Bulletin of Geography – **Physical Geography Series**
No 7/2014: 27–56 http://dx.doi.org/10.2478/bgeo-2014-0002

Marek Kejna, Joanna Uscka-Kowalkowska,
Andrzej Araźny, Mieczysław Kunz,
Rafał Maszewski, Rajmund Przybylak

Faculty of Earth Sciences, Nicolaus Copernicus University
Lwowska 1, 87-100 Toruń, Poland
e-mail: marek.kejna@umk.pl

SPATIAL DIFFERENTIATION OF GLOBAL SOLAR RADIATION IN TORUŃ AND ITS SUBURBAN AREA (CENTRAL POLAND) IN 2012

Abstract: This article investigates the spatial distribution of global solar radiation (K↓) in Toruń and its suburbs, observed in 2012. Measurements were taken at 12 points (7 within the city and 5 in the suburban area) using CNR4 net radiometers and automatic weather stations (Vantage Pro+). At all locations, the diurnal and annual courses of K↓ were typically related to the Earth's rotational movement and changes in the sun's declination over the year, and disturbed by clouds and atmospheric phenomena that enhance the extinction of solar radiation. A substantial spatial diversity of K↓ was observed in Toruń and its suburbs. The annual sum of K↓ at several urban locations accounted for over 70% of the solar radiation in the open space outside the city. The amount of incoming solar radiation in the urban area was more restricted in winter (<50%) than in summer (approx. 70%). The diurnal courses of K↓ were heavily disturbed by local obstacles which cast shadows (causing a considerable decrease of K↓), but there were instances of increases in K↓ (122%) augmented by radiation reflected from roofs, walls and windows surrounding the measurement point. The spatial diversity of K↓ in the urban area is heterogeneous, due to local meteorological conditions (cloudiness, fog, smog and airborne dust) and the obscuring of the horizon.

Keywords: global solar radiation, urban climate, Toruń, Poland

Introduction

Global solar radiation (K↓) is the hemispherical irradiance on a horizontal surface (Guide to Meteorological Instruments and Methods of Observation, WMO-No.8, 2008). K↓ reaches the Earth's surface in both direct and diffuse form. Its intensity depends on the angle at which the sun's rays strike the surface, which changes throughout the day and the year according to the Earth's rotation and revolution. The optical qualities of the atmosphere are also important, and include, most notably, the presence of clouds and atmospheric aerosol content. Measurements of K↓ should be taken in an open space, while in an urban environment different obstacles (terrain features, buildings, structures and vegetation) have a substantial influence on the size of the influx.

The influence of the city on solar radiation and radiation balance components has been the subject of numerous studies in which results obtained in both urban and suburban areas were compared. These studies have been conducted in such cities as Athens in Greece (Kambezidis et al. 1994), Basel in Switzerland (Christen and Vogt 2004), Brasov in Romania (Serban 2010), Delhi in India (Das et al. 2009), Hong Kong in China and Seoul in South Korea (Hii et al. 2011), Cairo in Egypt (Robaa 2006), London in Great Britain (Hamilton et al. 2009), Sao Paulo in Brazil (de Oliveira et al. 2002; Codato et al. 2004), and St. Louis in the USA (Petersen and Stoffel 1980). The solar climates of cities have also been compared in Europe (Piringer et al. 2005) and worldwide (Taha 1997). The results indicate a considerable diversity in the incoming solar radiation and heat balance of cities, depending on the climate zone, type of architecture, energy management and air pollution. The amount of solar radiation reaching cities is 5% to 15% less than that reaching suburban areas (Podstawczyńska 2007). Nevertheless, the radiation balance of cities is more favourable, due to the lower albedo of the surfaces and a greater yield of energy as a result of multiple reflections from the surfaces, walls and roofs of buildings, as well as the absorption of solar rays. However, the heat balance of a city is more favourable not only because of the greater absorption of solar radiation, but also because of additional emissions from sources of anthropogenic heat, which even exceeds the quantities of energy received in the form of solar radiation in winter. This thermal privilege of cities, as seen in the intensity of the urban heat island, increases proportionally to the number of inhabitants and degree of urbanisation. In densely built-up cities with tall buildings, restricted amounts of daylight have become a problem (Hii et al. 2011).

In Poland, regular actinometric measurements were initiated by W. Gorczyński in Warsaw in 1900. In subsequent years these were taken in other places, as well. A detailed inventory of the oldest actinometric measurements is included in an article by Uscka-Kowalkowska (2010). This kind of observation allowed an increasingly comprehensive understanding of the solar climate in Poland. Publications on this topic address such issues as the spatial distribution of global solar radiation in Poland (e.g. Paszyński 1966; Podogrocki 1978; Paszyński and Niedźwiedź 1991; Bogdańska and Podogrocki 2000; Lorenc 2005), the amount of absorbed solar radiation (Kozłowska-Szczęsna 1973) and the radiation balance (Miara et al. 1987). Inconsistency in the distribution of K↓ by latitude has also been noted: the greatest annual sums occur in the north (on the Baltic coastline), in central Poland, in the south east and at its mountain tops (>3800 MJ m^{-2}) (Kozłowska-Szczęsna 1973). This is an effect of the changing length of day (especially in summer), the absolute altitude (decreasing optical mass of the atmosphere), and the distribution of clouds and air pollution.

Reference sources describe and discuss trends in global solar radiation. In the 1950s and 1980s in numerous places throughout the world, a decrease in the amount of irradiance was observed (global dimming), followed by an increase in more recent times (global brightening) (Wild 2009). In the area of Poland, the published results of observations carried out at several weather stations in 1961–1995 show that the amount of K↓ had evidently increased (at 5 of 7 stations). In Warsaw, this increase was statistically relevant (Bogdańska and Podogrocki 2000). In some Polish cities, negative trends in K↓ have also been observed. For example, in Wrocław it decreased 2.7 MJ per year in 1875–2004 (Bryś and Bryś 2007). In Kraków, sunshine duration in 1861–1990 was similarly found to have decreased, while the cloud cover increased (Morawska-Horawska 2002). However, thanks to a reduction in air pollution in Kraków, insolation has improved in recent years (Matuszko 2007).

Solar conditions and their characteristics in cities have been juxtaposed with those of suburban areas, and analysed in detail in a number of studies. For example, long-term actinometric observations have been conducted in Kraków (Olecki 1973, 1975, 1980, 1986; Hess et al. 1980; Hess and Olecki 1990). As mentioned above, an improvement in air quality conditions in the city has recently been noted (lower air pollution), and thus a reduction in the difference between K↓ in Kraków and in its suburbs around Gaik-Brzezowa (Bokwa and Matuszyk 2007; Matuszko and Struś 2007). Multifaceted studies of the urban solar climate have also been carried out in Łódź and its suburban zone, and these have analysed global solar radiation, UV radiation, and radiation and heat balance (including the share of individual fluxes of sensible and latent heat) (Fortuniak 2003, 2010; Podstawczyńska and Pawlak 2006; Podstawczyńska 2007). It was concluded that the significant differences depended on the density of urban development and the courses of street canyons. In Upper Silesia, studies of the radiation balance, including K↓, have been conducted on the basis of observations made at weather stations in areas both urban (Sosnowiec) and rural (Ojców in the Kraków-Częstochowa Upland) (Budzik 2006; Caputa and Wojkowski 2009; Caputa and Leśniok 2010).

In Toruń, studies of the transmission of solar radiation through the atmosphere have been carried out in the city (Wójcik 1996) and its suburbs, in which single-family homes tend to predominate (Uscka 2004). Global solar radiation in forest and clearings has also been analysed in the Las Piwnicki Nature Reserve (Wójcik 1983), whereas studies of the radiation balance in the fields of the nearby village of Koniczynka have been conducted as part of the Integrated Environmental Monitoring Programme (Kejna et al. 2014).

The analysis of the distribution of K↓ under different exposure conditions is being supported more and more frequently by the methods offered by Geographic Information Systems (GIS). At a southern exposure, the amount of incoming energy may exceed the amount of energy reaching horizontal surfaces. Relevant studies have been conducted, e.g. for the area of Lublin (Dobek and Gawrysiak 2009) and the Kraków-Częstochowa Upland (Wojkowski 2007; Wojkowski and Skowera 2011). Radiation conditions are largely heterogeneous in mountainous areas, where ridges and peaks cast shadows on valleys, e.g. in the Beskidzkie Foothills (Hess et al. 1979; Bokwa and Matuszyk 2007; Matuszko and Struś 2007). Diversity in the solar irradiance and radiation balance then provides a basis for topoclimatic mapping (Paszyński et al. 1999). This method has been used, for example, to identify the topoclimate of Katowice (Radosz 2010). In studies of K↓, satellite observations are also increasingly being applied, but the data series are neither long enough nor homogeneous enough in comparison with conventional measurements (Petrenz et al. 2007).

The purpose of this article is to attempt an analysis of the spatial variability of K↓ in Toruń and its suburban area on the basis of measurements taken at 12 measurements points in 2012. The variability has been analysed in a diurnal and annual course in different weather conditions.

