PRZEGLĄD GEOFIZYCZNY

Rocznik LXIII 2018 Zeszyt 4

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ACTUAL SUNSHINE DURATION IN POLAND – COMPARISON OF SATELLITE AND GROUND-BASED MEASUREMENTS

Introduction

Measurements of sunshine duration in meteorological stations are performed for the purpose of determining changes in the radiation balance of the climatic system at varying spatial and temporal scales (Wu et al. 2016). Data on the duration of direct solar radiation to the Earth's surface is also used in studies in the scope of renewable energy, tourism, agriculture, and spa healthcare (Sanchez-Romero et al. 2015). The quality of measurement data concerning this meteorological element is related to a number of problems, the most serious of which seems to be the replacement of traditional measurement devices with automatic instruments. The difference in methods can prevent data from being compared, potentially leading to the false interpretation of study results (Matuszko 2012b, 2015). Metadata provided by the Institute of Meteorology and Water Management – National Research Institute (IMGW-PIB) states that the replacement of devices in Poland commenced at the end of the 1990s, and in 2014, electronic sensors registering sunshine duration were functioning at the majority of synoptic stations. The results of the changes presumably broke the homogeneity of long-term records of sunshine duration.

With the development of satellite measurements, it is already possible to estimate the value of the majority of meteorological elements. This permits the collection of datasets independent of ground-based measurements. The duration of satellite data series already exceeds 30 years, and the algorithms used contribute to increasingly accurate results (Kothe et al. 2017). Sunshine duration determined by means of spaceborne remote sensing has been the subject

of several papers in recent years (Kandirmaz 2006; Good 2010; Shamim et al. 2012; Kothe et al. 2013). According to these studies, satellite data constitutes a valuable source of information, particularly in research on the spatial variability of this meteorological element.

The objective of this study is to compare sums of actual sunshine duration in the territory of Poland, obtained based on satellite data and ground-based measurements from 1983-2015. No detailed studies exist so far demonstrating the comparison of the data for this part of Europe. The analysis is very important because it will allow to assess the usefulness of the values of sunshine duration from the satellite data in climatological studies.

Material and methods

The first group of data includes the results of measurements of daily sums of actual sunshine duration from the period 1983-2015, provided by IMGW-PIB. The values were obtained from 44 synoptic stations distributed in the territory of Poland, where gaps in the data series did not exceed 3% of daily sums. Throughout the majority of the analysed period, measurements of sunshine duration at the stations were recorded using standard devices (Campbell-Stokes sunshine recorders), and were later changed to automatic devices (depending on the station – Lambrecht, DSU12, and CSD3 sunshine duration sensors). The replacement of traditional measurement devices initially occurred successively from the end of the 20th century, with the majority of cases occurring within the period 2013-2015.

The study also employed values of sunshine duration from the product "SDU – Sunshine Duration, version 002" (Pfeifroth et al. 2017), derived from observations of the first and second generation geostationary Meteosat satellites, which monitor the atmosphere over Europe, Africa, the Atlantic Ocean, and a fragment of South America. The values were obtained from database SARAH-2, provided by the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), functioning in the scope of the Satellite Application Facility on Climate Monitoring (CM SAF). The data covers the period of 1983-2015, with a resolution is 0.05° × 0.05°. In this method, obtaining information on sunshine duration is based on algorithms considering day duration (when the height of the Sun over the horizon is > 2.5°) and direct solar radiation to the Earth's surface (I_m) with an intensity of ≥120 Wm^{-2} (Kothe et al. 2017). The values of radiation intensity in a given point are obtained in 30-minute intervals, and data from 24 adjacent pixels are used, with ascribed respective weights. Sunshine duration in a selected 30-minute interval is therefore a resultant of the number of "sunny" ($I_m \geq 120$ Wm^{-2}) and "cloudy" pixels ($I_m < 120$ Wm^{-2}), taking into account the previous time step. Moreover, the method employed an integrated self-calibration

parameter, minimising the impact of satellite changes and artificial trends due to the degradation of satellite instruments (the MVIRI and SEVIRI sensors). A detailed description of the procedure used to determine sunshine duration is included in Kothe et al. (2017).

