34	44.2	33	22.1	51	34.2
2.6-3.0	24	33.3	26	36.1	21	27.3	19	24.7	45	30.2	45	30.2
3.1-3.5	13	18.1	12	16.7	15	19.5	12	15.6	28	18.8	24	16.1
3.6-4.0	14	19.4	9	12.5	10	13.0	7	9.1	24	16.1	16	10.7
>4.0	10	13.9	8	11.1	3	3.9	0	0.0	13	8.7	8	5.4

n - number of measurements, % - annual or seasonal share

Table 3. Frequency of occurrence of differences in Linke's factor in the warm and the cold parts of the year between Warsaw and Belsk in 1969-2003

Class	Apr - Sep		Oct - Mar		Year	
	n	%	n	%	n	%
>1.00	2	2.8	0	0.0	2	1.3
0.76 ÷ 1.00	3	4.2	4	5.2	7	4.7
0.51 ÷ 0.75	8	11.1	9	11.7	17	11.4
0.26 ÷ 0.50	11	15.3	11	14.3	22	14.8
0.01 ÷ 0.25	24	33.3	30	39.0	54	36.2
-0.24 ÷ 0.00	11	15.3	19	24.7	30	20.1
-0.49 ÷ -0.25	8	11.1	4	5.2	12	8.1
-0.74 ÷ -0.50	3	4.2	0	0.0	3	2.0
-0.99 ÷ -0.75	1	1.4	0	0.0	1	0.7
≤ -1.00	1	1.4	0	0.0	1	0.7

in all seasons of the year and in the whole year in comparison to Belsk. The particularly great difference was noticeable in autumn and winter. Of all the atmospheric turbidity differences in 1969-1993, only the difference for the summer was not statistically significant. In the second of the separated periods (1994-2003), in each site turbidity decreased in all seasons. In spring, summer and autumn, the atmosphere in Warsaw was still more turbid than in Belsk, but this dependence remained statistically significant only in spring. In 1994-2003 atmospheric turbidity in winter was almost the same in both sites (Fig. 3). Among the differences in the Linke turbidity factor in 1994-2003, the difference for spring and for the whole year was statistically significant (Fig. 3).

Atmospheric turbidity may also be analysed with reference to occurring air masses (Fig. 4). Polar air masses prevailed over the locations of the measuring sites, of which polar continental were the most frequent, followed by polar maritime and finally polar maritime old air masses. Arctic masses occurred more than six times as often as tropical ones. The frequency of occurrence presented in Figure 4 only applies to those days on which direct solar radiation measurements were taken as well. This is a bit different from the corresponding structure for all days in the area concerned. Considering that polar maritime air masses are characterised by substantial amounts of cloud, they are underrepresented in the analysed data set, compared with an account of all days of the indicated period. On the other hand, arctic and polar continental air masses, are more frequent on the studied days than in the entire period of 1969-2003.

The relationship between Linke's turbidity factor in different air masses is similar at both measurement sites (Table 5). The least turbidity occurred in arctic air masses, whereas the greatest was observed in tropical air masses. Of the polar types of air masses, the polar maritime old air proved to be the least turbid, whereas polar continental air was the most turbid in Warsaw, and polar maritime air the most turbid in Belsk. When looking into the statistical significance of the differences in turbidity values between air masses in different sites, the

Table 4. Annual course of the mean Linke's turbidity factor (T_{L2}) with uncertainty on selected days in Warsaw and Belsk in 1969-1993 and 1994-2003

Season	1969-1993		1994-2003	
	Warsaw	Belsk	Warsaw	Belsk
Spring	3.33 ± 0.11	3.31 ± 0.11	2.96 ± 0.12	2.75 ± 0.12
Summer	3.49 ± 0.13	3.41 ± 0.13	2.72 ± 0.12	2.63 ± 0.13
Autumn	3.18 ± 0.09	2.99 ± 0.09	2.65 ± 0.09	2.53 ± 0.09
Winter	2.75 ± 0.07	2.59 ± 0.07	2.24 ± 0.06	2.24 ± 0.06
Year	3.19 ± 0.10	3.07 ± 0.10	2.64 ± 0.11	2.54 ± 0.11