Research area and methodology

Measurements of the global solar radiation were taken in Toruń and its suburbs. Toruń is an old, medieval city founded in 1233. The city is situated in the central of Poland (φ = 53.02°N, λ = 18.61°E) on the Vistula River, in the Toruń Valley (Fig. 1). The valley is surrounded by morainal plateaus: the Chełmno Lakeland in the north and Inowrocław Plain and Kujawskie Lakeland in the south (Kondracki 2011). At present, it is a typical academic city, with a population of about 205,000 inhabitants. The total surface within the city's administrative borders amounts to ca. 116 km^2, but only ca. 26 km^2 (23%) are built up. The largest single allocation of land use in the city district is that of forest, at about 30%. Green areas, once surfaces covered by brushwood, shrubs and grass are included, account for about 51% (Kunz et al. 2012).

The measurements of K↓ were taken at 12 measurements points in 2012. The points at Koniczynka (KON), Krobia (KRO) and Złotoria (ZLO) represent the suburban area. KON was used as a reference point, due to its open location (unobstructed horizon). The urban points are located in areas characterised by very diverse development and substantial obstruction of the horizon. Figure 1 presents the location of all the measurements points, while their coordinates and absolute height values are collected in Table 1 below. For each of the points, environmental characteristics were defined according to the classification of Steward and Oke (2012), who distinguishes "local climate zones" (LCZs) in urban and suburban space. They defined LCZs as regions of uniform surface cover, structure, material, and human activity that cover spans ranging from hundreds of metres to several kilometres across.

Table 1. Measurement points used for the observation of global solar radiation in Toruń and its suburbs in 2012

Symbol	Location	φ (N)	λ (E)	m a.s.l.	LCZs	Instruments	Lack of data
Toruń							
BAR	Barbarka, ul. Przysiecka	53°03’13”	18°32’26”	58.6	A	Vantage Pro+	7–13.02
BOR	ul. Komorowskiego-Bora	52°59’54”	18°37’29”	47.5	9D	Vantage Pro+	
WRZ	ul. Storczykowa	53°02’31’	18°35’45”	69.0	9C	AWS Vaisala	only climatic data
LO1	ul. Zaułek Prosowy	53°00’42”	18°36’27”	49.0	2	Vantage Pro+	1–7.01, 18–21.10
MAN	Mała Nieszawka	52°59’27”	18°33’37”	39.3	6D	Vantage Pro+	
OME	Obserwatorium Meteorologiczne UMK ul. Lwowska 1	53°01’18”	18°34’02”	50.3	6	CNR4, Vantage Pro+	25.05–2.06, 2–3.12
PSK	pl. Św. Katarzyny	53°00’47”	18°36’52”	53.5	8	Vantage Pro+	
RMA	ul. Żwirki i Wigury	53°01’43”	18°36’15”	64.2	5D	Vantage Pro+	
SAL	ul. Storczykowa	53°02’28”	18°35’36”	69.8	9D	Vantage Pro+	7–13.02
ZOO	ul. Szosa Bydgoska	53°00’31”	18°35’21”	46.1	5	Vantage Pro+	10–13.02
Suburbs Area							
KON	Koniczynka	53°04’45”	18°41’08”	88.1	D	CNR4	
KRO	Krobia, ul. Topolowa	53°01’59”	18°47’30”	76.6	9D	Vantage Pro+	1.01–6.02, 22–25.05
ZLO	Złotoria, ul. Toruńska	52°59’54”	18°42’01”	36.5	D	Vantage Pro+	19.11–6.12, 15–16.12

Explanations: LCZs according to Steward and Oke (2012): Land cover types: A – Dense trees; C – Bush, scrub; D – Low plants. Building types: 2 – Compact mid-rise; 5 – Open mid-rise; 6 – Open low-rise; 8 – Large low-rise; 9 – Sparsely-built.

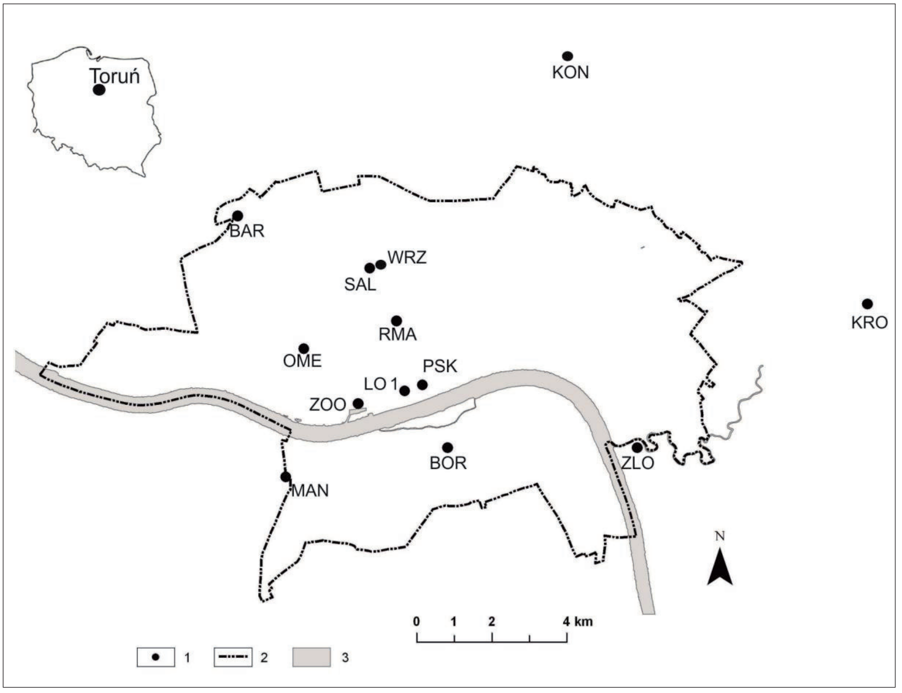

Fig. 1. Measurement points used for the observation of global solar radiation in Toruń and its suburbs in 2012: 1 – Measurement points; 2 – Administrative boundary of the city; 3 – The Vistula River

At each of the points, photographs were taken using a camera equipped with a fisheye lens in order to determine the obscuring of the horizon. The points differed considerably in terms of the openness of the horizon and numerous obstacles (particularly in the city) which limited the possibility of direct solar radiation reaching the measurement point. This was especially evident on winter days with a low sun, when direct sunlight did not reach the ground for most of the day. The obstruction of the horizon at selected points is shown in Figure 2.

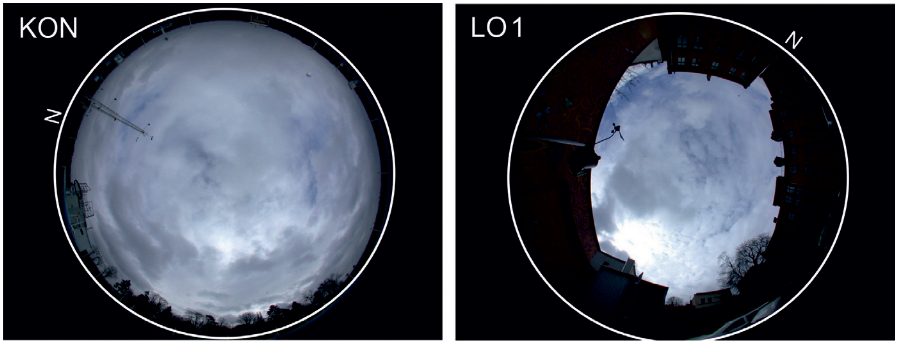

Fig. 2. The obstruction of the horizon at the KON and LO1 points (photo by Marcin Rzepa)

From the point of view of measuring K↓, KON has the most favourable setting, as the only obstacles are some trees in a park on the south-east horizon (Figs 2 and 3). At the LO1 point, on the other hand, the surrounding buildings prevent direct solar radiation from reaching the measurement point in winter months. Only in summer is the sun visible there around midday. At the BAR point, situated in a forest clearing, tall trees obscure the horizon. Although the least obstruction was found there in the morning hours, the sun's rays did not reach the measuring point directly in winter (Fig. 3).

At two of the measurement points (KON and OME) Kipp&Zonen CNR4 net radiometers were installed. These included a pyranometer to record the K↓. The instruments were individually calibrated and ventilated to prevent the deposition of dust, atmospheric pollutants and precipitation on their domes. Recording took place every 10 minutes. At all the other points, Vantage Pro+ automatic weather stations were used, equipped with K↓ sensors. There, the recording took place every 60 minutes (Fig. 4).