In this paper, data from a particular meteorological station was compared to data from the nearest pixel from the satellite data. The determination of the relationship and values of differences between daily sums of solar duration obtained from satellite and ground-based measurements involved the calculation of coefficients of simple linear correlations, and the application of two statistical measures; the mean difference (*MD*; bias) and the mean absolute difference (*MAD*). The differences were calculated for each meteorological station and for the entire territory of Poland, by means of the following formulas:

$$MD = \frac{1}{n}\sum_{i=1}^{n}(U_{SAT_i} - U_{Meteo_i})$$

$$MAD = \frac{1}{n}\sum_{i=1}^{n}\left|U_{SAT_i} - U_{Meteo_i}\right|$$

where: U_{SAT_i} is the daily sum of sunshine duration obtained from the satellite data; U_{Meteo_i} is the daily sum of sunshine duration from the meteorological station and n is number of days.

MD is the mean difference in the sunshine duration value, where positive differences denote the prevalence of higher values of sums of sunshine duration from the satellite data, and negative differences denote the same from ground-based measurements. The *MAD* value is the mean absolute difference between the data. Moreover, normalised *MD* values, calculated in this case based on the monthly sums of actual sunshine duration, were used for the presentation of the long-term variability of differences between the analysed data sets (at the scale of the country and selected meteorological stations).

Study results

In the territory of Poland, the values of coefficients of linear correlation (r) between daily sums of actual sunshine duration based on satellite data and ground-based measurements usually range between 0.80 and 0.95 (Fig. 1). The strongest correlation was determined in reference to meteorological stations located within the vicinity of the eastern national border and in Pomerania ($r > 0.90$). A lower covariance was characteristic of data from the area of central Poland ($0.80 < r \leq 0.85$), and particularly from Warsaw ($r = 0.67$). Irrespective of the region, the highest correlation coefficients between satellite and ground-

based data were retrieved from the period of April to October ($r \approx 0.90$), and the noticeably lower ($0.70 < r \leq 0.75$) winter months (Table 1).

A comparison of both databases focuses on information on the value of differences between U_{SAT} and U_{Meteo}. According to the research, mean differences (*MD*) in the territory of the country are small (Fig. 2a), whereas positive values are prevalent, i.e. somewhat higher daily sums of sunshine duration from the satellite data. The highest positive differences were determined in Tarnów, Zielona Góra, and Racibórz (+0.3 h), and equivalent negative values in Warsaw and on Kasprowy Wierch (–0.4 h). At the scale of the entire country, positive values are prevalent in the period from September to April (between +0.1 and +0.5 h), and negative from May to July (from –0.3 h to –0.2 h) (Table 1). The highest *MAD* values (≥1.1 h), reflecting absolute differences between both data sets, were obtained in the southern part of Poland (among others Kasprowy Wierch, Śnieżka, Rzeszów), and moreover in Warsaw, Mława, and Kalisz (Fig. 2b). The smallest mean differences of daily sums of sunshine duration (<0.9 h) were characteristic of meteorological stations located in Włodawa, Lesko, Siedlce, Leszno, and Hel. There were no large differences in *MAD* values determined between particular months (Table 1), whereas higher differences occur in spring (0.7 h), and smaller in summer (0.5 h). The obtained *MD* and *MAD* values are lower than those obtained for Europe by Kothe et al. (2017). This is due to the fact that these authors analyzed a much larger area that covered western part of Europe.

For a comparative analysis, the characteristics of the temporal variance of *MD* are important. This permits the determination of changes both in the value and sign of differences between satellite and ground-based data. In reference to the entire country, the prevalence of positive differences was determined in the initial period (1983-1995), followed by a change to negative values (Fig. 3a). This was also observed in particular meteorological stations, although

Table 1. Linear correlation coefficients and *MD* and *MAD* values (in hours) in particular months and seasons calculated on the basis of the daily sums of actual sunshine duration from 1983 to 2015 (for entire country)

