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Relationships between cloudiness, aerosol optical thickness, and sunshine duration in Poland

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ABSTRACT

The aim of this study is to explain the relationship between changes in the amount of low-level cloudiness, the frequency of occurrence of certain types of clouds, the aerosol optical thickness (AOT) of the atmosphere, and changes in relative sunshine duration in Poland in the years 1980–2018. The analytical part of the study first presents the spatial variability of area-average values of the discussed characteristics in seasonal terms, and then shows the strength and direction of trends of individual elements for each of the analysed meteorological stations and averaged over the entire country. In the next stage of the work, the impact of individual cloud types and the aerosol optical thickness of the atmosphere on the multi-annual changes in sunshine duration in Poland was assessed. As a result of the conducted research, a growing trend in area-average values of relative sunshine duration in each season of the year was found in Poland, the highest being in the spring and the smallest in the winter. It was shown that a reduction in aerosol optical thickness and a decrease in the incidence of low-level clouds, including mainly stratiform clouds, had the greatest impact on the changes in sunshine duration.

1. Introduction

Cloudiness or cloud cover, in addition to the transparency of the atmosphere, is the most important meteorological factor forming the stream of solar energy reaching the Earth's surface. The issue of the effects of cloudiness and aerosols on climate change is complex (e.g. Boucher et al., 2013; Bony et al., 2015; Schneider et al., 2019), with still a number of open questions, and requires both complicated experimental and model studies in the field of cloud physics, as well as climatological and statistical considerations based on measurement and observation data. For this reason, the analysis of the interrelationships between cloudiness, optical thickness of the atmosphere, and sunshine duration takes on special significance. In Poland and other regions of the world, there has been an increase in the frequency of vertical clouds and a decrease in the frequency of stratiform clouds in the last forty years (Sun and Groisman, 2000; Eastman and Warren, 2013; Matuszko and Węglarczyk, 2018), which may have an impact on the increasing trend in sunshine duration (Matuszko et al., 2019).

Studies on long-term variability of sunshine duration have been conducted in many European countries (e.g. Bednar, 1990, Horecka, 1990, Weber, 1990, Dobesch, 1992, Brázdil et al. 1994; Sanchez-Lorenzo et al., 2007; Norris and Wild, 2007; Sanchez-Lorenzo et al., 2008; Kitsara et al., 2012; Manara et al., 2015; Sanchez-Lorenzo, 2015, Dumitrescu et al., 2017). These results show similar trends of decrease (1950s to 1980s) and increase (since the 1980s) in sunshine duration.

Global dimming and *global brightening* have been repeatedly described in world climatological literature (e.g. Liepert, 2002; Stanhill and Cohen, 2005; Norris and Wild, 2007; Sanchez-Lorenzo et al., 2007; Sanchez-Lorenzo et al., 2008; Sanchez-Lorenzo, 2015; Manara et al., 2015). The occurrence of periods of lower and higher supply of solar radiation has been most often explained by changes in the concentration of aerosols, mainly of anthropogenic origin. In the aspect of global air temperature rise, the period of *global brightening* is particularly interesting, especially in the area of a country where the political and economic transformation (since the late 1980s to the beginning of the 21st century) caused a significant decrease in emissions. Poland is an example of a country in which, in the years 1992–2000, emissions of dust decreased by 71%, of sulphur dioxide by 46%, of nitrogen dioxide by 25%, and of volatile organic compounds by 25% (Napiórkowski et al., 2002). In the following years, emissions of almost all major types of air pollutants were further reduced. According to the Central Statistical Office of Poland (2018), from 2000 to 2016 emissions of sulphur dioxide decreased in Poland by 59%, of carbon monoxide by 23%, of dusts by 20%, of ammonia by 16%, and of nitrogen oxides by

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14%.

It can be assumed that the improvement of air quality and the change in the structure of cloudiness in Poland in recent decades affect the amount of direct solar radiation, and therefore, in studies on the changes in sunshine duration it is important to analyse the cloud variability and aerosol optical thickness (AOT) of the atmosphere.