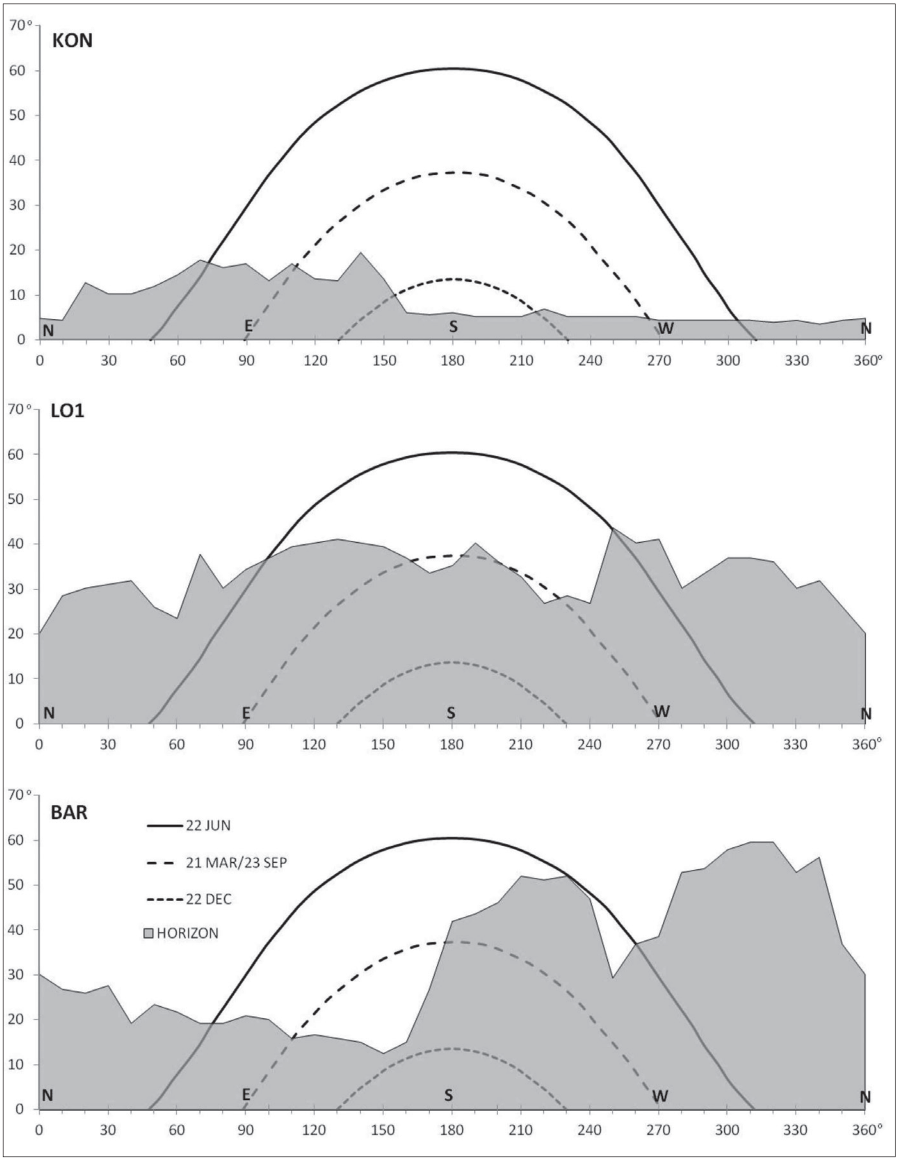

Fig. 3. The obstruction of the horizon at the KON, BAR and LO1 points, and the sun's path on 21 March/23 September, and on 22 June and 22 December

Fig. 4. A CNR4 net radiometer at the KON (left) and a Vantage Pro+ automatic weather station at the OME (photo by M. Kejna)

First of all, the consistency of measurements recorded using the CNR4 and the Vantage Pro+ instruments was ascertained. These instruments were used to simultaneously record K↓ at the OME throughout the year 2012. The results proved very compatible (Fig. 5), with 89.6% of days showing differences in the daily sums of K↓ within the limit of +/- 1 MJ·m^{-2}.

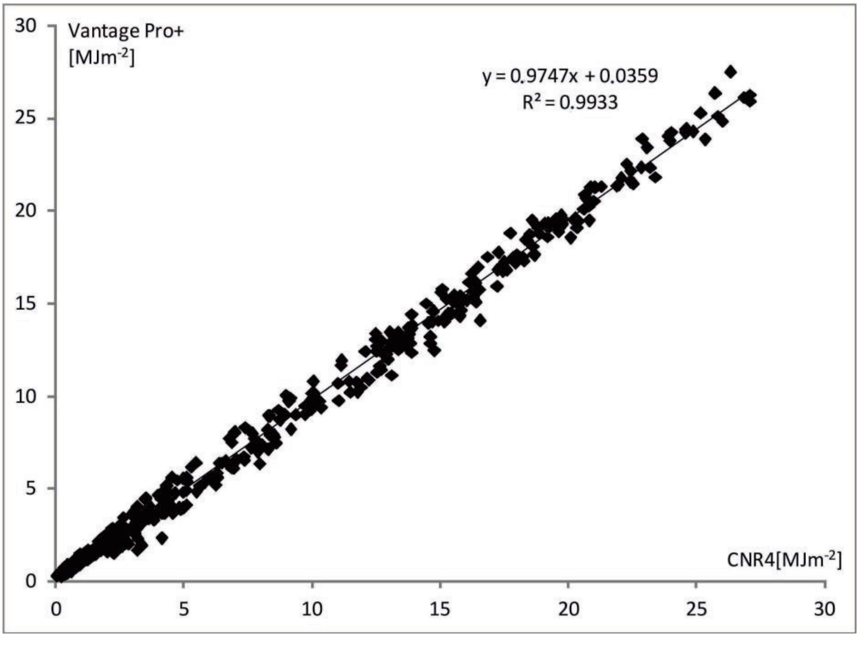

Fig. 5. Relation between mean diurnal sums of global solar radiation obtained by the CNR4 and the Vantage Pro+ instruments at the OME point in 2012

The data obtained using the CNR4 were complete, whereas in the case of the Vantage Pro+ some short breaks in the recording occurred at 7 measuring points (see Table 1). The missing data were supplemented by correlating the data from the nearest available measuring point.

Results

Cloudiness and sunshine duration in 2012

The pattern of K↓ is largely affected by cloudiness, which hinders the direct solar radiation. The mean diurnal values of cloudiness in 2012 (visual observations) come from the weather station of the Institute of Meteorology and Water Management – National Research Institute in Toruń (WRZ), situated in the Wrzosy residential estate. The values were compared with mean values of a longer series of observations during the period 1951–2000 (Table 2). In 2012, the mean degree of cloudiness in WRZ was 5.2, on a scale of 0–8, which was less than the mean value (5.4) for the years 1951–2000. In particular, the cloud cover was smaller in March (3.8), May (3.7) and July (4.5). June and November were more cloudy, at 5.8 and 7.0, respectively.

Sunshine duration is a measure of insolation conditions. The analysed year proved to be particularly rich in sunshine. In WRZ, the total duration of sunshine reached 1807.4 hours against a long-term mean of 1591.2 hours for 1961–2000 (Wójcik and Marciniak 2006). At Koniczynka in 2012, 1750.5 hours of sunshine were observed, in contrast with the multi-year mean for 1996–2012 of 1609.2 hours. The highest total sunshine duration was observed in May: 301.5 h in WRZ and 295.7 h in KON, and the lowest in December in WRZ (31.8 h) and in November at KON (22.7 h).

Table 2. Mean monthly and yearly values of cloudiness and sunshine duration in WRZ and KON in 2012

Station Period	Cloudiness (0–8)		Sunshine duration (hours)			
	WRZ 2012	WRZ* 1951–2000	WRZ 2012	WRZ* 1961–2000	KON 2012	KON 1996–2012
J	6.0	6.1	52.2	44.8	45.6	30.9
F	5.2	5.8	83.5	62.9	84.8	59.1
M	3.8	5.2	188.1	112.7	196.3	128.0
A	4.8	5.1	192.3	159.0	194.7	189.0
M	3.7	4.9	301.5	228.3	295.7	234.1
J	5.8	4.9	179.9	224.9	159.3	221.3
J	4.5	5.0	259.4	226.5	240.6	213.0
A	5.0	4.7	220.4	215.0	216.5	215.3
S	4.7	4.9	170.6	143.0	179.0	163.1
O	5.4	5.3	105.6	99.7	91.4	95.0
N	7.0	6.4	20.8	42.6	22.7	38.0
D	6.4	6.2	33.1	31.8	23.8	22.4
Year	5.2	5.4	1 807.4	1 591.2	1 750.5	1 609.2

* according to Wójcik and Marciniak (2006)

Potential irradiance

Potential irradiance changes with the declination of the sun, which affects the sun's apparent position over the horizon and the length of the day. The amount of solar radiation at the upper boundary of the atmosphere on the parallel 53^o north (i.e. the parallel that crosses the area of observations) was determined using the following formula (Hartmann 1994; Kędziora 1999):

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

where:

Q_d – diurnal sum of radiant energy reaching a horizontal surface at the upper atmospheric boundary ($MJ \cdot m^{-2}$),

$E_0 I_{SC}$ – solar constant calculated for each day of the year (I_{SC}=1367 $W \cdot m^{-2}$),

ς – number of seconds in 24 hours (86,400),

h_0 – solar hour angle (rad),

ϕ – latitude at the point of observation (rad),

δ – declination of the sun on a given day (rad).

