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UV and global solar radiation in Łódź, Central Poland

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ABSTRACT: With the overall aim of quantifying urban atmospheric effects on different parts of the solar spectrum, a multi year analysis of data collected at Łódź was undertaken. UV (290–400 nm) and global solar radiation measured by means of a Kipp and Zonen CUV3 radiometer and a Kipp and Zonen CM11 pyranometer in the center of Łódź between 1997 and 2001 are analysed. The mean annual sum of global and UV solar radiation equaled 3710.8 MJ m^{-2} and 154.1 MJ m^{-2}, respectively. The minimum monthly total of solar energy occurred in December (48.7 M Jm^{-2} – global; 2.1 MJ m^{-2} – UV); however, the maximum monthly total occurred atypically in May (620.9 MJ m^{-2} – global; 25.3 MJ m^{-2} – UV). UV clearness index (Kuv) is approximately half of the clearness index of the global solar radiation, indicating greater attenuation of that part of the spectrum (Kuv 0.14 in December to 0.26 in May). A linear regression model was fitted to the daily values of UV and global (g) solar irradiation ($Duv = a + Dg\ b$). The slope coefficient b and the coefficient of determination equal 0.039 and 0.98, respectively. Cloudiness exerts an important control on the solar radiation flux at the ground level and for the relation between UV and global solar radiation. The convective clouds caused an increase of global and UV solar irradiance by about 10–20% compared to clear days, the enhancement resulting from reflections. On clear days, UV comprises 3.3–4% of global solar irradiance (10-min values) on average, while during cloudy weather it increases to 8%. The results presented have implications for understanding the radiative transfer of UV and global solar radiation in the atmosphere over an urban area and the influence of clouds on transmission of solar radiation flux.

KEY WORDS broadband UV radiation; global solar radiation; clearness index of UV and global radiation; ratio of UV to global radiation; Łódź; Poland

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1. Introduction

At the top of the atmosphere, biologically active solar wavelengths 290–400 nm (UVB + UVA) comprise 7.9% of the solar constant (UVB irradiance 1.4%, UVA up to 6.5%) (Thekaekara, 1973). The transmission of UV radiation through the atmosphere depends on a number of factors including: solar elevation, ozone, content aerosols, dust particles, nitrogen dioxide (NO_2) and sulfur dioxide (SO_2) concentrations; and cloud parameters, e.g. optical thickness, liquid water content, droplets size and location in the sky. Generally, UV radiation reaching the Earth's surface in Europe does not exceed 5% of global solar radiation under cloud-free sky conditions; however, this does vary spatially and temporally (Feister and Grasnick, 1992; Martinez-Lozano *et al*., 1999). Knowledge of the amount of UV radiation reaching the Earth's surface is important given UV is known to be an agent in photobiological phenomena such as bactericidal effects, melanogenic and erythogenic processes (skin pigment, redness of skin etc.), eye diseases, skin cancer, photosensitivity reactions (photoallergy, phototoxicity), damage of plants and degradation of all polymeric materials like plastic, asphalt, paint, textiles, etc. (Zigman, 1977; Urbach, 1989; Horneck, 1995; Longstreth *et al*., 1998). UV also plays an important role in atmospheric photochemistry, especially in the formation of photochemical smog. For a long time, only UVB (290–320 nm) has been thought to be responsible for the negative environmental effects, but now there is abundant experimental and epidemiological evidence of strong biological effects of UVA (320–400 nm). These include photosensitivity reactions, initiating eye diseases (cataracts), and intensifying biological effects of UVB (Diffey, 1991).

Interest in UV radiation at the Earth's surface has increased since the 1980s when the magnitude of a ozone depletion was revealed. Significant research efforts have been undertaken to organize networks of UV ground-based measurements to assess the long-term and short-term spatial and temporal variability of UV radiation and to improve forecasting methods of UV radiation over Europe (COST-Action 713; COST-Action 726; WMO, 2007). Long-term surface UV measurements are mainly associated with the erythemal part of the solar spectrum – UVB. Most European UVB observing stations have reliable data records up to 10–15 years (Krzyścin *et al*., 2004). The data base of surface UVB longer than two decades is available for only one station in Europe, Belsk (Central Geophysical Observatory – 51.7 °N, 20.8 °E; Poland), where observations have been carried out since 1976 (Krzyścin, 1996; Borkowski,

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2000; Krzyścin *et al*., 2004). Surface UVB irradiance has been found to be increasing since the beginning of the 1990s in Central, Eastern and Northern Europe (Krzyścin *et al*., 2004; Josefsson, 2006; Chubarova, 2008).

Over the last decade the measurements of integrated UV radiation (UVB + UVA) have become more widespread. In Europe, analyses of short-term variability of broadband UV radiation have been undertaken at: Potsdam (Germany), (Feister and Grasnick, 1992); Valencia (Spain), (Martinez-Lozano and Casanovas, 1994; Martinez-Lozano *et al*., 1996; Martinez-Lozano *et al*., 1999); Bratislava (Slovakia), (Zavodska and Reichrt, 1985); Jungfraujoch (Switzerland), (Ambach *et al*., 1991, Blumthaler *et al*., 1994); and Granada (Spain), (Foyo-Moreno *et al*., 1998). In Poland, the monitoring of UV radiation focuses on erythemally weighted UV in rural areas (Belsk since 1976, Łeba, Legionowo, Kasprowy Wierch since 1993).

Measurements of solar irradiance in different part of spectrum are especially important in urban areas with a polluted atmospheres. UV radiation is a principal component of urban bioclimate, mainly due to the influence on air sanitary conditions and strong impact of human activities. Studies on broadband UV radiation flux inflow in the urban area remain uncommon in Poland and only a few results have been published for Łódź (Podstawczyńska and Pawlak, 2003; Podstawczyńska, 2007) and for Warsaw (Błażejczyk and Baranowski, 2003).

This study presents the results of investigations on the variability of UV and global solar radiation in the center of Łódź for a 5-year period. Attention is directed to the ratio of the solar radiation at ground level to the values at the top of the atmosphere, the relationship between UV and global solar radiation, and the effects of clouds on these relationships.

2. Data and methods

2.1. Study area

Łódź with its ~760 000 inhabitants is the second largest town in Poland. The solar radiation measurements have been conducted at the urban meteorological station located in the city center. The downtown of Łódź is densely built-up with compact residential and industrial 3–6 storey buildings, mostly dating back to the turn of the twentieth century. The old downtown is charaterized by an increased air turbidity in wintertime due to domestic coal-fire furnaces with intense anthropogenic effects on radiative transfer in the atmosphere. In the center of Łodź the concentrations of dustiness and sulphur dioxide, both of them important factors for attenuation of UV radiation, have decreased rapidly since 1990. Today, the concentrations do not exceed the admissible Polish limits. In the city center SO_2 concentrations per 24 h have not exceeded the Polish admissible norm on a special protection region (75 μg m^3) since the mid-1990s (Kłysik and Fortuniak, 1999). Studies of urban–rural differences of global solar radiation in Łódź in 1997–2001 revealed a 5% depletion of annual totals of solar energy in the city center (Podstawczyńska, 2007). This finding is smaller than the values of 15–20%, widely quoted in the literature (Landsberg, 1981; Oke, 1988).