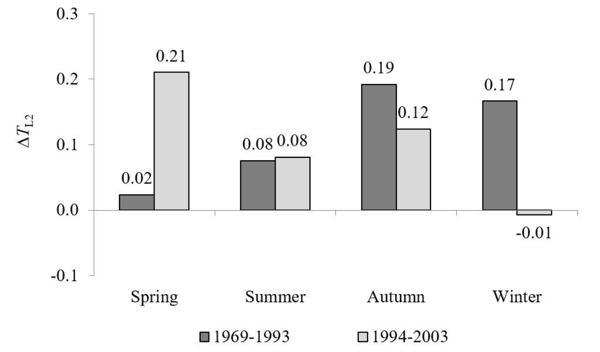

Fig. 3. Mean seasonal differences in Linke's turbidity factor between Warsaw and Belsk in 1969-1993 and 1994-2003

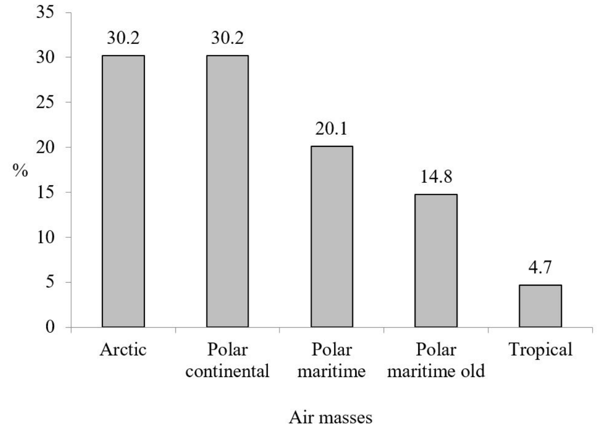

Fig. 4. Frequency of different air masses types over Warsaw and Belsk on selected days in 1969-2003

following observations can be made: in both Warsaw and Belsk, significantly greater atmospheric turbidity is caused by tropical and polar continental air masses than by the arctic type. In Belsk, polar maritime air also shows greater turbidity than in arctic air. All other differences in the degree of atmospheric turbidity between the different air masses are not statistically significant.

The largest differences in atmospheric turbidity between Warsaw and Belsk are observed for the tropical air masses, and the smallest occur when polar maritime air masses prevail (Fig. 5). In all examined air masses, average atmospheric turbidity was higher in Warsaw in comparison to Belsk. The large difference in T_{L2} occurred in the case of the tropical air masses, however, because of the low incidence of these masses, the difference was not statistically significant. Large and statistically significant differences in atmospheric turbidity occurred between Warsaw and Belsk for arctic and polar continental masses (Fig. 5).

On the analysed days, backward trajectories of air masses, determined using the HYSPLIT model, indicate that at a height of 0.5 km the advection of air masses from the east (32%), north (Warsaw 31%

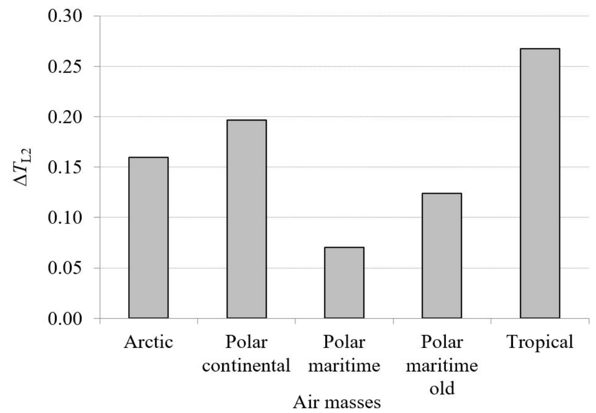

Fig. 5. Differences in the value of Linke's turbidity factor between Warsaw and Belsk for different air masses types in 1969-2003

and Belsk 32%) and west (30%) are comparably frequent (Table 6). The southern sector is where the air comes from the least (Warsaw 7%, Belsk 5%). At greater heights, the frequency of westerly advection increases (up to 77% in Warsaw and 75% in Belsk) while the share of all other sectors partially decreases.