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

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

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

where:

N_d = 360°/365 = 0.9863 [°] for a regular year and 360°/366 = 0.9836 [°] for a leap year;

J – number of the day in the year.

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

$$\cos h_0 = -\tan\varphi \cdot \tan\delta$$

The annual sum of extraterrestrial solar radiation, 53°N, amounted to 8575.7MJ·m^{-2} (Table 3). The greatest global solar radiation was seen, as is typical, in June (1241.1MJ·m^{-2}), whereas the smallest occurred in December (187.1 MJ·m^{-2}).

Table 3. Monthly and annual sums of extraterrestrial solar radiation K↓0 (53°N) at the selected points in Toruń and its suburb in 2012. The share of radiation at the ground surface in relation to K↓0 is expressed as a percentage

Month	K↓o	KON		LO1		OME		BAR	
	$MJ·m^{-2}$	$MJ·m^{-2}$	%	$MJ·m^{-2}$	%	$MJ·m^{-2}$	%	$MJ·m^{-2}$	%
J	227.4	68.0	29.9	25.7	11.3	55.6	24.5	36.7	16.1
F	373.1	145.2	38.9	54.6	14.6	111.5	29.9	72.5	19.4
M	665.4	329.4	49.5	205.0	30.8	299.7	45.0	212.0	31.9
A	921.1	436.6	47.4	313.8	34.1	413.7	44.9	318.8	34.6
M	1176.6	639.3	54.3	454.6	38.6	588.5	50.0	491.7	41.8
J	1241.1	502.6	40.5	358.9	28.9	455.2	36.7	381.3	30.7
J	1232.7	599.1	48.6	436.1	35.4	561.9	45.6	442.6	35.9
A	1040.1	476.3	45.8	327.6	31.5	435.0	41.8	329.0	31.6
S	745.3	347.3	46.6	225.9	30.3	312.7	42.0	226.4	30.4
O	493.3	189.3	38.4	100.0	20.3	163.0	33.0	110.4	22.4
N	272.6	60.5	22.2	37.6	13.8	53.5	19.6	38.8	14.2
D	187.1	46.5	24.9	24.2	12.9	42.6	22.8	22.5	12.0
Year	8 575.7	3 840.1	44.8	2 564.1	29.9	3492.9	40.7	2682.7	31.3

The annual course of the amount of K↓ varies throughout the year (Table 3, Fig. 6). The greatest transmission of K↓ occurs in spring (in May 54.3% at KON, 50.0% at OME and 38.6% at LO1 and 41.8 at BAR). This is a result of both the cloud cover and the optical characteristics of the atmosphere, especially dust and water vapour content, which themselves depend–among other things–on the type of incoming air masses (Wójcik 1996; Uscka 2004).

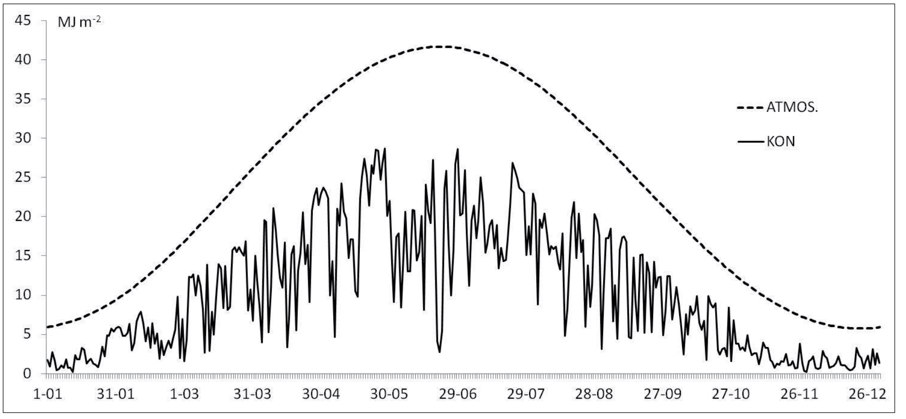

Fig. 6. The annual course of daily sums of global extraterrestrial solar radiation, 53ºN (ATMOS), and at KON in 2012

Spatial diversity of K↓ in an annual course

The values of solar radiation recorded in Toruń and its suburbs in 2012 were diverse. The greatest annual sum of K↓ occurred in the suburban area and reached 3840.1 MJ·m^{-2} at KON and 3838.0 MJ·m^{-2} at KRO. The smallest K↓ was found to be typical of the city centre (LO1), at 2564.1 MJ·m^{-2}, and also of the forest (BAR), at 2682.7 MJ·m^{-2} (Table 4).

The transmission of K↓ in relation to extraterrestrial solar radiation is also varied. More energy reaches the suburban areas, such as the KON with 44.8% of the potential irradiance, and less is observed in the city centre (LO1) with a mere 29.9% (Table 3).

At all points, the greatest monthly sums of solar radiation were determined in May 2012 and ranged from 454.6 MJ·m^{-2} at LO1, to 639.3 MJ·m^{-2} at KON. This is connected with low cloudiness in that month (3.7 on a scale of 0 to 8) (Fig. 7). May also saw the greatest transmission of radiation through the atmosphere, reaching 54.3% of the potential irradiance at KON, and 38.6% at LO1.

Table 4. Monthly and yearly sums of global solar radiation (in MJ·m^{-2}) in Toruń and its suburban area in 2012

Month	Toruń										Suburb area		
	BAR	BOR	LO1	MAN	OME		PSK	RMA	SAL	ZOO	KON	KRO	ZLO
					CNR4	V Pro+							
J	36.7	64.9	25.7	60.8	54.2	55.6	-	49.4	64.3	60.4	68.0	70.8	-
F	72.5	119.8	54.6	113.8	115.1	111.5	-	98.3	123.8	111.3	145.2	144.9	-
M	212.0	311.9	205.0	296.8	316.6	299.7	-	295.0	315.5	303.9	329.4	339.0	-
A	318.8	439.7	313.8	400.9	422.1	413.7	405.9	404.1	427.5	413.2	436.6	447.1	418.7
M	491.7	628.3	454.6	555.9	599.5	588.5	577.0	544.4	600.9	569.6	639.3	626.8	570.5
J	381.3	471.9	358.9	421.0	450.6	455.2	441.6	398.9	462.7	435.0	502.6	475.0	422.3
J	442.6	579.1	436.1	539.5	563.1	561.9	544.0	501.9	577.1	541.6	599.1	584.8	533.1
A	329.0	457.7	327.6	412.3	443.4	435.0	422.1	410.0	449.5	424.0	476.3	479.8	433.7
S	226.4	323.0	225.9	301.1	321.7	312.7	301.8	312.8	325.0	318.3	347.3	350.5	321.1
O	110.4	168.9	100.0	168.8	177.1	163.0	152.2	153.3	172.5	168.8	189.3	200.1	171.0
N	38.8	57.1	37.6	55.6	56.8	53.5	50.1	48.4	55.8	54.2	60.5	63.5	57.1
D	22.5	48.1	24.2	44.1	49.9	42.6	37.9	35.1	45.6	43.5	46.5	55.8	46.2
Year	2682.7	3670.5	2564.1	3370.6	3570.1	3492.9	-	3251.7	3620.1	3443.9	3840.1	3838.0	-

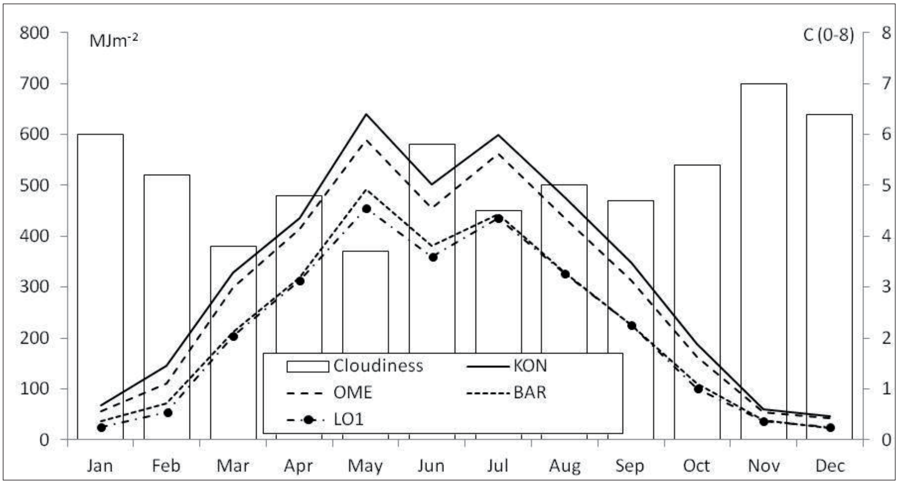

Fig. 7. Course of monthly sums of global solar radiation ($MJ·m^{-2}$) at selected stands and cloudiness (C on a scale of 0–8) in Toruń in 2012

In June, when the sun reaches its highest position over the horizon and when the day is longest, lower values of K↓ were recorded: 358.9 $MJ·m^{-2}$ and 502.6 $MJ·m^{-2}$ at the LO1 and KON, respectively. This was due to the substantial cloud cover in that month (5.8). The distribution of the monthly sums of K↓ in June is presented in Figure 8. The lowest values were typical for December, when the sums of K↓ ranged from 22.5 $MJ·m^{-2}$ at the BAR to 55.8 $MJ·m^{-2}$ at KRO. This is also when the lowest transmission of radiation through the atmosphere occurred; only 24.9% of the potential solar energy reached the ground surface at KON, and even less, 12.9%, at LO1 (Table 3).