2.2. Instrumentation and data processing

The measurements of broadband UV radiation (290–400 nm, UVB + UVA) and simultaneous measurements of global solar radiation (302–2800 nm, direct and diffuse radiation) were initiated in the city center of Łódź at the meteorological station of the Department of Meteorology and Climatology of the University of Łódź in 1997. The station, called Łódź–Lipowa (51°45′N, 19°26′E), is located at the roof of the building of the Institute of Physical Geography, 18 m above street level (220 a.s.l.). The measurements have been carried out by means of a new CUV3 Kipp & Zonen radiometer and a new CM11 Kipp & Zonen pyranometer calibrated by the manufacturer. The stability of the CM11 pyranometer calibration factor was checked under field conditions (at Łódź–Lipowa) using a second new detector of the same type in June and July of 1999. In 2001, the CM11 was calibrated at the Actinometric Laboratory of Institute of Meteorology and Water Management, Warsaw. The calibration procedure was performed in two ways: first, under field conditions using a radiometer which had a calibration traced to a WMO intercomparison; second, using a standard lamp. Through these instrument stability of ±2% per year has been established. This is in accordance with the expectation of manufacturer.

Checks of the CUV3 radiometer stability were performed twice during the period 1997–2001 at Łódź–Lipowa. The CUV3 instrument was compared with a new identical instruments (calibrated by Kipp and Zonen) in June and July in 1999 and 2001. The comparisons and the annual repeatability of the data provide some indication that the instrument sensitivity did not change more than 3% between 1997 and 2001. Again, this is in accordance with the expectation of manufacturer.

The horizon for the radiometers is unobstructed and unchanged through the measurement period. The Sky View Factor is 0.993. The solar radiation (Wm^{-2}) is sampled every 10 s and 10-min averages are recorded on a 21× Campbell Sci. Ltd. data logger. In the present study, 10-min averages of UV and global solar irradiance, as well as the daily, monthly and annual solar irradiation for the period 1997–2001 have been analysed.

The UV and global solar irradiation on horizontal surface at the top of the atmosphere and *clearness index* of global and UV irradiation (*Kg, Kuv*) were calculated. *Kg* and *Kuv* are defined as the ratio of incoming solar radiation on the Earth's horizontal surface to the extraterrestrial solar radiation on the horizontal surface (Liu and Jordan, 1960; Iqbal, 1983; Sadler, 1992; Martinez-Lozano and Casanovas, 1994). The Solar Constant equals 1365 Wm^{-2} (NOAA Data Geophysical Data Center). The Solar Constant for the wavelengths 290–400 nm equals 108 Wm^{-2} (obtained from the spectral values given by Thekaekara (1973). The data collected also include hourly values of cloud cover and type of clouds from visual observations for the 5-year study period. Kasten's (1966) formula for the calculation of optical air mass has been used. The relationship between daily UV and global solar irradiation has been analysed, and general linear models of the form $y = a + bx$ is calculated. The ratio of UV 10-min irradiance and the daily UV irradiation to global 10-min irradiance and the daily global irradiation also has been calculated and the types of cloud affecting the ratios were analysed.

3. Results and discussion

3.1. Annual variability of UV and global solar irradiance

Over the year, the maximum daily solar elevation at the Łódź–Lipowa station varied from 14.7° (December) to 61.7° (June). Together with atmospheric transmission conditions, this determines the annual course of solar irradiance. Figure 1 illustrates isopleths of the mean hourly solar radiation flux for the year. The monthly mean hourly UV (Iuv) and global (Ig) solar irradiance (all data sets) at noon in December equaled 3.9 Wm^{-2} and 93.3 Wm^{-2}, respectively. The average for clear days was 7.5 Wm^{-2} (Iuv) and 240 Wm^{-2} (Ig). Under cloudless conditions in June, Iuv and Ig did not exceed 40 Wm^{-2} and 920 Wm^{-2}, respectively. The maximum monthly mean hourly UV and global solar irradiance occurred unexpectedly in May: 27.1 Wm^{-2} (Iuv) and 643.6 Wm^{-2} (Ig) (Figure 1). The secondary annual maximums were observed in August (Tables IV and II). The reduction of solar radiation in June and July is a consequence of the intensity of the zonal circulation and the resulting increased cloudiness.

In general, the highest hourly values of Iuv and Ig occur between 1100 and 1300 h (Tables I and II). Figure 2 shows the annual course of the absolute maximum of UV and global 10-min irradiance per day recorded at the Łodź–Lipowa station for the 5-year study period. Mostly, the absolute maximum values were observed for cloudy skies (Figure 2). In December, 10-min maximum irradiance of Iuv and Ig reached 9 Wm^{-2} and 300 Wm^{-2}; in the summer the values were 43 Wm^{-2} (Iuv) and 1095 Wm^{-2} (Ig). Strong increases of solar irradiance, 10–20% above equivalent in clear-sky values, were observed in Łódź in the summer months when convective clouds occurred. This usually lasted for duration of less than an hour, most frequently of 10–20 min. Clouds generally reduce the incoming solar radiation flux to the Earth's surface as the solar disk is obscured, but they may also enhance solar irradiance, especially UV, when the solar disk is partly covered by clouds (Thiel *et al*., 1997; Degünther and Meerkötter, 2000). Values of 5–15% are commonly cited in the literature (Monteith and Unsworth, 1988; Robinson, 1977). Enhancements of irradiance are caused by reflection from the lateral sides of clouds, especially of *cumulus*-type, the so-called 'silver lining scattering effect' (Monteith and Unsworth, 1988). Segal and Davis (1992) suggest that deep *cumulus* clouds in Colorado (USA) caused an enhancement of global solar irradiance up to 250 Wm^{-2} for short-time periods (less than an hour). In the case of the UV radiation flux observed at the ground, it could increase by 15–27% in relation to the values observed under clear skies due to *cumulus* downward scattering effects (Mims and Frederick, 1994; Estupinan and Raman, 1996; Degünther and Meerkötter, 2000). Investigations of the effects of clouds on UV-B radiation at Belsk (Poland), on the basis of 2-year measurements, have revealed a maximum enhancement of *ca*. 20% above the equivalent clear-sky values (Krzyścin *et al*., 2003). Figure 3 illustrates the influence of *cumulus*-type clouds on the daily course of UV and global solar irradiance. The maximum 10-min global solar irradiance on cloudy days was 1037 Wm^{-2}. This exceeded the maximum value for clear skies. The enhancement equaled 139 Wm^{-2} (i.e. 15%). UV irradiance recorded on cloudy days reached 40.8 Wm^{-2} and it was 4 Wm^{-2} (i.e. 11%) higher than the maximum