The purpose of the article is to attempt to explain the relationship between changes in the amount of low-level cloudiness, the frequency of occurrence of certain types of clouds, the aerosol optical thickness (AOT) of the atmosphere, and changes in relative sunshine duration in Poland in the years 1980–2018.

The first stage of the work was to develop a methodology for identifying types of cloudiness based on the cloud observation results encoded in the SYNOP message. A new method of calculating mean “daytime” cloudiness was proposed so that it would only cover observation hours from sunrise to sunset, i.e. when the sunshine duration is recorded. The analytical part of the study first presents the spatial variability of area-average values of the discussed characteristics in seasonal terms, and then shows the strength and direction of trends of individual elements for each of the analysed meteorological stations and averaged over the entire country. In the next stage of the work, the impact of individual cloud types and the aerosol optical thickness of the atmosphere on the multi-annual changes in sunshine duration in Poland was assessed.

2. Source materials and methods

The basic source data used in the study were the daily totals of sunshine duration and the hourly data on the degree of cloudiness and the types of low clouds from the years 1980–2018, from 28 meteorological stations in Poland belonging to the *Polish Institute of Meteorology and Water Management - National Research Institute* (IMGW PIB) (Fig. 1). In addition, satellite data were used, i.e. the mean daily aerosol optical thickness (AOT) values at 550 nm, referring to the geographical coordinates of meteorological stations from the same period. The AOT values came from the product “M2T1NXAER v5.12.4” (GMAO, 2015) with a spatial resolution of 0.5° × 0.625°, which was the result of measurements made by the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument, located on NASA's Terra and Aqua satellites. The AOT data are included in the Modern-Era Retrospective analysis for Research and Applications version 2 (MERRA-2). It is a NASA atmospheric reanalysis for the satellite era using the Goddard Earth Observing System Model. More information on obtaining this type of data and the practical possibilities of their use in geophysical research can be found in the studies of, among others, Randles et al. (2017), Che et al. (2019), Rizza et al. (2019), and also Sun et al. (2019).

To minimize the effect of cloudiness on the magnitude of the relationship between AOT and sunshine duration, this relationship was first analysed during the days without low clouds (N_h) but, because of their small number (6% of all days), the number of days with the size of cloud cover with low-level clouds $N_h < 20\%$ was taken into account. According to the synoptic code (WMO, 2017), N_h means “the size of cloud cover with all CL (low level) clouds, and in their absence by all CM (middle level) clouds”.

The initial stage of the work consisted in the verification and homogenization of a series of actual sunshine duration data (Matuszko et al., 2019; Bartoszek et al., 2020). In the next step, daily values of relative sunshine duration (RSD) were calculated for a series from each station, using information about the length of the day at a given latitude (NOAA Solar Calculator, 2019). Relative sunshine duration has been chosen as the basic characteristic of sunshine duration, because determined as the ratio of actual sunshine duration to possible sunshine duration, it eliminates the seasonal and spatial variability of day length in the study area and thus better reflects the impact of meteorological conditions (cloudiness, transparency of the atmosphere) on sunshine duration.

Data regarding the magnitude of cloudiness and the types of clouds of the low level (number of the C_L code) and the *Nimbostratus,* and