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Spring	Summer	Autumn	Winter	Year
r	0.71	0.75	0.81	0.89	0.91	0.90	0.90	0.90	0.90	0.89	0.83	0.72	0.88	0.90	0.88	0.73	0.87
MD	0.2	0.1	0.2	0.3	−0.2	−0.3	−0.3	0.0	0.5	0.4	0.3	0.2	0.1	−0.2	0.4	0.2	0.1
MAD	0.6	0.6	0.8	0.6	0.5	0.6	0.6	0.5	0.7	0.6	0.5	0.5	0.7	0.5	0.6	0.6	0.6

r – linear correlation coefficients; *MD* – mean difference (bias); *MAD* – mean absolute difference

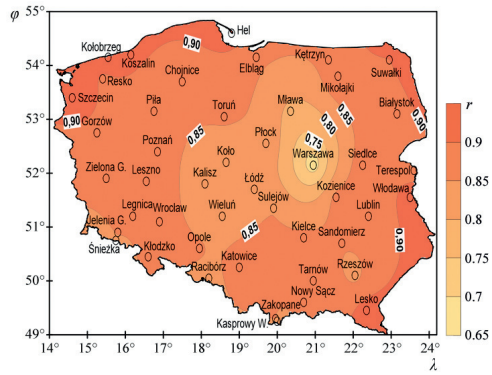

Fig. 1. Spatial variability of the values of linear correlation coefficients between the daily sums of actual sunshine duration based on satellite data and ground-based measurements (1983-2015)

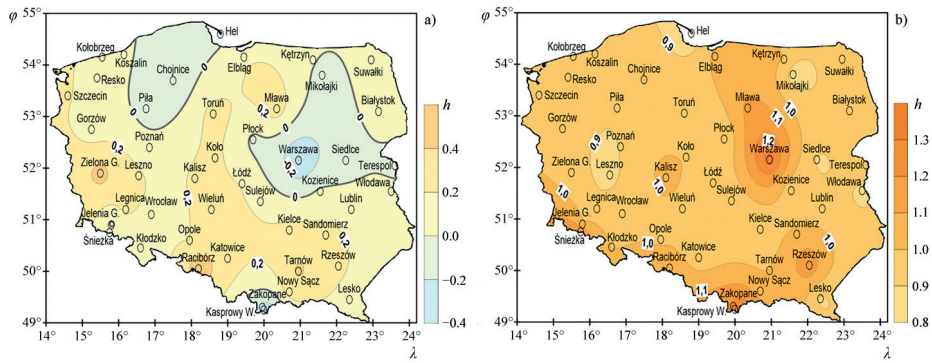

Fig. 2. Spatial variability of the values of (a) *MD* and (b) *MAD* from the daily sums of actual sunshine duration (in hours) in Poland from 1983 to 2015

the value of *MD* can be considerably divergent, e.g. in Warsaw, the deviations were approximately 3 times higher than in Leszno (Fig. 3b and 3c).

Small differences were observed in the case of the long-term variance of mean annual sums of actual sunshine duration obtained from two sources of data for the entire territory of Poland (Fig. 4). In the years of 1983-1993, the mean difference was 130 h (higher values of sunshine duration were derived for satellite data), however, after 1995, differences between both data series were much smaller, at an average of 4 h. It could be due to an underestimation of aerosols optical depth (AOD) in the satellite method, what was noted during the "global dimming" period in the 1980s.

In the spatial approach, positive differences in mean multi-year sums of sunshine duration (between 100 and 150 h) occurred in Zielona Góra, Racibórz, Katowice, Tarnów and Mława. Higher values of sunshine duration from

ground-based measurements (between 50 and 150 h) were determined in the case of Warsaw, Chojnice, and Kasprowy Wierch (Fig. 5).