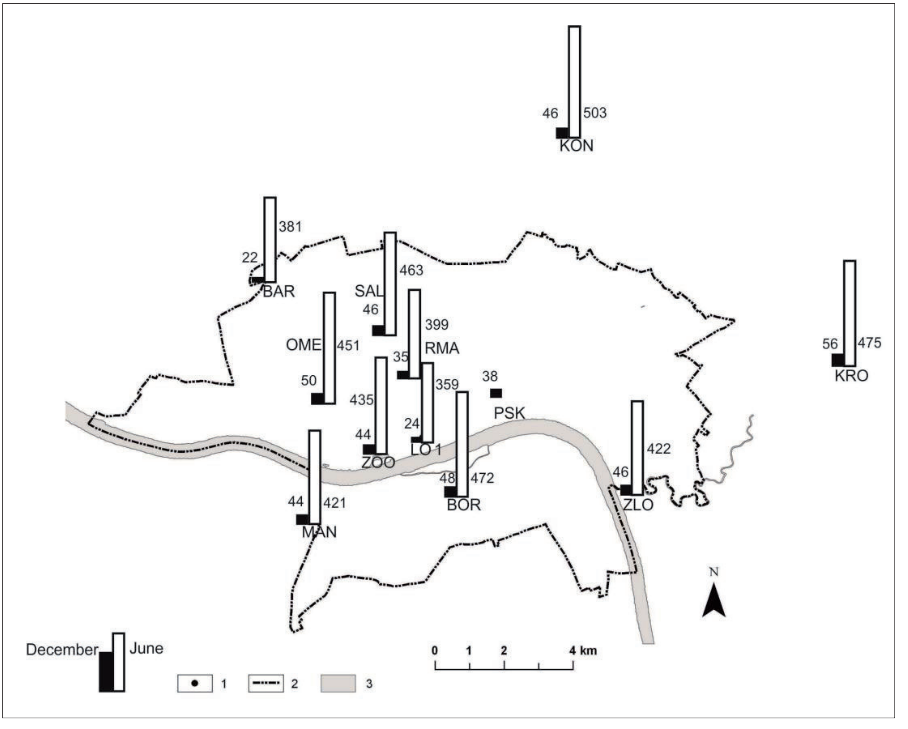

Fig. 8. Monthly sums of solar radiation (in MJ·m^{-2}) in Toruń and its suburbs in June and December 2012: 1 – Measurement points; 2 – Administrative boundary of the city; 3 – The Vistula River

The annual course of K↓ reveals a correlation between the length of day, the apparent height of the sun over the horizon, and the cloudiness which restricts the influx of solar energy. The greatest diurnal sums of K↓ were observed on 28 May and ranged from 20.78 MJ·m^{-2} at LO1 to 28.68 MJ·m^{-2} at KON. In winter, K↓ was lower than 0.5 MJ·m^{-2} (0.04 MJ·m^{-2} on 12 January at OME), and 0.20 MJ·m^{-2} at KON (Fig. 9).

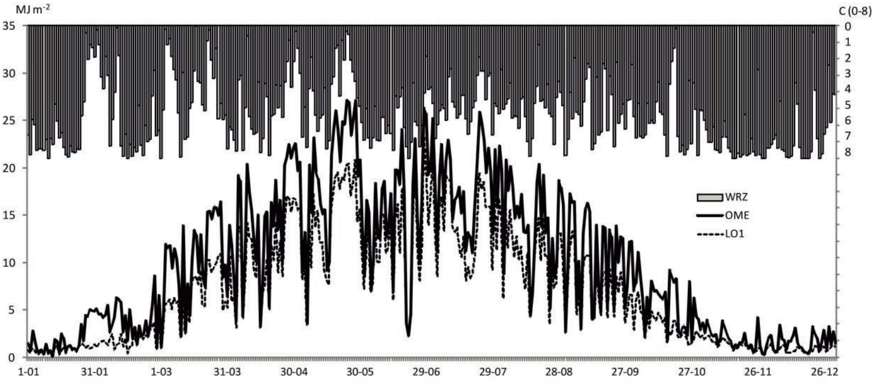

Fig. 9. Annual course of cloudiness (C) in Toruń (WRZ) and solar global radiation at the OME and LO1 in 2012

In all months, there is a negative correlation between K↓ and cloudiness. The influence of clouds is the most evident in June, when the sun is at its highest over the horizon (Fig. 10).

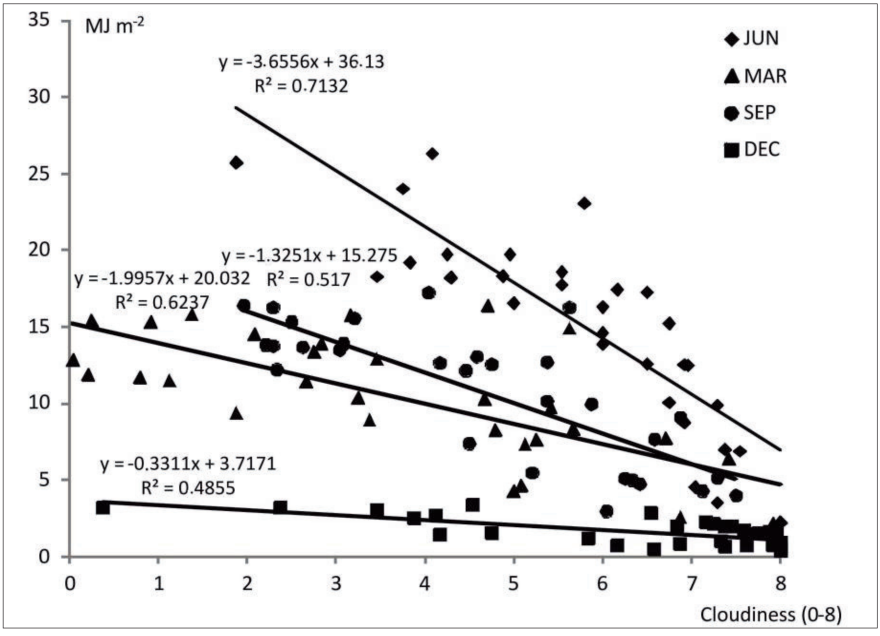

Fig. 10. Relation between diurnal values of cloudiness (WRZ) and global solar radiation in OME in March (MAR), June (JUN), September (SEP) and December (DEC) 2012

Spatial diversity of K↓ in a diurnal course

In a diurnal course, the values of K↓ change from sunrise to sunset and with the apparent height of the sun over the horizon. A regular diurnal course of K↓ is disturbed by cloudiness and other atmospheric phenomena, particularly fog, blizzards and air pollution in the vicinity of the measurement points. In an urban environment the area surrounding the location of the measuring instruments is important (horizon obstruction). The influence of obstacles is especially evident at low solar angles, i.e. in the winter season.

Figure 11 shows averaged diurnal courses of K↓ in selected months at three of the points. The most regular course can be seen at KON, which was situated in an open space. The highest values of K↓ occur in the midday hours, reaching, on average, 600 Wm^{-2} in June, but just 100–150 Wm^{-2} in December. The points where the horizon was more obscured revealed disturbances in the diurnal course of K↓, e.g. at BAR (situated in a forest clearing), where K↓ decreases noticeably in the afternoon, when the point lies in shade (Fig. 3). Conversely, a distinctly limited value of K↓ was observed at LO1 in the morning, due to the easterly obstruction of its horizon (Figs 2 and 3).

The variation of the K↓ that results from the obstruction of the horizon occurs in all seasons of the year. Diffuse radiation prevails on winter days with substantial cloud cover: diffuse radiation is not as dependent on the openness of the horizon as direct solar radiation is. Each measurement point's data reveal a correlation with local terrain obstacles.

On individual days, the influence of cloudiness on the spatial diversity of K↓ is also evident. Figure 12 presents the courses of K↓ at the time of the summer solstice, when irradiance is highest. Nevertheless, the sky was overcast on 21 June 2012, thus the greatest values of K↓ ranged from 96 Wm^{-2} (LO1) to 192 Wm^{-2} (KON). The course of K↓ was uniform and differences among the individual points were negligible. On the other hand, on 28 June 2012 the cloud cover was sparse, with the occasional occurrence of Cu clouds. The maximum intensity of K↓ ranged from 682 Wm^{-2} (BAR) to 922 Wm^{-2} (KON) and 947 Wm^{-2} (OME). On that day, significant differences among the points occurred, for example, at 08:00, K↓ reached 624 Wm^{-2} at KON, but only 77 Wm^{-2} at LO1. The appearance of clouds at 14:00 resulted in a substantial decrease of K↓ at KON, but an increase of 300 Wm^{-2} was observed at the same time at LO1, where the sun was shining.