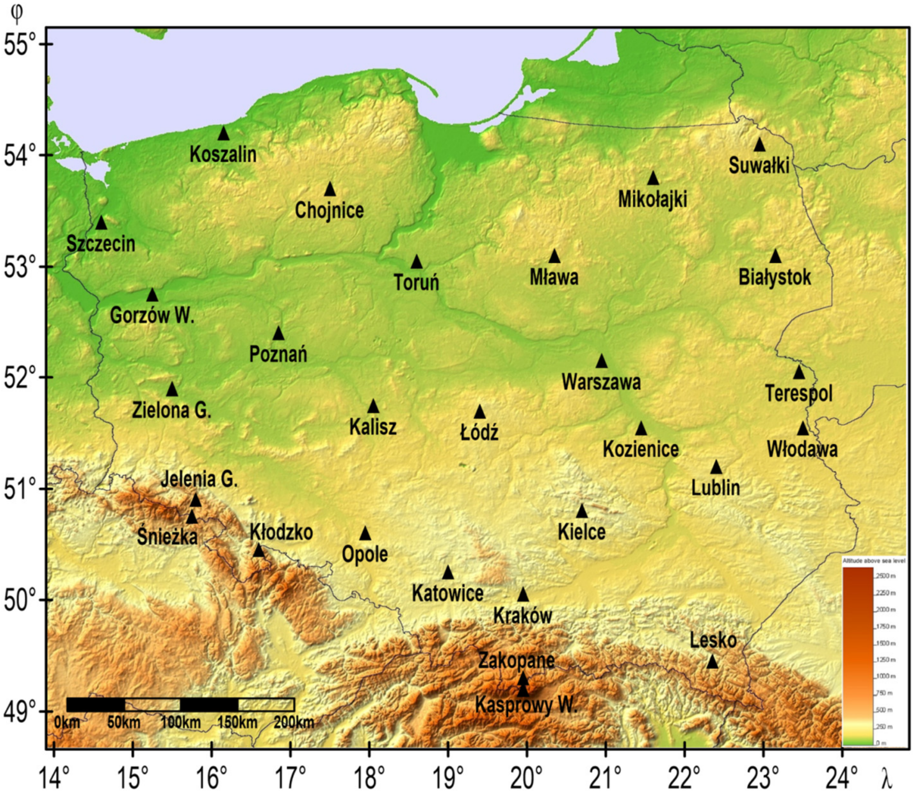

Fig. 1. The location of meteorological stations used in the study.

partly the *Altostratus* from the middle level (number of the C_M code) from the observation hours at 06, 09, 12, 15, 18 UTC, recorded in the form of a SYNOP message, were used in the analysis of the relationship between cloudiness and sunshine duration. However, it should be remembered that the "synoptic" (WMO, 2017) system of recording these types impairs the assessment of actual cloudiness, because there is a need to use only one number of the code to describe cloudiness, although there may be cloud types corresponding to two or even three numbers of the code of the same level. For low level clouds, the division (WMO, 2017) is as follows:

Low level clouds (C_L) represented by cloud genera: *Stratus*, *Stratocumulus*, *Cumulus* and *Cumulonimbus*:

$C_L = 0$ - no C_L clouds.

$C_L = 1$ - *Cumulus humilis* or *Cumulus fractus* of dry weather or both.

$C_L = 2$ - *Cumulus mediocris* or *congestus*, with or without *Cumulus* of species *fractus* or *humilis* or *Stratocumulus*, all having their bases at the same level.

$C_L = 3$ - *Cumulonimbus calvus*, with or without *Cumulus*, *Stratocumulus*, or *Stratus*.

$C_L = 4$ - *Stratocumulus cumulogenitus*; *Cumulus* may also be present.

$C_L = 5$ - *Stratocumulus* non-*cumulogenitus* (not resulting from the spreading out of *Cumulus*).

$C_L = 6$ - *Stratus nebulosus* or *Stratus fractus* of dry weather, or both.

$C_L = 7$ - *Stratus fractus* or *Cumulus fractus* of wet weather, or both (pannus), usually below *Altostratus* or *Nimbostratus*.

$C_L = 8$ - *Cumulus* and *Stratocumulus* other than *Stratocumulus cumulogenitus*, with bases at different levels.

$C_L = 9$ - *Cumulonimbus capillatus* (often with an anvil), with or without *Cumulonimbus calvus*, *Cumulus*, *Stratocumulus*, *Stratus*, or *pannus*.

$C_L = /$ - C_L clouds are not observable owing to darkness, fog, blowing dust or sand, or other similar phenomena.

$C_M = 2$ - *Altostratus opacus* or *Nimbostratus*.

The frequency of occurrence of individual types of clouds was analysed according to the SYNOP code (WMO 2017), modified by the authors to a simplified method assigning the appropriate type or types of clouds the code number in the following way:

- stratiform ($N_{St+Ns+As}$) - (*Stratus, Nimbostratus* including *Altostratus opacus*: $C_L = 6, 7$; $C_M = 2$)
- cumuliform (N_{Cu+Cb}) - *Cumulus*, *Cumulonimbus* partly with *Stratocumulus*: $C_L = 1, 2, 3, 4^*, 8^*, 9$
- cumuliform-stratiform (N_{Sc}) - *Stratocumulus*: $C_L = 4^*, 5, 8^*$

* half of the cases of occurrence of a given type of cloud.