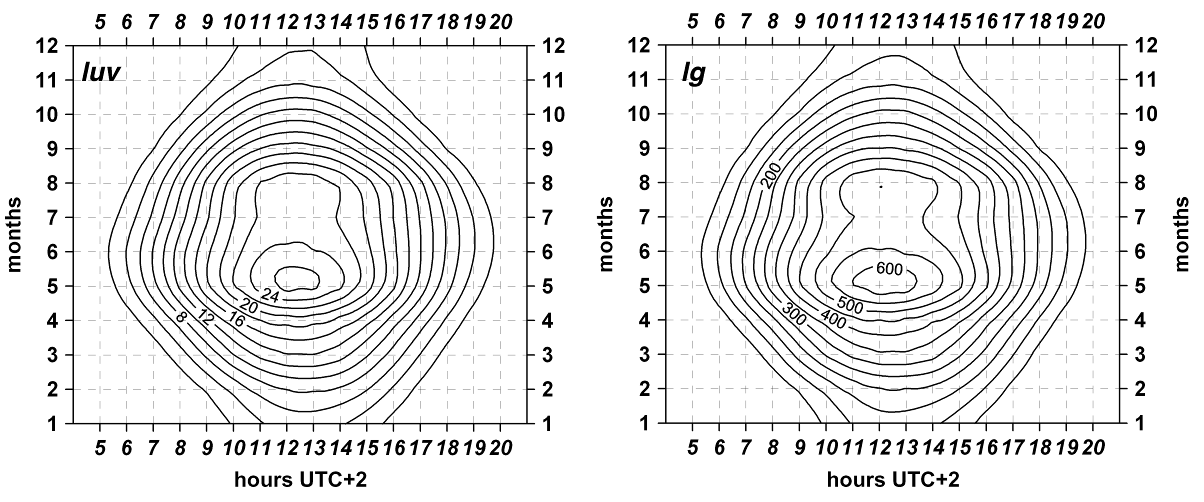

Figure 1. Annual course of the mean hourly values of UV (Iuv, Wm^{-2}) and global solar irradiance (Ig, Wm^{-2}) at Łódź–Lipowa station in 1997–2001. Isopleths at 2 Wm^{-2} (Iuv) and 50 Wm^{-2} (Ig) intervals.

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Table I. The mean monthly global solar irradiance (Wm^{-2}) in hourly intervals at Łódź–Lipowa station for the period 1997–2001. The highlighted values are the greatest monthly values.

Hour	3–4	4–5	5–6	6–7	7–8	8–9	9–10	10–11	11–12	12–13	13–14	14–15	15–16	16–17	17–18	18–19	19–20	20–21
Jan	0	0	0	0	0.2	15.3	57.9	104.4	130.9	129.4	108.4	74.2	30.1	3	0	0	0	0
Feb	0	0	0	0.1	10.2	55.6	113.1	166.3	196.1	196.7	187	149.7	94.8	34.4	2	0	0	0
Mar	0	0	0.3	16.3	79.9	172.1	258	315	343.7	343.7	319	256.7	185.2	102.6	31.2	1.3	0	0
Apr	0	0.6	20.8	89.6	183.9	286.2	368.6	430.1	444.8	435.8	403.9	356.1	268.1	180.9	91.3	22.2	0.3	0
May	0.1	15.3	87.8	201.8	328	447.4	541.8	603.6	643.6	632.6	581.9	513.2	408.6	288.2	176.3	80.8	12.9	0
Jun	0.8	30	106.8	212.3	326.9	423.2	487.2	541.6	551.6	537.6	519.7	474.8	385.6	293.3	192.1	103.8	33.1	1.5
Jul	0.2	13.9	70.8	159.6	268.4	367.3	457	496.9	500.8	509.5	479.4	446.2	369.2	285.4	187.7	99.1	26.8	0.8
Aug	0	1.3	35.4	122.2	239.5	363.6	470	529.4	554.1	542.1	511.6	451.4	377.2	270	145.7	54.3	4.2	0
Sep	0	0	3.5	45.8	133.7	236.6	326.2	383.8	397.5	388.1	361.2	296.8	220.6	128.5	44.6	3.4	0	0
Oct	0	0	0	5.2	44.1	104.8	181.5	236.6	266.3	264.8	221	161.6	98.1	31	1.8	0	0	0
Nov	0	0	0	0	6.2	37.1	79.2	111.8	126.1	123.7	105.1	66.8	23.8	1.3	0	0	0	0
Dec	0	0	0	0	0.2	10.7	40.1	70.6	91.2	93.3	75.2	44.1	10.9	0.1	0	0	0	0

Table II. The mean monthly UV solar irradiance (Wm^{-2}) in hourly intervals at Łódź–Lipowa station for the period 1997–2001. The highlighted values are the greatest monthly values.

Hour	3–4	4–5	5–6	6–7	7–8	8–9	9–10	10–11	11–12	12–13	13–14	14–15	15–16	16–17	17–18	18–19	19–20	20–21
Jan	0	0	0	0	0	0.7	2.2	3.8	4.9	5	4.2	2.9	1.3	0.2	0	0	0	0
Feb	0	0	0	0	0.5	2.2	4.5	6.7	8	8.2	7.7	6.1	3.7	1.4	0.1	0	0	0
Mar	0	0	0	0.7	3.1	6.4	10	12.6	13.9	14	12.8	10.2	7.1	3.9	1.3	0.1	0	0
Apr	0	0	0.9	3.4	7	11.3	15	17.8	18.6	18.5	17	14.6	10.8	7.1	3.6	1	0	0
May	0	0.7	3.3	7.4	12.5	17.7	22	25.1	27.1	26.7	24.5	21.1	16.4	11.3	6.7	3	0.7	0
Jun	0.1	1.3	4.1	8.2	13.1	17.5	20.9	23.7	24.4	24	22.9	20.5	16.4	12.1	7.7	4.1	1.4	0.1
Jul	0	0.7	2.9	6.4	11	15.6	19.8	22.1	22.7	23	21.6	19.6	15.9	11.8	7.6	3.9	1.2	0.1
Aug	0	0.1	1.5	4.7	9.3	14.5	19.3	22.2	23.7	23.4	21.8	18.9	15.3	10.5	5.8	2.2	0.3	0
Sep	0	0	0.2	1.9	5.3	9.5	13.4	16	16.9	16.6	15.2	12.2	8.8	5	1.8	0.2	0	0
Oct	0	0	0	0.3	1.9	4.4	7.4	9.8	10.9	10.8	9	6.5	3.8	1.3	0.1	0	0	0
Nov	0	0	0	0	0.3	1.6	3.2	4.6	5.3	5.1	4.3	2.7	1	0.1	0	0	0	0
Dec	0	0	0	0	0	0.5	1.8	3	3.8	3.9	3.2	1.9	0.6	0	0	0	0	0