Table 5. Linke's turbidity factor (T_{L2}) with uncertainty as well as its standard deviation (σ) in the distinguished air masses in Warsaw and Belsk in 1969-2003

Air mass	Warsaw		Belsk	
	T_{L2}	σ	T_{L2}	σ
Arctic	2.85 ± 0.10	0.55	2.69 ± 0.10	0.54
Polar continental	3.18 ± 0.10	0.73	2.98 ± 0.10	0.68
Polar maritime	3.11 ± 0.11	0.66	3.04 ± 0.11	0.59
Polar maritime old	2.91 ± 0.12	0.63	2.79 ± 0.12	0.69
Tropical	3.42 ± 0.09	0.64	3.16 ± 0.10	0.51

The greatest extinction of solar radiation occurs at all analysed heights in the southerly advection of air masses, with the exception of 5 km, at which it occurs when easterly air masses prevail. A smaller extinction can be observed when air masses come from the west or the north. Mean values do not indicate an increase in atmospheric turbidity in Belsk from the northerly advection, that is from the direction of Warsaw (Fig. 6).

The relationship between the ratio of the distance travelled by air mass to the straight line distance of the back trajectory can be used as the parameter describing the possible transformation of the air mass. The high value of this parameter indicates usually slow anticyclone circulation which in Central Europe leads to an increase of the AOT.

Table 7 presents such a relationship for selected back trajectory altitudes. In the case of the lowest heights (500 m and 1000 m), increased atmospheric turbidity is evident, as the mean speed of air mass drops, particularly where the above-described turbidity factor exceeds 3. At greater heights this relationship is not present.

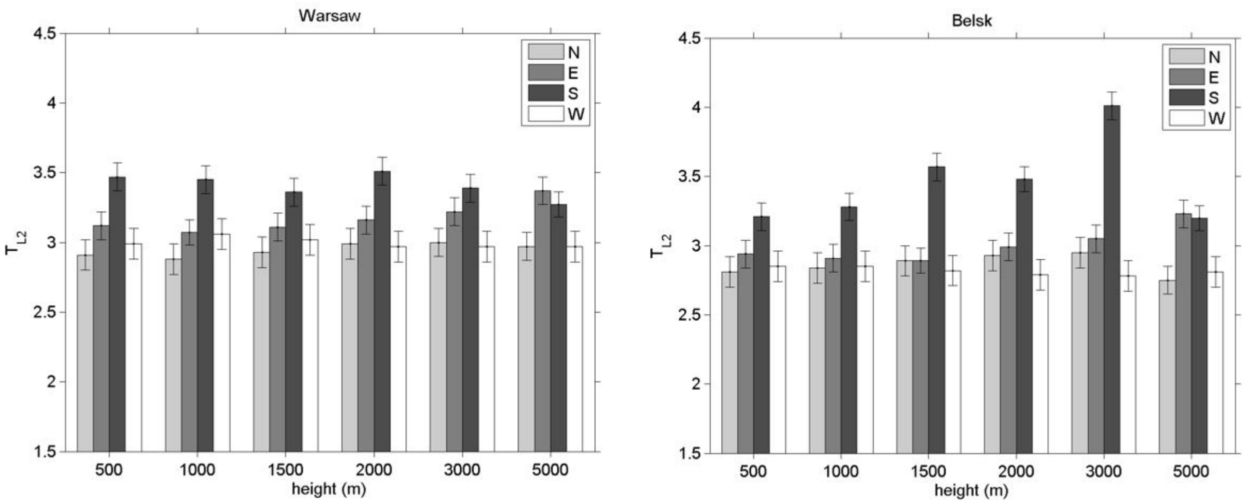

Fig. 6. Atmospheric turbidity as a function of the backward trajectory altitude and direction in Warsaw and Belsk on selected days in 1969-2003. The error bars show uncertainty of Linke's turbidity factor