In the case of simultaneous occurrence of the *Nimbostratus* ($C_M = 2$) and the *Stratus* ($C_L = 7$), these clouds were counted together as one case, because both types belong to the category of stratiform clouds, while the simultaneous occurrence of the *Nimbostratus* ($C_M = 2$) and the *Stratocumulus* ($C_L = 5$) was counted as two cases: one to the stratiform group and one to the *Stratocumulus* group (N_{Sc}). Analysing cloud types, not the individual genera, has additional significance because it minimizes possible observer errors resulting from observation subjectivity.

The frequency of occurrence of cloud types over a multi-annual period was calculated for only one hour, 1200 UTC, because the "daily averaging" of the generic composition does not give a proper view of cloudiness throughout the day, and analysing cloudiness for each synoptic observation hour would be too detailed, which seems unnecessary in view of the purpose of the work. Cloudiness observations at 1200 UTC are the most objective because at the morning observation hour there is a possibility of occurrence of fog and low stratiform clouds covering the clouds lying above while the evening hour observations may be questionable because of the difficulty in determining cloudiness after sunset and would be inconsistent with the assumption that "daytime" cloudiness is being analysed. It should be noted, however, that at noon in the warm half of the year *Cumulus* clouds prevail, which means that their frequency is higher than it would appear from the analysis of cloudiness throughout the day. However, owing to their vertical structure, it is possible to observe other co-occurring clouds.

In order to eliminate cloudiness data from the hours after sunset and before sunrise, an original method of calculating mean "daily" cloudiness was adopted, according to which this mean was calculated based on the observations made at the hours of the day depending on the season:

- summer (May–June-July): 0600, 0900, 1200, 1500, 1800 UTC.
- winter (Nov-Dec-Jan): 0900, 1200, 1500 UTC.
- transitional (Feb-Mar-Apr and Aug-Sep-Oct): 0600, 0900, 1200, 1500 UTC.

To ensure compliance with the division into seasons used in this method, a similar division into seasons was adopted also in all other analyses (summer: May, June, July; winter: November, December, January; spring: February, March, April; autumn: August, September, October.

In order to assess the impact of AOT and individual cloud types (stratiform, cumuliform, and *Stratocumulus*) on RSD, multiple linear regression models were applied for each season. All statistical analysis was performed using STATISTICA 13.0 software (TIBCO Software Inc., StatSoft Inc., Tulsa, OK, USA).

3. Results

3.1. Temporal variability and spatial diversity of seasonal relative sunshine duration, cloudiness, and AOT

Mean multi-annual area-average annual relative sunshine duration in Poland is 36.6%. Among seasonal means, the highest value is reached by the summer mean (48.7%) and the lowest by the winter one (20.2%). In individual years, the area-average relative sunshine duration changed from a minimum of 14% in winter at the turn of 1980/1981, to a maximum of 61% in summer in 2006 (Table 1).

In the spatial distribution, the multi-annual mean winter relative sunshine duration is the largest (30%) in the mountains in the south and south-west of Poland, and the smallest (below 15%) in the north-east (Fig. 2). The RSD spatial diversity of patterns corresponds well with the patterns in the magnitude of low-level cloud cover (N_h) which increases from the south-west, from 59% in the Tatras, to the north-east, up to a maximum of 77% in the Suwałki region. The number of days with stratiform clouds ($N_{St+Ns+As}$) also increases from the south and south-west (< 4 days) to the north, with a maximum (28 days) in the north-east. The occurrence of stratiform clouds reveals quite small annual variability (Table 1). *Stratocumulus* clouds are most common at this time of the year. The spatial variability of the N_{Sc} frequency of occurrence ranges from over 40 days in the mountains to less than 30 days on the central Baltic coast, as well as in the vicinity of Zielona Góra and in the south-east of Poland. Cumuliform clouds occur most often in the latter region ($N_{Cu+Cb} > 34$ days) and are the least often observed ($N_{Cu+Cb} < 10$ days) in the area of Kraków and Suwałki. The multi-annual mean aerosol optical thickness is the smallest in the mountainous areas in the south of Poland (AOT = 0.115) and gradually increases towards the centre of the country, where it reaches its maximum (AOT = 0.181), and then decreases to the north and west.