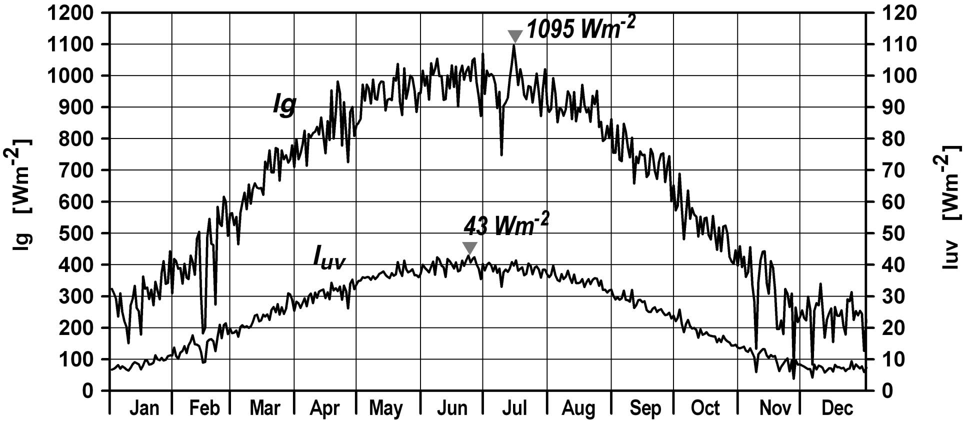

Figure 2. Annual course of absolute maximum of 10-min average of UV (Iuv, Wm^{-2}) and global solar irradiance (Ig, Wm^{-2}) at Łódź–Lipowa station in 1997–2001. Dots – absolute maximum values for 5-year period.

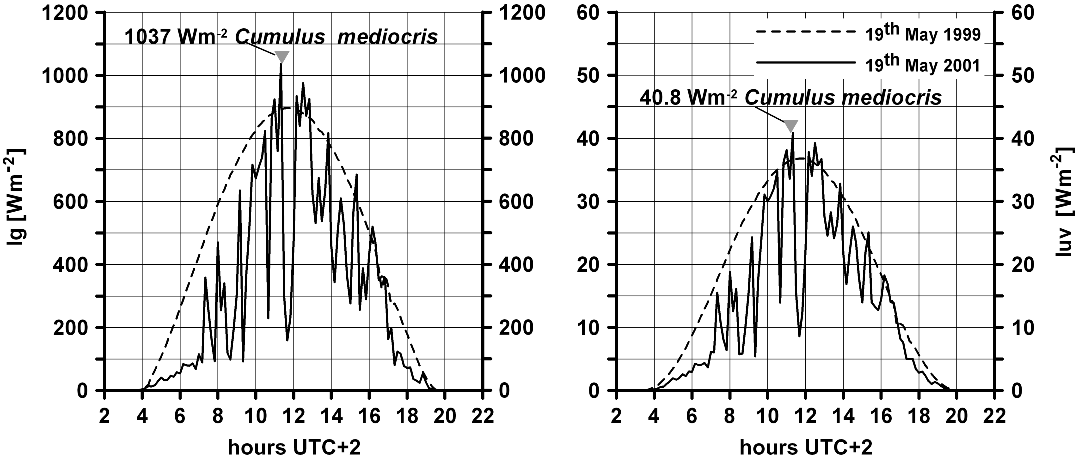

Figure 3. Daily course of global (Ig) and UV (Iuv) solar irradiance on the clear day (19th May 1999) and on a day with convective clouds (19th May 2001) at Łódź–Lipowa station.

irradiance observed on clear days (Figure 3). When the solar disk was obscured, the values of solar radiation flux decreased rapidly by up to 159 Wm^{-2} (Ig) and 8.6 Wm^{-2} (Iuv) (Figure 3, see 11 : 40). Forty cases were analysed in the period 1997–2001 when global irradiance measured at the Łódź–Lipowa station was equal or higher than 1000 Wm^{-2} due to the occurrence of cumulus-type clouds (in 65% of cases: *Cumulus mediocris*; remaining cases: *Cumulus congestus, Cumulonimbus, Cumulus humilis*). This phenomenon occurred in May (5 cases), June (25 cases) and in July (10 cases), with a duration of 10–40 min. The analysis revealed that the absolute maximum enhancement of global and UV irradiance compared to clear-sky values did not exceed 20 and 15%, respectively.

3.2. Annual, monthly and daily values of UV and global solar irradiation, clearness index of UV and global solar irradiation

In Łódź, for the period 1997–2001 the annual averages of global solar irradiation was 3710.8 MJ m^{-2} (standard deviation 108.6 MJ m^{-2}) and UV 154.1 MJ m^{-2} (standard deviation 5.2 MJ m^{-2}), i.e. 4% of solar irradiation across the whole spectrum. Seventy eight percent of the annual total of solar energy (UV and global) was recorded in spring and summer (from March to August), only 7% was recorded in winter (Table III). The minimum monthly totals of UV and global solar irradiation occurred in December, 2.1 MJ m^{-2} and 48.7 MJ m^{-2}, respectively. The maximum monthly totals occurred atypically in May, 25.3 MJ m^{-2} and 620.9 MJ m^{-2} (Table III). The decrease of surface monthly solar energy in June and July was due to an increase of cloudiness. This was also observed in other stations in Poland, e.g. Warszawa and the stations located in the North: Gdynia, Kołobrzeg, Suwałki, as well as in the South: Zakopane, Kasprowy Wierch (Bogdańska and Podogrocki, 2000).

At the top of the atmosphere, the maximum daily totals of global irradiation (on a horizontal surface, Dg0) occurred in June. They did not exceed 45 MJ m^{-2}. At the Łódź–Lipowa station the absolute daily values reached 30.4 MJ m^{-2} (Dg) (Figure 4). UV irradiation was strongly attenuated in the atmosphere and the extraterrestrial values were three times higher than the values observed at the ground level. Annually, the absolute maximum UV daily values (Duv) occurred in

Table III. Annual and monthly totals of UV (Muv) and global solar irradiation (Mg) in MJ m^2 and monthly clearness index of global and UV solar irradiation (Kg, Kuv) at Łódź–Lipowa station for the period 1997–2001.