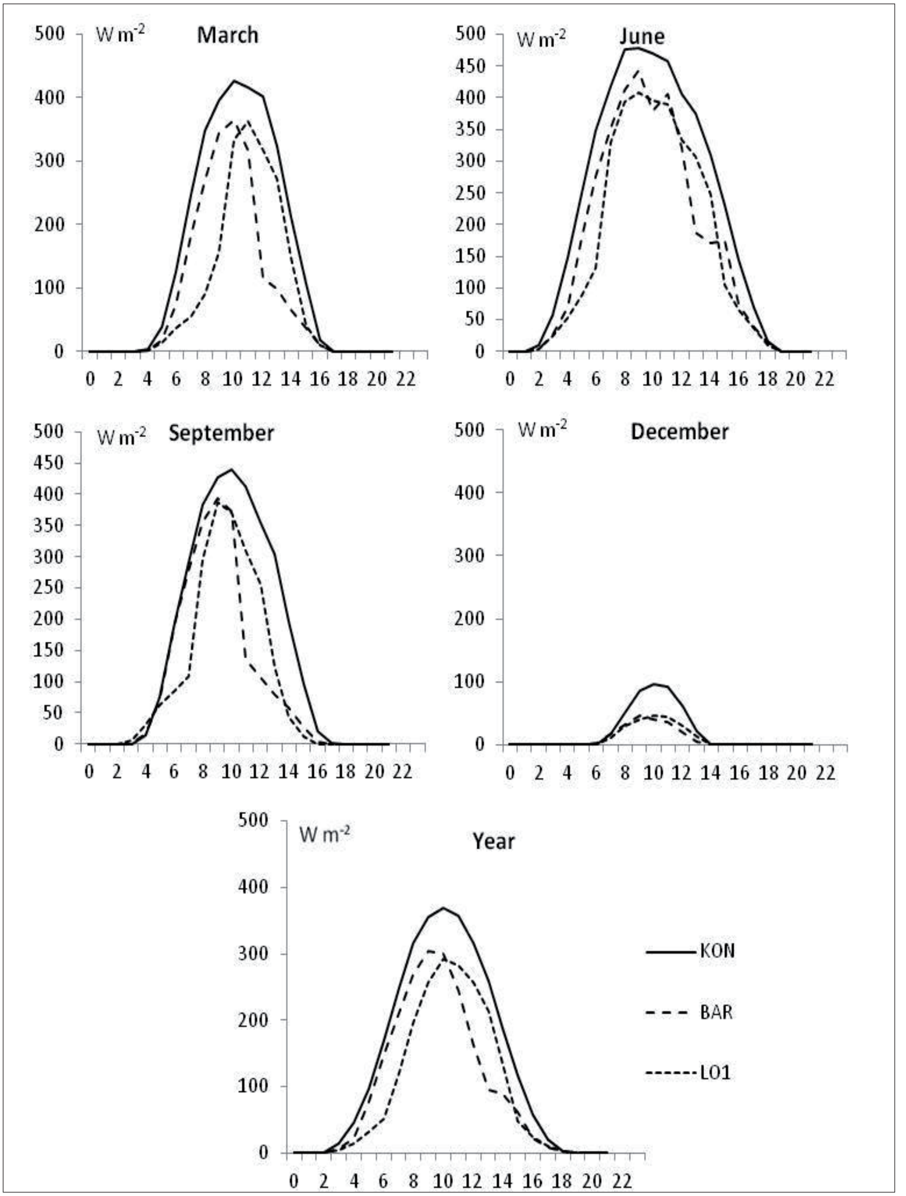

Fig. 11. Daily course of solar global radiation in selected months and year at KON, BAR and LO1 in 2012 (zonal time)

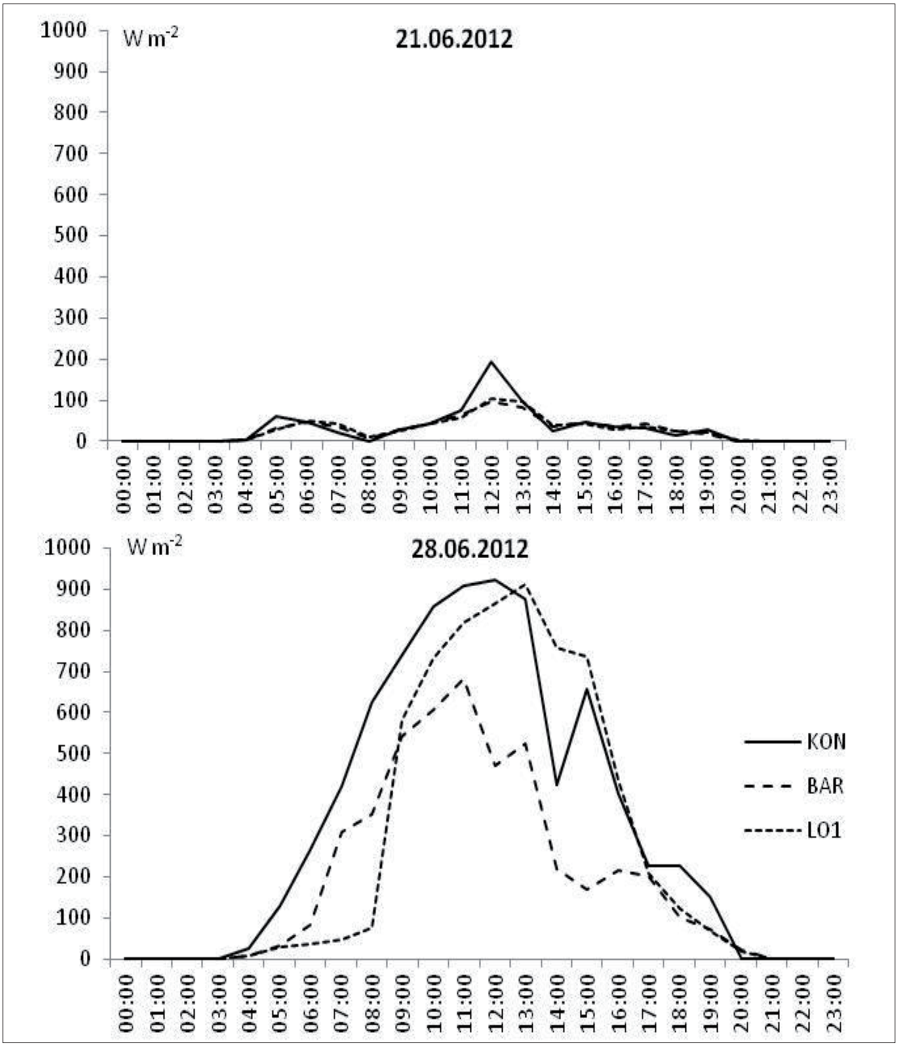

Fig. 12. Daily course of solar global radiation at KON, BAR and LO1 in 21 and 28 June, 2012 (zonal time)

Summary

There are some specific climatic conditions that occur in a city which are not limited to the occurrence of urban heat islands, but also include a highly modified solar profile. Increased cloudiness, greater dust content in the air, and a greater frequency of fog and smog all contribute to a decrease in global solar radiation (K↓) reaching the ground. Obscuring of the horizon is yet another factor reducing irradiance, especially in densely built-up urban developments. In these places, the height of obstacles and their location with regard to the points of the compass are also significant.

The problem of the spatial diversity of the K↓ was analysed using the example of Toruń, a city with heterogeneous architecture, comprising Gothic-style old town buildings, and detached and terraced houses, as well as tower blocks. The obtained results were compared with those obtained in suburban areas, where the horizon is more open. The observations were carried out in 2012, a year with a smaller degree of cloudiness (5.2 on a scale of 0–8) in comparison to the mean value for 1951–2000 (5.4), but with greater sunshine duration (1807.4 hours in Toruń) against the mean value of 1591.2 h for the years 1961–2000 (Wójcik and Marciniak 2006).

At the points where the horizon was open, K↓ reached 3570.1 $MJ\cdot m^{-2}$ at OME and 3840.1 $MJ\cdot m^{-2}$ w at KON, which are typical values for lowland Poland (Bogdańska and Podogrocki 2000). These are similar to mean values recorded for Toruń in the years 1956–1975 (3689.3 $MJ\cdot m^{-2}$ – Miara et al. 1987) and 1983–1991 (3823.6 $MJ\cdot m^{-2}$ – Wójcik 1996) – Table 5.

Compared with the potential radiation at the upper boundary of the atmosphere (8575.7 $MJ\cdot m^{-2}$ at 53°N) in the area of Toruń, the amount of solar energy reaching the surface of the ground ranges from 29.9% (LO1) to 44.8% (KON). In an annual course of K↓ the greatest monthly sums occurred in May (from 454.6 $MJ\cdot m^{-2}$ at LO1 to 639.3 $MJ\cdot m^{-2}$ at KON), and the lowest in December (from 22.5 $MJ\cdot m^{-2}$ at BAR to 55.8 $MJ\cdot m^{-2}$ at KRO). The greatest diurnal sums of K↓ were identified on 28 May and ranged from 20.78 $MJ\cdot m^{-2}$ at LO1 to 28.68 $MJ\cdot m^{-2}$ at KON. In winter, these K↓ values fell below 0.5 $MJ\cdot m^{-2}$.