Table 6. Percentage share of the inflow of air masses from different directions at selected heights (m) in Warsaw and Belsk

Height (m)	500	1000	1500	2000	3000	5000
			Warsaw			
N	30.9	25.5	20.8	17.4	16.1	4.7
E	32.2	30.9	28.2	27.5	20.8	15.4
S	6.7	5.4	4.0	2.0	2.0	3.4
W	30.2	38.3	47.0	53.0	61.1	76.5
			Belsk			
N	32.2	28.9	24.2	18.8	18.1	6.0
E	32.2	30.9	28.9	25.5	20.8	16.1
S	5.4	4.0	4.0	2.7	1.3	2.7
W	30.2	36.2	43.0	53.0	59.7	75.2

Table 7. Atmospheric turbidity (T_{L2}) with uncertainty dependent on the relationship between the distance covered by air mass (d) and the straight line distance to the measurement point (f), for 72-hour backward trajectories in Warsaw and Belsk

d/f	Height (m)					
	500	1000	1500	2000	3000	5000
			Warsaw			
<1.5	3.05 ± 0.11	3.04 ± 0.11	3.02 ± 0.11	3.03 ± 0.11	3.07 ± 0.11	3.11 ± 0.11
1.6-2.0	2.77 ± 0.10	3.03 ± 0.10	3.16 ± 0.09	3.04 ± 0.10	2.92 ± 0.10	2.86 ± 0.10
2.1-3.0	3.14 ± 0.11	2.95 ± 0.09	3.09 ± 0.11	3.06 ± 0.10	3.13 ± 0.09	2.97 ± 0.11
>3.0	3.15 ± 0.09	3.17 ± 0.11	3.01 ±0.09	3.09 ± 0.10	2.54 ± 0.07	2.95 ± 0.09
			Belsk			
<1.5	2.89 ± 0.11	2.90 ± 0.11	2.88 ± 0.11	2.88 ± 0.11	2.91 ± 0.11	2.91 ± 0.11
1.6-2.0	2.78 ± 0.10	2.74 ± 0.09	2.91 ± 0.09	2.93 ± 0.09	2.85 ± 0.10	2.85 ± 0.11
2.1-3.0	2.94 ± 0.11	2.96 ± 0.11	2.98 ± 0.10	2.94 ± 0.09	2.69 ± 0.08	2.88 ± 0.10
>3.0	3.14 ± 0.09	2.94 ± 0.11	2.64 ± 0.12	2.77 ± 0.12	2.73 ± 0.09	2.76 ± 0.09

Discussion and summary

The amount of incoming solar radiation is a fundamental factor shaping climatic conditions. Changes in this amount caused by a polluted urban atmosphere can trigger a change in climatic conditions in the city, compared to its neighbouring non-urban areas. In order to study the extent of a city's influence on the extinction of solar radiation in the atmosphere, the results of parallel observations from an urban and a non-urban site are required. The distance between the two sites should be long enough to ensure that anthropogenic influences from the urban site do not reach the other non-urban, however, natural conditions at both sites should be as similar as possible. There are not many climatological works in which long data series from sites satisfying these conditions are utilised.

The problem of the influence of urban conditions on the extinction of direct solar radiation, based on the example of the city of Warsaw and the village of Belsk, has already been studied for the period 1957-1980 (Michałowska-Smak 1981). In that case, Linke's turbidity factor was also used, however it was determined using a different methodological approach which makes it impossible to directly relate to the results here. On the other hand, the turbidity relationship found between Warsaw and Belsk can still be used. It should be noted that the observations concerned independent data sets, which means that the results for both sites might have been obtained on different days. In all months of the year, the atmospheric turbidity in Warsaw was greater than in Belsk, with the greatest difference in autumn: November (15.1%) and October (12.4%). In the cold part of the year (October-February), the differences in atmospheric turbidity were greater than in the warm part (March-September). This resulted from the atmospheric extinction caused by aerosol content, whereas the degree of extinction caused by water vapour was comparable at both sites (Michałowska- Smak 1981). On average, the annual atmospheric turbidity in Warsaw was about 4% greater than in Belsk. For more recent years, studies of the influence of pollution emitted in the city (Warsaw) on aerosol characteristics were conducted by Zawadzka et al. (2013). Observations were carried out using, for example, CIMEL and Microtops II photometers in 2005-2011. A 10%-15% influence of the city on increased optical thickness of the atmosphere was demonstrated. The influence was found to be much greater when exceptionally unfavourable weather conditions prevailed (anticyclonic weather, weak wind) (Zawadzka et al. 2013).