	Jan	Feb	Apr	Mar	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Mg	73.0	121.6	270.6	387.0	620.9	564.0	528.9	521.4	320.8	180.4	73.6	48.7	3710.8
Muv	2.8	4.9	10.7	15.8	25.3	24.0	23.0	21.6	13.3	7.4	3.1	2.1	154.1
Kg	0.30	0.33	0.40	0.41	0.50	0.43	0.40	0.48	0.42	0.36	0.27	0.25	0.41
Kuv	0.15	0.17	0.20	0.21	0.26	0.23	0.22	0.25	0.22	0.19	0.14	0.14	0.22

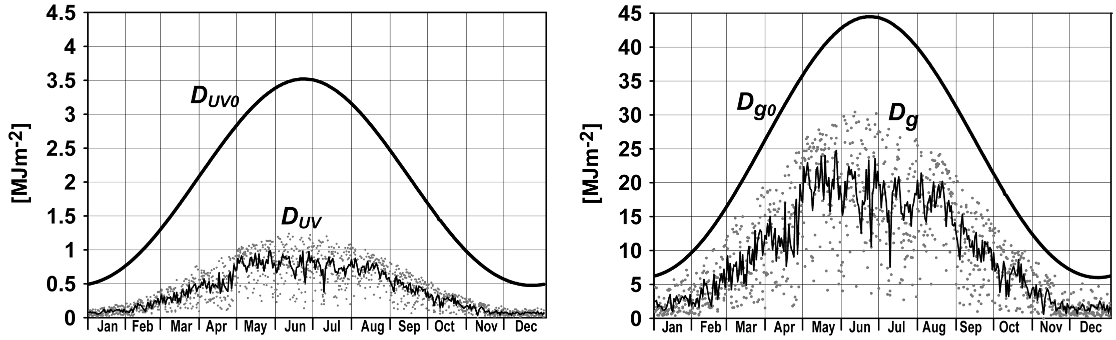

Figure 4. The annual course of the mean (line) and the observed (dots) daily totals of UV and global solar irradiation at the ground level (*Duv, Dg*) compared to the values on the upper limit of the atmosphere (*Duv0, Dg0*) at Łódź–Lipowa station for the period 1997–2001.

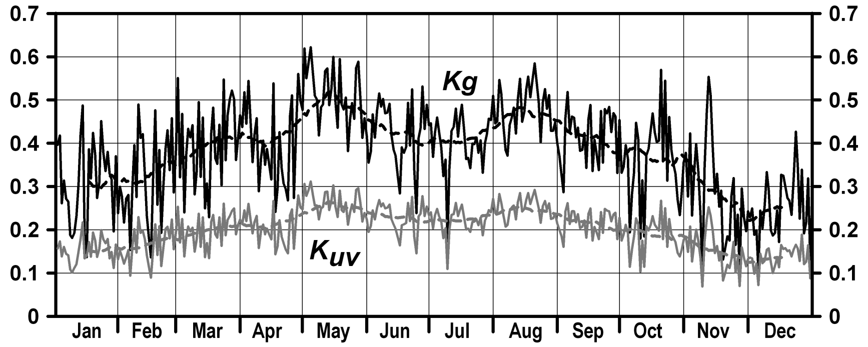

Figure 5. Annual course of the daily clearness index of global (*Kg*) and UV (*Ku*v) solar irradiation at Łódź–Lipowa station for the period 1997–2001. Dashed line – 31-day running average.

June, 1.2 MJ m^{-2} (Figure 4). The lowest Duv and Dg were recorded in December (Duv = 0.01 MJ m^{-2}; Dg = 0.3 MJ m^{-2}). In general, totals of solar energy at the Łódź–Lipowa station were characterized by high day-to-day variability, especially from April to August, due to the occurrence of deep convective clouds (Figure 4).

The clearness index provides a measure of atmospheric transmission conditions for solar radiation (Liu and Jordan, 1960; Iqbal, 1983; Sadler, 1992; Martinez-Lozano and Casanovas, 1994). Figure 5 presents the annual course of the clearness index calculated for the daily totals of UV (Kuv) and global (Kg) solar irradiation at the Łódź–Lipowa station. The monthly mean of Kg varied from 0.25 in December to 0.50 in May; whereas Kuv was approximately half of these values, ranging from 0.14 in December to 0.3 in May (Table III). As noted above, May had more clear days than June and July, in the period analysed. The maximum daily Kg and Kuv values in May were 0.6 and 0.3, respectively. The minimum daily values of 0.2 (Kg) and 0.1 (Kuv) were observed during winter months (Figure 5).

Two main factors determine the variability of daily solar energy transmission through the atmosphere – air turbidity and cloudiness. In winter, the low clearness index values in the city center resulted from strong urban influences of increased air turbidity and high frequency of cloudiness. The high level of air turbidity in the vicinity of the Łódź–Lipowa station was caused by the emissions of soot from old domestic coal-fired heating system. The dustiness and cloudiness together reduced UV irradiation to below 10% of extraterrestrial values. In summer, especially in June and July, the attenuation of solar energy in the city can be attributed to the high frequency of deep convective clouds.

3.3. Relationship between UV and global solar irradiation for clear and cloudy days

The relationship between the daily UV and global solar irradiation values was investigated using linear equations

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fitted to the daily values. The result was as follows:

$$\text{Duv} = 0.022 + 0.039 \text{ Dg} \quad n = 1811$$

with ±5% standard error of estimate and coefficient of determination $r^2 = 0.98$.

The regression coefficient (slope) indicates that the daily UV irradiation constituted approximately 4% of global solar irradiation. This value is similar to those reported in the literature: 3% (for Valencia, 39°30′N lat., Martinez-Lozano *et al.*, 1999); 4.8% (for Kuwait, 29°20′N lat., Al-Aruri, 1990); 5.4% (for Bratislava, 48°10′, Zavodska and Reichrt, 1985). The local atmospheric conditions result in the variability between sites. For example, in Valencia the ratio varied from 2.9 to 3.5% (Martinez-Lozano *et al.*, 1999), in Dhahran (Saudi Arabia) from 2.1% on dusty days to 4.6% on rainy days (Elhadidy *et al.*, 1990), in Potsdam with overcast sky the ratios varied between 5 and 6%, whereas on cloudless days they did not exceed 4.5% (Feister and Grasnick, 1992).

The relation was then analysed for shorter, 10-min values, and for clear and cloudy days. Table IV presents the ratios for cloudless skies stratified by the solar height (Hs) and the optical air mass (m). In general, Ruv/g (for 10-min values) increases with increasing solar height and decreasing optical air mass from 3.3 to 4.0% (Table IV). During times of low solar elevation, the highest variability of Ruv/g occurs (values ranging from 1.5 to 4.9%). The greater absorption of UV than global irradiance during high optical air mass could have been caused by the presence of SO_2 and dustiness in the polluted urban atmosphere. The increase of the relative contribution of UV in global solar irradiation at time of low solar elevation, up to 4.9%, could result from the fact that the absorption by water vapor in the near infra-red part of the spectrum was stronger than for shorter wavelengths (Elhadidy *et al.*, 1990; Martinez-Lozano *et al.*, 1999). Ratios (Ruv/g) varied little for solar elevations over 40°: 3.5 to 4.3% (Table IV). The analysis of Ruv/g by cloud conditions revealed an increase in the ratios even up to 9% for 10-min irradiance and 7.4% for the daily irradiation (Figures 6 and 8). Figure 6 shows the annual variability of the daily mean and extreme Ruv/g (for daily values of irradiation) in Łódź in 1997–2001. For clear days, Ruv/g varied between 2.1 and 4.1% from January to June (Figure 6). Considering all the clear and cloudy days, the highest mean values of Ruv/g, of up to 5.5%, were observed from November to February when cloudiness increased. Those months were also characterized by the lowest Ruv/g, of 2–3%, due to high air turbidity. The greatest day-to-day variability occurred in January and the lowest variability was observed in August (Figure 6). The absolute maximum of Ruv/g for the daily irradiation values in 1997–2001, i.e. 7.4%, was recorded for overcast skies (low clouds types, *stratus fractus, Nimbostratus*) on 22nd June 1999. Cloudiness is the main factor determining the annual and daily variability of Ruv/g (Figures 6 and 8).