In the city of Toruń and in its suburban areas, considerable spatial diversity of K↓ was seen–a result not only of the compromised transparency of the atmosphere over the city, but primarily of the obscuring of the horizon. The annual sum of K↓ at the LO1 accounted for just 66.8% of the radiation observed at KON, and 69.9% at BAR. K↓ was more restricted in winter, with its low sun paths, e.g. in January it amounted to 37.8% at LO1, or 48.4% at BAR in December. In summer, on the other hand, when the sun appears higher over the horizon, the obstruction provided by obstacles wanes, and in June the sums of K↓ therefore increased to 71.4% and 75.9%, respectively. This proves that sums of K↓ are smaller in the city centre than in the suburbs.

Table 5. Comparison of global solar radiation in Toruń (OME) and Koniczynka (KON) in 2012 and Toruń (TOR) in the years 1956–1975* and 1983–1991**

Period	OME	KON	TOR*	TOR**
J	54.2	68	71.0	70.7
F	115.1	145.2	120.6	143.6
M	316.6	329.4	268.5	275.6
A	422.1	436.6	379.2	418.5
M	599.5	639.3	535.1	595.2
J	450.6	502.6	591.6	548.7
J	563.1	599.1	566.7	607.3
A	443.4	476.3	494.5	499.7
S	321.7	347.3	345.9	314.4
O	177.1	189.3	183.8	209.6
N	56.8	60.5	79.8	86.4
D	49.9	46.5	52.7	53.9
YEAR	3570.1	3840.1	3689.3	3823.6

* – data from Toruń and Bydgoszcz in the years 1956–1975 according to Miara et al. (1987)
** – data from Toruń in the years 1983–1991 according to Wójcik (1996)

However, the values cited in literature are definitely smaller. For example, mean global solar radiation in the centre of Łódź is usually 5% lower than the sums registered at points located out of town. These diversities become even more evident in winter, reaching a difference of 25% in the case of diurnal sums (Podstawczyńska 2007). This is similar to Kraków, where in 1968–1975, mean values of K↓ recorded at midday hours were 7% lower than in the countryside weather station of Gaik-Brzezowa, which was more distinct in winter (a 25% reduction) than in summer (4–7%) (Matuszko and Struś 2007). Nevertheless, one cannot compare such values directly, because the values provided for Łódź and Kraków were obtained at points with open horizons, and the differences were affected by greater air pollution and thus a greater extinction of solar radiation by the urban atmosphere. The values recorded for Toruń are instead referable to experimental studies conducted in a street canyon in Łódź, where the intensity of incoming solar radiation reached 78%, despite a 60% obstruction of the horizon (Podstawczyńska and Pawlak 2006).

In the diurnal course, maximum values of solar radiation (over 900 Wm^{-2}) occurred at midday hours in June. The K↓ is heterogeneous and depends on the location of the measuring point and the presence or absence of obstacles. For example, the amount of global solar radiation that reaches LO1 is equal to 36% of the radiation at KON at 09:00, 72% at 12:00 and 103% at 16:00. A greater irradiance in the open space is particularly evident in summer (as much as 122% at 17:00 in July), which may be the result of multiple reflections of the sun's rays off the roofs and walls of the buildings surrounding the measuring point. This is a typical phenomenon in urban areas, especially in street canyons characterised by diverse geometries, orientations and arrangements of buildings (Podstawczyńska and Pawlak 2006).

The measurements taken in Toruń and its suburban areas indicate a considerable local diversity of K↓, which depends on the openness of the horizon and the location of relevant obstacles-typical features of an urban environment with diverse architecture and organisation of urban space. Studies like this are a form of applied science, as they allow urban energy resources to be determined, for instance, for solar thermal collectors and active heating systems. The role of solar radiation in the passive heating of buildings is also significant. Solar energy resources are strictly determined by latitude, but also depend on exposure, roof pitch, the absorptive qualities of walls and roofs, the size of windows etc. (Chwieduk 2010).

Acknowledgments

This study was conducted as part of National Science Centre Project No. N N306 723040, with the Integrated Environmental Monitoring programme at the Station of Integrated Monitoring of Natural Environment at Koniczynka.

References

BOGDAŃSKA B., PODOGROCKI, J., 2000, Zmienność całkowitego promieniowania słonecznego na obszarze Polski w okresie 1961–1995, Mat. Bad. IMGW, Meteorologia, 30, IMGW, Warszawa, 43 pp.

BOKWA. A., MATUSZYK, K., 2007, Zmiany promieniowania całkowitego w Krakowie i Gaiku-Brzezowej, Pam. Puławski, 144, 5–12.

BRYŚ K., BRYŚ T., 2007, Zmienność klimatu solarnego Wrocławia w latach 1875–2004, Pam. Puławski, 144, 13–33.

BUDZIK T., 2006, Pomiary promieniowania krótkofalowego i długofalowego w Sosnowcu w latach 2002–2005 z wykorzystaniem bilansomierza CNR-1 (Net Radiometr Kipp & Zonen), Ann. Univ. M. Curie-Skłodowska, Geogr., Sectio B, LXI, 100–106.

CAPUTA Z., LEŚNIOK M., 2009, Struktura bilansu promieniowania na obszarach miejskich i wiejskich - system pomiarowy i wybrane wyniki pomiarów na Wyżynie Śląsko-Krakowskiej, Prace Geogr. UJ., 122, 23–38.

CAPUTA Z., WOJKOWSKI J., 2009, Struktura promieniowania w pełnym zakresie widma na obszarze Ojcowskiego Parku Narodowego, Prądnik, Prace i Materiały Muzeum im. prof. Władysława Szafera, 19, 119–140.

CHRISTEN A., VOGT R., 2004, Energy and radiation balance of a Central European city, Int. J. Climatol., 24, 1395–1421.

CHWIEDUK D., 2010, Solar energy use for thermal application in Poland, Polish J. Environ. Stud., 19 (3), 473–477.

CODATO G. DE OLIVEIRA A.P. ESCOBEDO J.P., 2004, Comparative study of solar radiation in urban and rural areas, Anais do XIII Congresso Brasileiro de Meteorologia, Fortaleza, Brazil. http://www.iag.usp.br/meteo/labmicro/Georgia_CBMet2004.pdf.

DAS Y., PADMANABHAMURTY B., MURTY A.S.N., 2009, Spatial and temporal distributions of radiation balance components over Delhi, Contributions to Geophysics and Geodesy, 39/4, 355–377.

DOBEK M., GAWRYSIAK L., 2009, Rozkład przestrzenny nasłonecznienia w Lublinie, Prace Geogr., Inst. Geogr. i Gospod. Przestrz. UJ Kraków, 122, 49–53.

DE OLIVEIRA A.P., MACHADO A.J., ESCOBEDO J.F., SOARES J., 2002, Diurnal evolution of solar radiation at the surface in the city of Sao Paulo: seasonal variation and modeling, Theor. Appl. Climatol., 71, 231–249.

FORTUNIAK K., 2003, Miejska wyspa ciepła. Podstawy energetyczne, studia eksperymentalne, modele numeryczne i statystyczne, Wyd. Uniw. Łódzkiego, 233 pp.

FORTUNIAK K., 2010, Radiacyjne i turbulencyjne składniki bilansu cieplnego terenów zurbanizowanych na przykładzie Łodzi, Wyd. Uniw. Łódzkiego, Łódź, 231 pp.

Guide to Meteorological Instruments and Methods of Observation, 2008, WMO-No.8.

HAMILTON I.G., DAVIES M., STEADMAN P., STONE A., RIDLEY I., EVANS S., 2009, The significance of the anthropogenic heat emissions of London's buildings: A comparison against captured shortwave solar radiation, Build. and Environ., 44, 807–817.

HARTMANN D. L., 1994, Global physical climatology, Academic Press, New York., 408 pp.

HESS M., LEŚNIAK B., OLECKI Z., RAUCZYŃSKA-OLECKA D., 1980, Wpływ krakowskiej aglomeracji miejsko-przemysłowej na promieniowanie słoneczne dochodzące do powierzchni ziemi, Zesz. Nauk. UJ, Prace Geogr., 51, 8–71.

HESS M., OLECKI Z., 1990, Wpływ zanieczyszczenia powietrza na stosunki radiacyjne w Krakowie, Zesz. Nauk. UJ, Prace Geogr., 77, 29–43.

HESS M., OLECKI Z., RAUCZYŃSKA-OLECKA D., 1979, Radiacyjne cechy klimatu na Pogórzu Wielickim, Zesz. Nauk. UJ, Prace Geogr., 49, 7–102.