The spring multi-annual mean relative sunshine duration in Poland is little diversified in spatial terms (Fig. 2), while area-average RSD is very variable in time (Table 1). The spring multi-annual mean RSD ranges from 36% in the west of the country, to 32% in the south; the area-average RSD varies from 25% in 1983, to 46% in 2011. The area-average spring RSD has the highest coefficient of variation (Table 1) among all seasons ($C_v = 15.7\%$). In the spring, low-level clouds cover the sky moderately. The highest N_h cloudiness (61%) is in the north-

Table 1
Characteristics of the area-average seasonal values of the analysed variables in Poland (1980–2018).

		Winter	Spring	Summer	Autumn	Year
RSD (%)	Mean	20.2	34.7	48.7	42.9	36.6
	Max	26 (2016/17)	46 (2011)	61 (2006)	58 (2018)	45 (2018)
	Min	14 (1980/81)	25 (1983)	33 (1984)	33 (1980)	28 (1980)
	C_V (%)	14.9	15.7	12.7	12.8	9.7
N_h (%)	Mean	66.4	56.9	48.3	50.1	55.4
	Max	73 (2012/13)	63 (2017)	60 (1984)	59 (1980)	62 (1980)
	Min	58 (1983/84)	48 (2011)	40 (2006)	39 (2005)	50 (1982)
	C_V (%)	4.9	7.9	9.4	9.2	4.5
$N_{St+Ns+As}$ at 12 UTC (days)	Mean	17.3	8.4	2.6	4.7	33.0
	Max	23 (2005/06)	16 (1980)	7 (1980)	8 (1985)	46 (1981)
	Min	12 (2006/07)	4 (2014)	1 (2006)	2 (1999)	25 (2008)
	C_V (%)	14.8	28.7	48.3	32.4	14.1
N_{Cu+Cb} at 12 UTC (days)	Mean	17.1	37.1	73.0	54.4	181.4
	Max	25 (2004/05)	51 (2000)	80 (2016)	62 (1997)	201 (2008)
	Min	10 (1984/85)	25 (2013)	67 (2010)	48 (1985)	164 (1996)
	C_V (%)	23.5	16.9	4.2	6.7	5.8
N_{Sc} at 12 UTC (days)	Mean	35.0	23.3	8.8	16.0	83.1
	Max	46 (2017/18)	37 (2013)	15 (2010)	21 (1996)	108 (2013)
	Min	26 (1986/87)	17 (1990)	5 (2006)	12 (1987)	66 (1982)
	C_V (%)	12.0	16.3	22.6	15.4	10.2
AOT	Mean	0.163	0.249	0.280	0.233	0.231
	Max	0.314 (1991/92)	0.411 (1992)	0.490 (1981)	0.378 (1981)	0.359 (1981)
	Min	0.103 (2015/16)	0.151 (1997)	0.181 (2014)	0.155 (2016)	0.157 (2016)
	C_V (%)	34.7	29.8	31.4	28.5	29.1

C_V (%) – coefficient of variation.

east, and the lowest (55%) in central and central-west Poland. Stratiform clouds ($N_{St+Ns+As}$) prevail in the north of the country. The number of cloudy days, $N_{St+Ns+As}$ decreases to the south and south-west, and it is in these regions that the largest share of days with *Stratocumulus* clouds (N_{Sc}) is observed. In the spring, the occurrence of cumuliform clouds is more frequent than in the winter, it is most visible in the south-east and decreases to the north-east and south-west. The aerosol optical thickness is greater than in the winter, and the highest multi-annual mean AOT values occur in the industrialized areas of Silesia and Lesser Poland, decreasing to the north-west and to the south.