The relationships between Ruv/g and global solar irradiance for clear and overcast skies, when solar elevation exceeded 50°, are illustrated in Figure 7. On clear days, the ratio ranged from 3.6 to 4.5% when global solar irradiance varied between 700 and 900 Wm^{-2}. On the days with totally overcast skies (solar elevation exceeded 50°), Ruv/g amounted to 5.7% on average and varied between 3.9 and 8.3%. Differences in cloud thickness influenced the transmission of UV to a lesser extent than global solar irradiance. Generally as global irradiance decreased with increase in Ruv/g. The highest values of Ruv/g, of over 6% were observed when *Cumulonimbus* and *Cumulus congestus* clouds occurred and irradiance decreased below 100 Wm^{-2} (Figure 7). Thus, it can be concluded that clouds reduce global solar radiation proportionally

Table IV. The ratio of UV to global solar irradiance (Ruv/g, %) for periods of cloudless conditions stratified by of the solar height (Hs) and the optical air masses (m) at Łódź–Lipowa station for the period 1997–2001. N – number of cases.

H_s	m	$R_{uv/g\ mean}$	$R_{uv/g\ min}$	$R_{uv/g\ max}$	N
5.0°–10.0°	8.8–5.1	3.5	1.5	4.9	164
10.1°–15.0°	5.0–3.5	3.3	1.8	4.5	214
15.1°–20.0°	3.5–2.7	3.3	1.9	4.3	202
20.1°–30.0°	2.7–2.0	3.4	2.2	4.1	257
30.1°–40.0°	1.9–1.5	3.7	3.1	4.0	215
40.1°–50.0°	1.5–1.3	3.9	3.5	4.2	141
50.1–61.7°	1.3–1.1	4.0	3.6	4.3	68

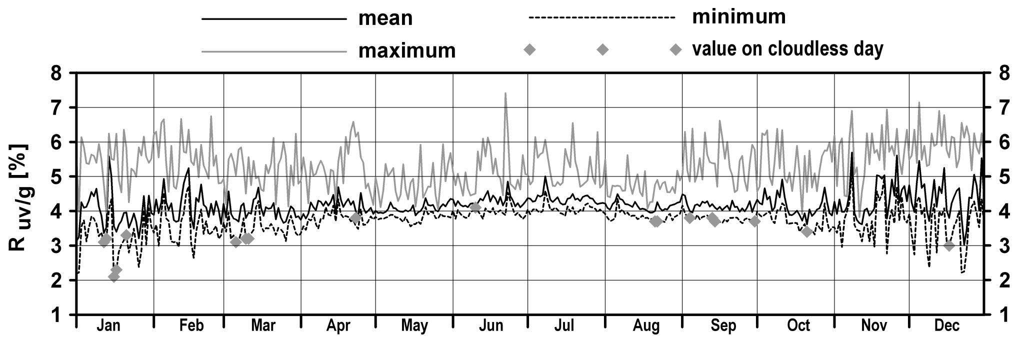

Figure 6. Annual course of the mean and the extreme ratio of UV to global solar irradiation (Ruv/g for daily values, in %) at Łódź–Lipowa station for the period 1997–2001.

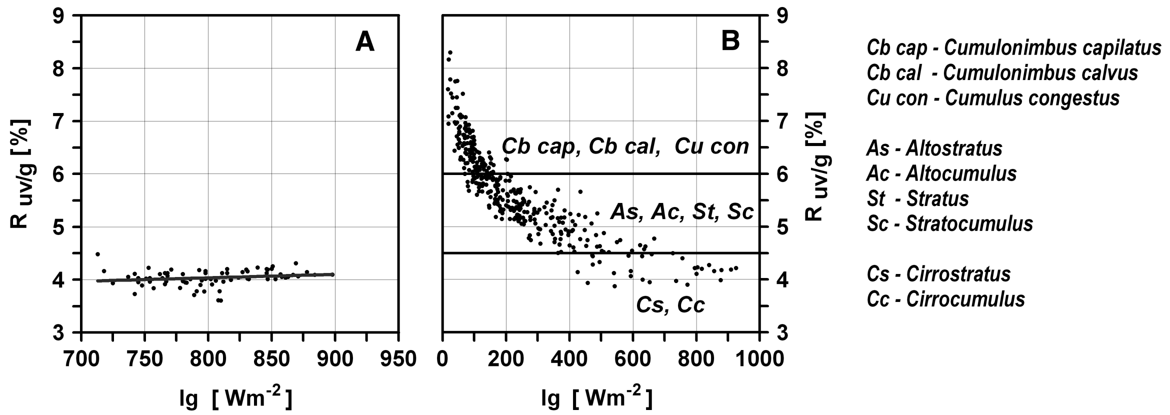

Figure 7. The ratio Ruv/g (%) as a function of global solar irradiance (Ig, Wm^{-2}) for various atmospheric conditions: A – cloudless sky, sun elevation ≥50°, B – overcast sky, sun elevation ≥50° at Łódź–Lipowa station in 1997–2001.