HII D.J.C., HENG C.K., MALONE-LEE L.C., Z., J., IBRAHIM N., HUANG Y., JANSSEN, P., 2011, Solar radiation performance evaluation for high density urban forms in the tropical context, Proceedings of Building Simulation, 12th Conference of International Building Performance Simulation Association, Sydney, 2595–2602.

JAKUBIEC J.A., REINHART C.F., 2012, Towards validated urban photovoltaic potential and solar radiation maps based on lidar measurements, GIS data, and hourly day simulations, Proceedings of SimBuild, Madison, Wisconsin, 1–10.

KAMBEZIDIS H. D., PSILOGLOU B. E., GUEYMARD C., 1994, Measurements and models for total solar irradiance on inclined surface in Athens, Greece, Solar Energy, 53 (2), 177–185.

KEJNA M., USCKA-KOWALKOWSKA J., ARAŹNY A., 2014, Bilans promieniowania w Koniczynce k. Torunia w latach 2011–2012, Przegl. Nauk. Inżynieria i Kształt. Środowiska, 63, 26–42.

KĘDZIORA A., 1999, Podstawy agrometeorologii, Państwowe Wydawnictwo Rolnicze i Leśne, Poznań.

KONDRACKI J., 2011, Geografia regionalna Polski, Wyd. Nauk. PWN, Warszawa, 444 pp.

KOZŁOWSKA-SZCZĘSNA T., 1973, Promieniowanie pochłonięte na obszarze Polski, Zakład Narodowy im. Ossolińskich, Wyd. PAN, Wrocław, 118 pp.

KUNZ M., USCKA-KOWALKOWSKA J., PRZYBYLAK R., KEJNA M., ARAŹNY A., MASZEWSKI R., 2012, Zróżnicowanie klimatów lokalnych Torunia – założenia projektu i wstępne wyniki badań, Rocz. Geomatyki, X, 3 (55), 85–94.

LORENC H. (ed.), 2005, Atlas klimatu Polski, Instytut Meteorologii i Gospodarki Wodnej, Warszawa, 116 pp.

MATUSZKO D., STRUŚ, P., 2007, Przestrzenne zróżnicowanie warunków solarnych Pogórza Zachodniobeskidzkiego (próba metodyczna), Pam. Puławski, 144, 105–113.

MATUSZKO D., 2007, Synchronous and asynchronous periods of cloudiness and sunshine duration in Cracow (over 1884–2003), Prace Geogr. UJ, 115, 39–47.

MIARA K., PASZYŃSKI J., GRZYBOWSKI J., 1987, Zróżnicowanie przestrzenne bilansu promieniowania na obszarze Polski, Przegl. Geogr., 4, 487–509.

MORAWSKA-HORAWSKA M., 2002, Tendencje zachmurzenia i usłonecznienia Krakowa w latach 1861-1990, [in:] G. Wójcik, K. Marciniak (eds.) Działalność naukowa profesora Władysława Gorczyńskiego i jej kontynuacja, UMK Toruń, 341–351.

OLECKI Z., 1973, Wpływ miasta na niektóre elementy bilansu radiacyjnego na przykładzie Krakowa, Zesz. Nauk. UJ, Przegl. Geogr., 32, 105–118.

OLECKI Z., 1975, Oddziaływanie dużego ośrodka miejsko-przemysłowego na dopływ promieniowania słonecznego (na przykładzie Krakowa), Zesz. Nauk. UJ, Przegl. Geogr., 41, 37–86.

OLECKI Z., 1980, Rola dużego ośrodka miejsko-przemysłowego w kształtowaniu promieniowania słonecznego na przykładzie Krakowa, Acta Univ. Lodz., Zesz. Nauk. UŁ, Nauki Mat.-Przyr., ser. II, 28, 105–113.

OLECKI Z., 1986, On the components of the radiation balance in Cracow, Zesz. Nauk. UJ, Przegl. Geogr., 69, 27–38.

PASZYŃSKI J., 1966, Atlas bilansu promieniowania w Polsce. Dok. Geogr. IG PAN, Warszawa, 4, 18 pp.

PASZYŃSKI J., MIARA. K., SKOCZEK. J., 1999, Wymiana energii między atmosferą a podłożem jako podstawa kartowania topoklimatycznego, Dok. Geogr., IG PAN, Warszawa, 14, 127 pp.

PASZYŃSKI J., NIEDŹWIEDŹ T., 1991, Klimat [in:] Starkel L. (ed.) Geografia Polski. Środowisko przyrodnicze, Wyd. Naukowe PWN, Warszawa, 296–355.

PETERSEN J.T., STOFFEL T.L., 1980, Analysis of urban-rural solar radiation data from St. Louis, Missouri, J. Appl. Meteorol., 19, 275–283.

PETRENZ N., SOMMER M., BERGER F.H., 2007, Long-time global radiation for Central Europe derived from ISCCP Dx data, Atmos. Chem. Phys., 7, 5021–5032.

PIRINGER M., JOFFRE S.,, BAKLANOV A., BURZYNSKI J., DE RIDDER K., DESERTI M., KARPPINEN A., MESTAYER P., MIDDLETON D., TOMBROU M., VOGT R., CHRISTEN A., 2005, The urban surface energy budget and the mixing height: some results of recent European experiments stimulated by the cost – action 715, 9th Int. Conf. on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes, 137–141.

PODOGROCKI J., 1978, Spatial distribution of global solar radiation in Poland, Publ. Inst. Geophys. Pol. Acad. Sci., D5-120, 17–30.

PODOGROCKI J., ŻÓŁTOWSKA K., WIŚNIEWSKA J., GARDYAS B., 1998, Opracowanie metodyki automatyzacji pomiarów aktynometrycznych i optymalizacja przetwarzania danych, Opracowanie M-9.7, IMGW, Warszawa.

PODSTAWCZYŃSKA A., 2007, Cechy solarne klimatu Łodzi, Acta Geogr. Lodz., Folia Geogr. Phys., 7, 294 pp.

PODSTAWCZYŃSKA A., PAWLAK W., 2006, Pomiary wybranych elementów meteorologicznych w kanionie ulicznym Łodzi, Universitatis Annales M. Curie-Skłodowska, LXI, 43B, 370–379.

RADOSZ J., 2010, Topoklimat Katowic na tle charakterystyki środowiska geograficznego, Kształtowanie środowiska geograficznego i ochrona przyrody na obszarach uprzemysłowionych i zurbanizowanych, 42, Uniwersytet Śląski, WBiOŚ, WNoZ, Katowice-Sosnowiec, 60–69.

ROBAA S.M., 2006, A study of solar radiation climate at Cairo urban area, Egypt and its environs, Int. J. Climatol., 26, 1913–1928.

SERBAN C., 2010, Estimating Clear Sky Solar Global Radiation Using Clearness Index for Brasov, Urban Area, Proceedings of the 3rd International Conference on Maritime and Naval Science and Engineering, Constantza, Romania, 150–153.

STEWART I.D., OKE T.R., 2012, Local climate zones for urban temperature studies, Bull. Amer. Met. Soc., 93, 1879–1900, DOI:10.1175/BAMS-D-11-00019.1.

TAHA H., 1997, Urban climates and heat islands: albedo, evapotranspiration, and anthropogenic heat, Energy and Buildings, 25, 99–103.

USCKA J., 2004, Przezroczystość atmosfery w strefie podmiejskiej Torunia w latach 1999-2001, [in:] Kejna M., Uscka J. (eds.) Zintegrowany Monitoring Środowiska Przyrodniczego, Biblioteka Monitoringu Środowiska, 177–186.

USCKA-KOWALKOWSKA J., 2010, The oldest heliographic and actinometric measurements in Poland, Acta Agrophys., Rozpr. i Monografie, 5 (184), 24–34.

WILD M., 2009, Global dimming and brightening: A reviev, J. Geophys. Res., 114, D00D16, doi: 10.1029/2008JD011470.

WOJKOWSKI J., 2007, Modelowanie dopływu promieniowania słonecznego przy użyciu GIS na przykładzie obszaru Ojcowskiego Parku Narodowego, Annales Univer. M. Curie-Skłodowska, B, LXI, Geographia, 468–478.

WOJKOWSKI J., SKOWERA B., 2011, Spatial differentiation in absorbed solar radiation in the Ojców National Park, [in:] Středová W.H., Rožnovský J., Litschmann T. (eds.) Mikroklima a mezoklima krajinných struktur a antropogenních prostředí, Skalní mlýn, 2–4.2.2011, 3–11.

WÓJCIK G., 1983, Promieniowanie globalne na polanie i na dnie lasu w Rezerwacie Piwnickim, Acta Univ. Nic. Copernici, Biologia XXV, 55, 3–21.

WÓJCIK, G., 1996, Globalne promieniowanie słoneczne i jego transmisja przez atmosferę w Toruniu, Acta Univ. Nic. Copernici, Geografia XXVII, 97, 65–73.

WÓJCIK G., MARCINIAK K., 2006, Klimat [in:] Andrzejewski L., Weckwerth P., Burak Sz. (eds.), Toruń i jego okolice - monografia przyrodnicza, UMK Toruń, 99–127.