In Poland, similar research has been carried out in Krakow (Olecki 1992). The atmospheric transparency in Krakow and at a site located outside the city was compared for days with a cloudless sky in 1968-1985. It was established that the atmosphere was more transparent outside the city in all months of the year. Major differences occurred in winter, with the difference in atmospheric transparency reaching over 17% in December. The smallest differences in transparency were found in summer, with the minimum value in June when it was below 4% (Olecki 1992).

Outside Poland, similar research has been carried out in Moscow and at a suburban weather site situated 40 km south-west of the city. In the period between 1955-1974, it was found that the turbidity in the city is higher (on average 9%) than in the suburban area (Abakumova et al. 1983).

The results of this study, as well as the results previously reported in other papers, indicate that a cool period, i.e. winter, is the one when the city's influence on radiation extinction is the greatest. This is evident in periods with generally greater extinction values. In the case of Warsaw and Belsk and selected days of 1969-2003, the city's significant influence on extinction of solar radiation in the period from autumn to spring is also evident. The increased extinction of solar radiation in the city compared to the suburban area in the cold season may be associated with increased emissions of pollutants into the atmosphere due to increased use of domestic heating stoves and central heating furnaces.

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References

ABAKUMOVA G.M., EVNEVICH T.W., NIKOLSKA N.P., 1983, Wlianiye goroda na prozrachnost atmosfery. Izdatelstvo Moskovskogo Universitieta, Moscow.

ACKERMAN B., 1986, Climatology of Chicago area urban-rural differences in humidity. Journal of Climate and Applied Meteorology, 26: 427-430.

ADEBAYO Y.R., 1991, Day-time effects of urbanization on relative humidity and vapour pressure in a tropical city. Theoretical and Applied Climatology, 43: 17-30.

BŁAŻEJCZYK K., 2002, Znaczenie czynników cyrkulacyjnych i lokalnych w kształtowaniu klimatu i bioklimatu aglomeracji warszawskiej, Dokumentacja Geograficzna, 26.

DAILY METEOROLOGICAL BULLETINS, 1979–2003, Institute of Meteorology and Water Management, Warsaw.

CHUBAROVA N.Y., SVIRIDENKOV M.A., SMIRNOV A., HOLBEN B.N., 2011, Assessments of urban aerosol pollution in Moscow and its radiative effects. Atmospheric Measurements Techniques, 4: 367-378.

FORTUNIAK K., KŁYSIK K., WIBIG J., 2006, Urban-rural contrasts of meteorological parameters in Łódź. Theoretical and Applied Climatology, 84: 91-101.

GRENIER J.C., DE LA CASINIÈRE A., CABOT T., 1994, A spectral model of Linke's turbidity factor and its experimental implications. Solar Energy, 52: 303-313.

GUEYMARD C., 1993, Critical analysis and performance assessment of clear sky solar irradiance models using theoretical and measured data. Solar Energy, 51: 121-138.

JAROSŁAWSKI J., PIETRUCZUK A., 2010, On the origin of seasonal variation of aerosol optical thickness in the UV range over Belsk, Poland. Acta Geophysica, 58, 6: 1134-1146.

KOZŁOWSKA-SZCZĘSNA T., BŁAŻEJCZYK K., KRAWCZYK B., 1996, Atlas Warszawy. 4, PAN IGiPZ, Warszawa.

LANDSBERG H.E., 1981, The Urban Climate, Academic Press, New York.

LINKE F., 1922, Transmissions Koefficient und Trübungsfaktor. Beträge zur Physik Freien Atmosphäre, 10: 91–103.