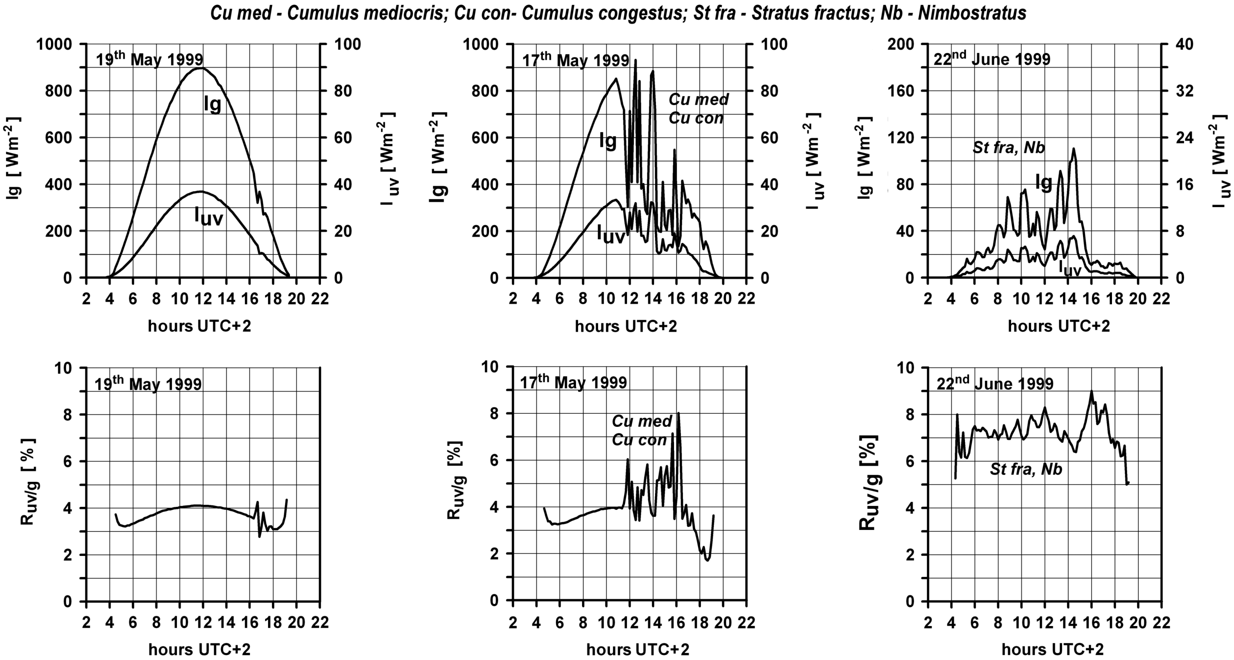

Figure 8. Daily course of global (Ig) and UV solar irradiance (Iuv) (upper diagrams) and the ratio of UV to global solar irradiance (Ruv/g) (lower diagrams) on a clear day (19th May 1999), a day with convective clouds (17th May 1999), and a day with overcast conditions (low stratified cloud types, 22nd June 1999 – the absolute maximum of the ratio for the period 1997–2001) at Łódź–Lipowa station.

to a greater degree than UV radiation. UV radiation is more reflected and scattered by cloud elements and air molecules than the whole solar spectrum. Moreover, the absorption of solar radiation by water vapor is stronger in near infra-red wavelengths than at shorter ones (Spinhirne and Green, 1978; Ambach *et al*., 1991; Blumthaler *et al*., 1994; Bordewijk *et al*., 1995). The increase of Ruv/g under cloudy skies has been observed at other European stations; e.g. Potsdam (Germany), (Feister and Grasnik, 1992), Valencia (Spain), (Martinez-Lozano and Casanovas, 1994; Martinez-Lozano *et al*., 1999), Bratislava (Slovakia), (Zavodska and Reichrt, 1985), Jungfraujoch (Switzerland), (Ambach *et al*., 1991; Blumthaler *et al*., 1994), Granada (Spain), (Foyo-Moreno *et al*., 1998). Figure 8 shows the daily course of UV, global solar irradiance and Ruv/g on a cloudless day, on a day with convective clouds, and on a day with an overcast sky due to low clouds. Generally, solar elevation determines the daily course of solar irradiance; the highest values were observed at solar noon. It also determines the daily course of Ruv/g. On clear days, Ruv/g increases from 3% in the morning and in the afternoon to 4.1% at solar noon (Figure 8, 19th May). Convective clouds resulted in the great variability of surface UV and global irradiance. When the irradiance decreased, the ratio of UV radiation increased up to 6–8% (Figure 8, 17th May). Strong attenuation of UV and global irradiance below 100 Wm^{-2} and 10 Wm^{-2}, respectively, and a strong increase of Ruv/g up to 9% were observed on cloudy days with low thick clouds – *Nimbostratus* (Figure 8, 22nd June). The mean Ruv/g value on a day with the above conditions was 7.4% – the highest daily Ruv/g recorded in Łódź in the period 1997–2001.

4. Conclusions

The analysis of 5 years of measurements of broadband UV (UVB + UVA) and global solar radiation in the center of Łódź reveals the following results:

First, the mean UV radiation (irradiance in Wm^{-2} and total energy in MJ m^{-2}) exhibited a similar annual pattern to global solar radiation, with maximum values in May and minimum values in December. Large day-to-day variability was observed in broadband UV and global solar radiation. This was most evident from April to August due to greater cloudiness in these months.

Second, the 'silver lining scattering effect' of clouds caused short-time increases of UV and global solar irradiance up to 120% of the clear-sky values. The phenomenon partly compensates for losses of UV radiation in a polluted urban atmosphere. Further investigation is needed to determine the influence of clouds on total UV energy registered in urban areas.

Third, the clearness index of UV radiation was only half that of global solar radiation and varied from 0.14 (December) to 0.26 (May). In the winter months, the combination of low solar elevations, cloudiness and the strong urban impact, i.e. an increase of air turbidity due to the emissions of soot from domestic coal-fired heating system in the vicinity of the Łodź–Lipowa station, reduced UV irradiance below 10% of the extraterrestrial value. The air quality in the centre of Łódź in winter proved to be a dominant factor responsible for decreasing solar energy near the ground.

Fourth, cloudiness resulted in the great variability of surface UV and global radiation. In general, clouds reduced solar radiation flux when the solar disk was obscured but caused enhancement of the relative contribution of UV to global radiation. On clear days, UV constituted 3.3–4% of global solar irradiance (for 10-min values) on average, while Ruv/g under cloudy conditions exceeded 8%. Higher albedo, the stronger scattering effect of cloud on UV wavelengths, and the stronger absorption by water vapor in the near infra-red wavelength contributed to this increase of the ratio of UV to global radiation. Ruv/g in the winter months (i.e. Nov., Dec., Jan., and Feb.) was characterized by the highest mean values, up to 5.5%, and the greatest day-to-day variability.

The results from the Łódź–Lipowa station are consistent with other studies in Europe and The Middle East indicating some commonalities in urban effects. However, the role of winter air turbidity due to soot is more pronounced in Poland. The present study has implications for understanding urban atmospheric effects on different parts of the solar spectrum and the influence of clouds on the relation between UV and global solar radiation.

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References

Al-Aruri SD. 1990. The empirical relationship between global radiation and global ultraviolet (0.290–0.385) μm solar radiation components. *Solar Energy* **45**(2): 61–64.

Ambach W, Blumthaler M, Wendler G. 1991. A comparison of ultraviolet radiation measured at an Arctic and an Alpine Site. *Solar Energy*. **47**(2): 121–126.

Błażejczyk K, Baranowski J. 2003. Solar and UV radiation in the Warsaw Downtown. *Proceedings of Fifth International Conference on Urban Climate, 1–5 September 2003, £ód1/4, Poland*, **1**: 263–266.

Blumthaler M, Ambach W, Salzgeber M. 1994. Effects of cloudiness on global and diffuse UV irradiance in high-mountain area. *Theoretical and Applied Climatology* **50**: 23–30.

Bogdańska B, Podogrocki J. 2000. Zmienność całkowitego promieniowania słonecznego na obszarze Polski w okresie 1961–1995. *Materiały Badawcze, Meteorologia – 30, IMGW, Warszawa*: 43. (in polish).

Bordewijk JA, Hill WJ, Reisel GC, Tiao GC. 1995. Total solar radiation and the influence of clouds and aerosol on the biological effective UV. *Geophysical Research Letters* **22**: 2151–2154.