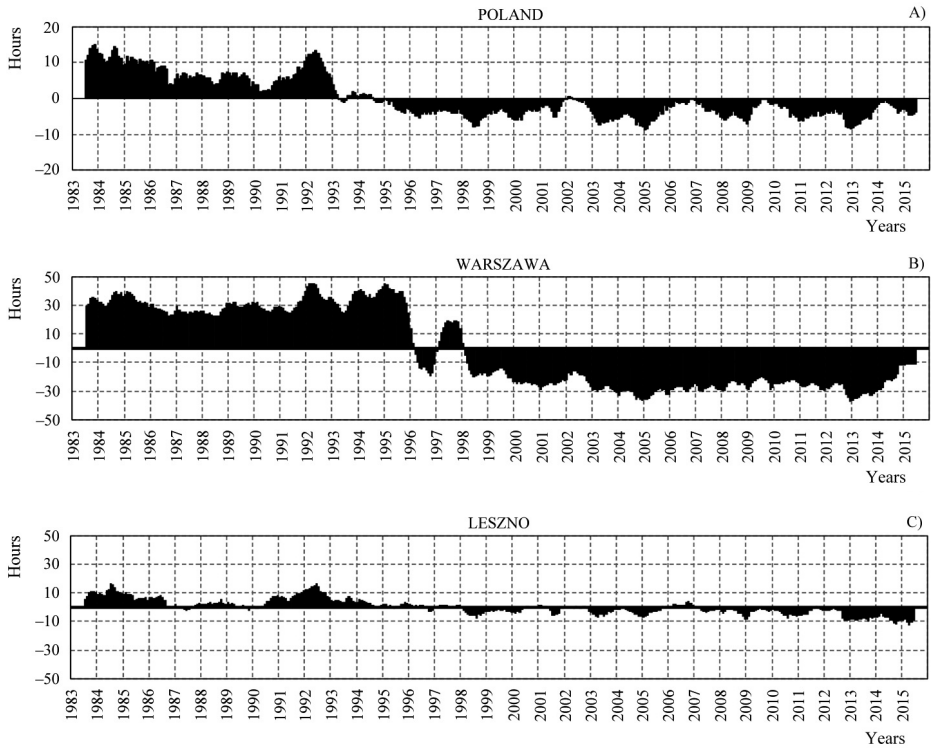

Fig. 3. Long-term variability of normalized average deviations (*MD*) of the monthly sums of actual sunshine duration (in hours), from 1983 to 2015; values are smoothed by a 13-element low-pass filter

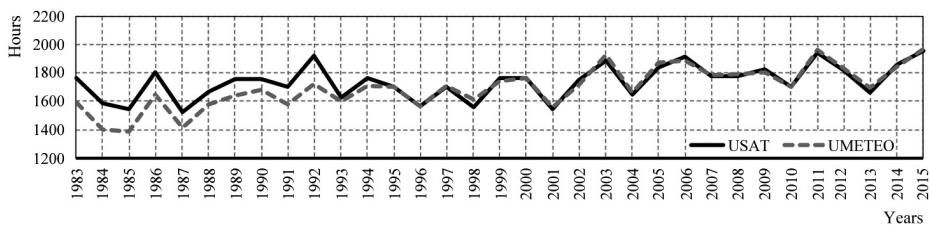

Fig. 4. The course of the mean annual sums of actual sunshine duration (in hours) in Poland, defined on the basis of satellite and ground-based measurements

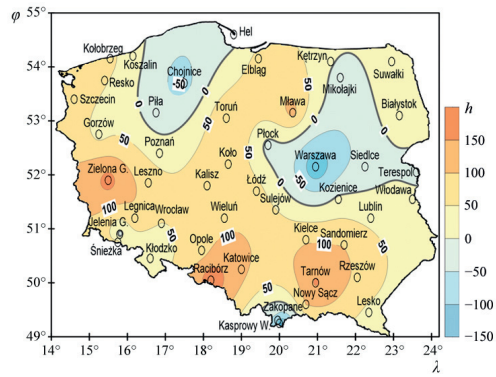

Fig. 5. Differences (in hours) of the mean multi-year sums of actual sunshine duration (U_{SAT} – U_{Meteo}), in Poland from 1983 to 2015

Conclusions

The values of the daily sums of actual sunshine duration obtained based on satellite data cannot be perceived as equivalent to values measured in meteorological stations. In spite of this, results showed no significant differences between the analysed data sets, as confirmed by the high values of correlation coefficients and the approximate course of annual sums of sunshine duration. It is worth mentioning that mean daily differences in sunshine duration are approximate to differences between readings from the CSD3 sunshine duration sensor and the Campbell-Stokes sunshine recorder presented by Matuszko (2012a) for Kraków. The observed differences between both data series are presumably caused by the following:

- Replacing the manual measurement sensors in meteorological stations with automatic devices (first in Warsaw). The sensitivity threshold of the Campbell-Stokes sunshine recorder is more than two times greater (approximately 280 Wm^{-2}) than the threshold adopted in the satellite and electronic sensors (120 Wm^{-2}). Moreover, the differences result from the partial obscuring of the horizon by trees or land elevations in the vicinity of the location of the ground-based measurements.
- The spaceborne remote sensing method does not consider aerosol optical depth (AOD), resulting in the first part of the analysis period showing higher values of sunshine duration for the territory of Poland compared to ground-based measurements. This, however, demonstrated the transition from the so-called "global dimming" period to the period of "global brightening" that occurred at the turn of the 1980s and 1990s (Sanchez-Lorenzo 2015; Matuszko 2016). A short-term increase in positive differences between data in 1992 can be interpreted by a higher amount of aerosols in the atmosphere

as a result of the Pinatubo volcano eruption in 1991 (Kothe et al. 2017).

- Values of sunshine duration obtained from ground-based measurements depend on cloud types covering the Sun's disc (Matuszko 2012a, 2015), which is not considered in the satellite method. A certain underestimation of sunshine duration in the summer period is suggested by negative *MD* values. At this time of the year, the contribution of convective clouds is higher than average. They rapidly cover and uncover the Sun's disc, which cannot be considered for the case of satellite images collected at the temporal resolution of 30 minutes.
- Lower correlation coefficients values of sunshine duration in the winter period probably result from the difficulty to differentiate between snow cover and cloudiness in satellite imagery. Moreover, at this time of the year in urban areas, where some of the meteorological stations are located, aerosol optical depth is higher than average due to dust pollutants.
- For meteorological stations located in the mountains (Kasprowy Wierch, Śnieżka), the upper boundary of clouds can often be located below 1500 m a.s.l. Therefore, sunshine duration, according to the satellite method, is underestimated.

In summary, breaking the homogeneity of the series of sunshine duration data in synoptic stations in Poland in the 21st century forces the search for other sources of information concerning this meteorological component. As evidenced in the paper, satellite data available from the first half of the 1980s can constitute, with certain reservations, as valuable material for further climatological research. For the next stage, the author will use high spatial resolution satellite data (3.5 km × 5.5 km) for the expansion of information on the effect of local factors on the duration of direct radiation to the Earth's surface and will relate this to other meteorological elements. The aim of the new approach will be to assess the impact of the type of land cover on sunshine duration.

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Summary

The objective of the study was to compare the sum of actual sunshine duration in Poland, based on satellite and ground-based measurements during the period of 1983-2015. Results from the first group of data were derived from sunshine duration measurements from 44 surface synoptic stations belonging to the Polish Institute of Meteorology and Water Management (IMGW-PIB). The second group of data includes values from observations of Meteosat geostationary satellites (SARAH-2 climate data record), provided by the EUMETSAT Satellite Application Facility on Climate Monitoring (CM SAF). The study showed that in Poland, values of linear correlation coefficients (r) between both datasets are high, and range between 0.80 and 0.95. Differences in daily sums of sunshine duration are low, with the prevalence of positive deviations, i.e. slightly higher values for satellite data. The largest positive deviations were found in Tarnów, Zielona Góra, and Racibórz (+0.3 h), with equivalent negative deviations

in Warsaw and on Kasprowy Wierch (−0.4 h). Moreover, minor discrepancies were found for the long-term variability of the mean annual sums of actual sunshine duration. However, after 1995, the deviations were insignificant, and averaged 4 hours. Differences between both data series are caused by several factors, including an underestimation of aerosols optical depth (AOD), as well as the failure to consider the type of clouds covering the Sun's disc. With its high spatial resolution (0.05° × 0.05°), the satellite data can be a valuable source of information, particularly in regional studies of the spatial variation of sunshine duration.

Keywords: sunshine duration, satellite data, ground measurements, Meteosat, Poland.