LINKE F., 1929, Messungen der Sonnenstrahlung bei vier Freiballonfahrten. Beträge zur Physik Freien Atmosphäre, 15: 176–185.

MACISZEWSKA A., MARKOWICZ K., WITEK M., 2010, A Multiyear Analysis of Aerosol Optical Thickness over Europe and Central Poland Using NAAPS Model Simulation. Acta Geophysica, 58(6): 1147-1163.

MARKOWICZ K.M., USCKA-KOWALKOWSKA J., 2015, Long-term and seasonal variability of the aerosol optical depth at Mt. Kasprowy Wierch (Poland). Journal of Geophysical Research: Atmospheres, 120 (5): 1865-1879.

MICHAŁOWSKA – SMAK A., 1981, Seasonal and secular changes of atmospheric turbidity in Warsaw and Belsk in the interval 1957–1980. Publications of the Institute of Geophysics Polish Academy of Sciences, D-13 (149): 115–131.

MOHAN A., PATHAN S.K., NARENDRAREDDY K., KANDYA A., PANDEY S., 2011, Dynamics of Urbanization and Its Impact on Land-Use/Land-Cover: A Case Study of Megacity Delhi. Journal of Environmental Protection, 2: 1274-1283.

OHVRIL H., OKULOV O., TERAL H., TERAL K., 1999, The atmospheric integral transparency coefficient and the Forbes effect. Solar Energy, 66, 4: 305-317.

OLECKI Z., 1992, Przezroczystość atmosfery w Krakowskiej aglomeracji miejsko – przemysłowej. Zeszyty Naukowe UJ, nr MXLII, Prace Geograficzne, 90: 23–34.

POSYNIAK M., SZKOP A., PIETRUCZUK A., PODGÓRSKI J., KRZYŚCIN J., 2016, The long-term (1964 - 2014) variability of aerosol optical thickness and its impact on solar irradiance based on the data taken at Belsk, Poland. Acta Geophisica, 64, 5: 1858-1874.

PRZYBYLAK R., USCKA-KOWALKOWSKA J., ARAŹNY A., KEJNA M., KUNZ M., MASZEWSKI R., 2017, Spatial distribution of air temperature in Toruń (Central Poland) and its causes. Theoretical and Applied Climatology, 127, 1-2: 441-463.

SIVKOV S.I., 1968, Methods to compute solar radiation characteristics, Gidrometeotologicheskoye Izdatelstvo, Leningrad.

STEIN A.F., DRAXLER R.R., ROLPH G.D., STUNDER B.J.B., COHEN M.D., NGAN F., 2015, NOAA's HYSPLIT atmospheric transport and dispersion modeling system. Bulletin of the American Meteorological Society, 96: 2059-2077.

STEWART I.D., OKE T.R., 2012, Local climate zones for urban temperature studies. Bulletin of the American Meteorological Society, 93: 1879-1900.

SUN L., WEI J., DUAN D.H., GUO Y.M., YANG D.X., JIA C., MI X.T., 2016, Impact of Land–Use and Land-Cover Change on urban air quality in representative cities of China. Journal of Atmospheric and Solar-Terrestial Physics, 142: 43-54.

SYNOPTIC BULLETINS, 1969-1973, State Hydrological and Meteorological Institute, 1974-1978. Institute of Meteorology and Water Management, Warsaw.

UNKAŠEWIĆ M., JOVANOVIĆ O., POPOVIĆ T., 2001, Urban-suburban/rural vapour pressure and relative humidity differences at fixed hours over the area of Belgrade city. Theoretical and Applied Climatology, 68: 67-73.

USCKA-KOWALKOWSKA J., 2013, An analysis of the extinction of direct solar radiation on Mt. Kasprowy Wierch, Poland. Atmospheric Research, 134: 175-185.

ZAWADZKA O., MARKOWICZ K.M., PIETRUCZUK A., ZIELINSKI T., JAROSŁAWSKI J., 2013, Impact of urban pollution emitted in Warsaw on aerosol properties. Atmospheric Environment, 69: 15–28.

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