Borkowski JL. 2000. Homogenization of the Belsk UV-B time series (1976–1997) and trend analysis. *Journal of Geophysical Research* **105**: 4873–4878.

Chubarova NY. 2008. UV variability in Moscow according to long-term UV measurements and reconstruction model. *Atmospheric Chemistry and Physics Discussions* **8**: 893–906.

COST-Action 713. UV-B forecasting. European Project (COST – European Cooperation in the field of Scientific and Technical Research) founded by EU in 1996-2001. http://www.cost.esf.org. [accessed: 2001].

COST-Action 726. Long term changes and climatology of UV radiation over Europe. European Project (COST – European Cooperation in the field of Scientific and Technical Research) founded by EU in 2004–2009. http://www.cost.esf.org. [accessed: 2008].

Degünther M, Meerkötter R. 2000. Effect of remote clouds on surface UV irradiance. *Annales Geophysicae* **18**: 679–686.

Diffey BL. 1991. Solar ultraviolet radiation effects on biological systems. *Physics in Medicine and Biology* **36**: 299.

Elhadidy MA, Abdel-Nabi DY, Kruss PD. 1990. Ultraviolet solar radiation at Dhahran, Saudi Arabia. *Solar Energy* **6**: 315–319.

Estupinan JG, Raman S. 1996. Effects of clouds and haze on UV-B radiation. *Journal of Geophysical Research* **101**(D11): 16807–16816.

Feister U, Grasnick KH. 1992. Solar UV radiation measurements at Potsdam (52°22 N, 13°5 E). *Solar Energy* **49**(6): 541–548.

Foyo-Moreno I, Vida J, Alados-Arboledas L. 1998. Ground based ultraviolet (290–395 nm) and broadband solar radiation measurement in South-Eastern Spain. *International Journal of Climatology* **18**: 1389–1400.

Horneck G. 1995. Quantification of the biological effectiveness of environmental UV radiation. *The Journal of Photochemistry and Photobiology B: Biology* **31**: 43–49.

Iqbal M. 1983. *An Introduction to Solar Radiation*. Academic Press: New York; 390.

Josefsson, W. 2006. UV-radiation 1983–2003 measured at Norrköping, Sweden. *Theoretical and Applied Climatology* **83**(1): 59–76.

Kasten F. 1966. A new table and approximate formula for the relative optical air mass. *Archives of Meteorology Geophysics and Bioclimatology Series B* **14**(2): 206–223.

Kłysik K, Fortuniak K. 1999. Wieloletnie tendencje zmian stężenia dwutlenku siarki w Łodzi. *Stan środowiska w województwie łódzkim w 1998 roku, cz. III. Wojewódzki Inspektorat Ochrony Środowiska, Łódź*. 71–77 (in polish).

Krzyścin JW. 1996. UV controlling factors and trends derived from the ground-based measurements taken at Belsk, Poland, 1976–1994. *Journals of Geophysical Research* **101**: 16797–16805.

Krzyścin, JW, Eerme K, Janouch M. 2004. Long-term variations of the UV-B radiation over Central Europe as derived from the reconstructed UV time series. *Annales Geophysicae* **22**(5): 1473–1485.

Krzyścin, JW, Jaroslawski J, Sobolewski PS. 2003. Effects of clouds on the surface erythemal UV-B irradiance at northern midlatitudes: estimation from the observations taken at Belsk, Poland (1999–2001). *Journal of Atmospheric and Solar-Terrestrial Physics* **65**(4): 457–467.

Landsberg HE. 1981. *The Urban Climate*. Academic Press: 285.

Liu BYH, Jordan RC. 1960. The interrelationship and characteristic distribution of direct, diffuse and total solar radiation. *Solar Energy* **4**: 1–19.

Longstreth J, Gruijl FR, Kripke ML, Abseck S, Arnold F, Slaper HI, Velders G, Takizawa Y, van der Leun JC. 1998. Health risks. *The Journal of Photochemistry and Photobiology B: Biology* **46**: 20–39.

Martinez-Lozano JA, Casanovas AJ. 1994. Comparison of global ultraviolet (290–385 nm) and global irradiation measured during the warm season in Valencia, Spain. *International Journal of Climatology* **14**: 93–102.

Martinez-Lozano JA, Tena F, Utrillas P. 1996. Measurement and analysis of ultraviolet solar irradiation in Valencia, Spain. *International Journal of Climatology* **16**: 947–955.

Martinez-Lozano JA, Tena F, Utrillas P. 1999. Ratio of UV global broad band irradiation in Valencia, Spain. *International Journal of Climatology* **19**: 903–911.

Mims FM, Frederick JE. 1994. Cumulus clouds and UV-B. *Nature* **371**: 291–291.

Monteith JL, Unsworth MH. 1988. *Principles of Environmental Physics*. Edward Arnold: London; 292.

Oke TR. 1988. The urban energy balance. *Progress in Physical Geography* **12**: 471–508.

Podstawczyńska A. 2007. The solar characteristics of climate of £ód1/4. *Acta Universitatis Lodzensis. Folia Geographica Physica* **7**: 294 (in polish).

Podstawczyńska A, Pawlak W. 2003. Daily course of ultraviolet and total solar radiation in urban canyon – £ód1/4 case study. *Proceedings of Fifth International Conference on Urban Climate, 1–5 September 2003, œódY, Poland*, **1**: 275–278.

Robinson PJ. 1977. Measurements of downwards scattered solar radiation from isolated Cumulus clouds. *Journal of Applied Meteorology* **16**: 620–625.

Sadler GW. 1992. Ultraviolet radiation at Edmonton, Alberta, Canada. *Solar Energy* **49**(1): 13–17.

Segal M, Davis J. 1992. The impact of deep Cumulus reflection on the ground – level global irradiance. *Journal of Applied Meteorology* **31**: 217–222.

Spinhirne JD, Green AES. 1978. Calculation of relative influence of cloud layers on received ultraviolet and integrated solar radiation. *Atmospheric Environment* **12**: 2449–2454.

Thekaekara MP. 1973. Solar energy outside the earth's atmosphere. *Solar Energy* **14**: 109–127.

Thiel S, Steiner K, Seidlitz HK. 1997. Modification of global erythemally effective irradiance by clouds. *Photochemistry and Photobiology* **60**(6): 969–973.

Urbach F. 1989. Potential effects of altered solar ultraviolet radiation on human skin cancer. *Photochemistry and Photobiology* **50**: 507–513.

WMO. 2007. Scientific assessment of ozone depletion: 2006, global ozone research and monitoring project, Report No. 50. Geneva: 572.

Zavodska E, Reichrt J. 1985. Ultraviolet and total global radiation in Bratislava. *Contributions of the Slovak Acadamy of Sciences. Series of Meteorology* **5**: 21.

Zigman S. 1977. Near UV light and cataracts. *Photochemistry and Photobiology* **26**: 437–441.

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