In the summer, the area-average relative sunshine duration is the highest in the year, exceeding 50% in the northern half of Poland, with a maximum in the vicinity of Terespol. Sunshine duration decreases to the south and south-west (Fig. 2), in line with the increasing trend of low-level cloudiness. Stratiform clouds at this time of year are rare, occurring from 1 day in the Tatras, to 5 days at the central Baltic. *Stratocumulus* clouds appear more often, especially in the vicinity of Kraków and Gorzów ($N_{Sc} > 14$ days). Cumuliform clouds prevail in the south-eastern part of Poland. The number of days with *Cumulus* and *Cumulonimbus* clouds decreases from east to west, from the maximum ($N_{Cu + Cb} > 79$ days) in Terespol to the minimum (61 days) in Koszalin. The highest summer area-average mean relative sunshine duration (RSD = 61%) that occurred in 2006 was associated with a very low frequency of stratiform clouds and the *Stratocumulus* (Table 1). The distribution of AOT values is almost latitudinal in the northern half of Poland, with increasing tendency up to a maximum in Silesia (AOT $>$ 0.319). In foothill and mountain areas, AOT values are gradually decreasing.

In the autumn, the area-average values of relative sunshine duration are not very diverse in Poland. They range from 40% in the south to 44% in the central-eastern, central, and central-western parts of the country (Fig. 2), which is associated with small low-level cloud cover in these areas. The lowest autumn area-average mean RSD for the country (33%) was recorded in 1980, when the minimum for area-average mean annual values also occurred (28%; Table 1). The frequency of stratiform clouds increases from 3 days in the mountains to 7 days in the north-eastern and north-western ends of Poland. At this time of year, the *Stratocumulus* clouds get more numerous, with most of them ($N_{Sc} > 20$ days) occurring in the vicinity of Kraków, Jelenia Góra, and Suwałki. The proportion of cumuliform clouds is still quite significant, with a maximum ($N_{Cu + Cb} > 64\%$) in south-eastern Poland. The spatial distribution of AOT values is very similar to the spatial distribution of AOT in the summer, but the values are slightly lower because the maximum values do not exceed 0.260.

3.2. The multi-annual course and temporal trends of area-average values of sunshine duration, AOT, magnitude and types of cloudiness

Series of area-average seasonal and annual values of all the studied variables were linearly regressed on time. The results are shown in Table 2 and Fig. 3.

In the years 1980–2018, the area-average values of relative sunshine duration in Poland showed an upward trend for every season (Fig. 3). However, the magnitude of the trend and the periods of increases and decreases in values were different, and extreme values usually occurred in other years. In the winter, the increase in the country mean values of relative sunshine duration in the studied years was statistically insignificant and amounted to only 0.9%/10 years (Table 2). The period of increased values was the last decade of the 20th century and the first years of the 21st century, with the maximum occurring in the 2015/16 and 2016/17 seasons (25.5 and 26.3%, respectively). Small RSD in winters occurred in 1980/81, 1982/83, 2009/10 and 2012/13. In the spring, the increase of RSD in the studied period was statistically significant, and was the largest of all the seasons in relation to relative values (Table 2). Nevertheless, what was characteristic was the large year-to-year variability often reaching 10%. The lowest relative sunshine duration (24.7%) occurred in 1983, while the highest (45.9%) in 2011. Until 2003, there were no values exceeding 40%, while in the 21st century they occurred six times, i.e. in the years: 2003, 2007, 2011, 2012, 2014, 2018. Also in the summer there was a clear increasing RSD trend (by 3.0%/10 years), and the highest values (> 55%) were recorded in 1992, 1994, 2006, 2008, 2018. Until the last decade of the 1990s, RSD was lower (< 50%, except for 1982). In 1980 and 1984, it did not exceed even 34%. In the autumn, the increase in sunshine duration in Poland was also noticeable (by 2.8%/10 years; Table 2). Minimum sunshine duration (33%) occurred in 1980 and 1996, and the highest values (> 50%) occurred in 2005, 2011, 2015 and 2018.

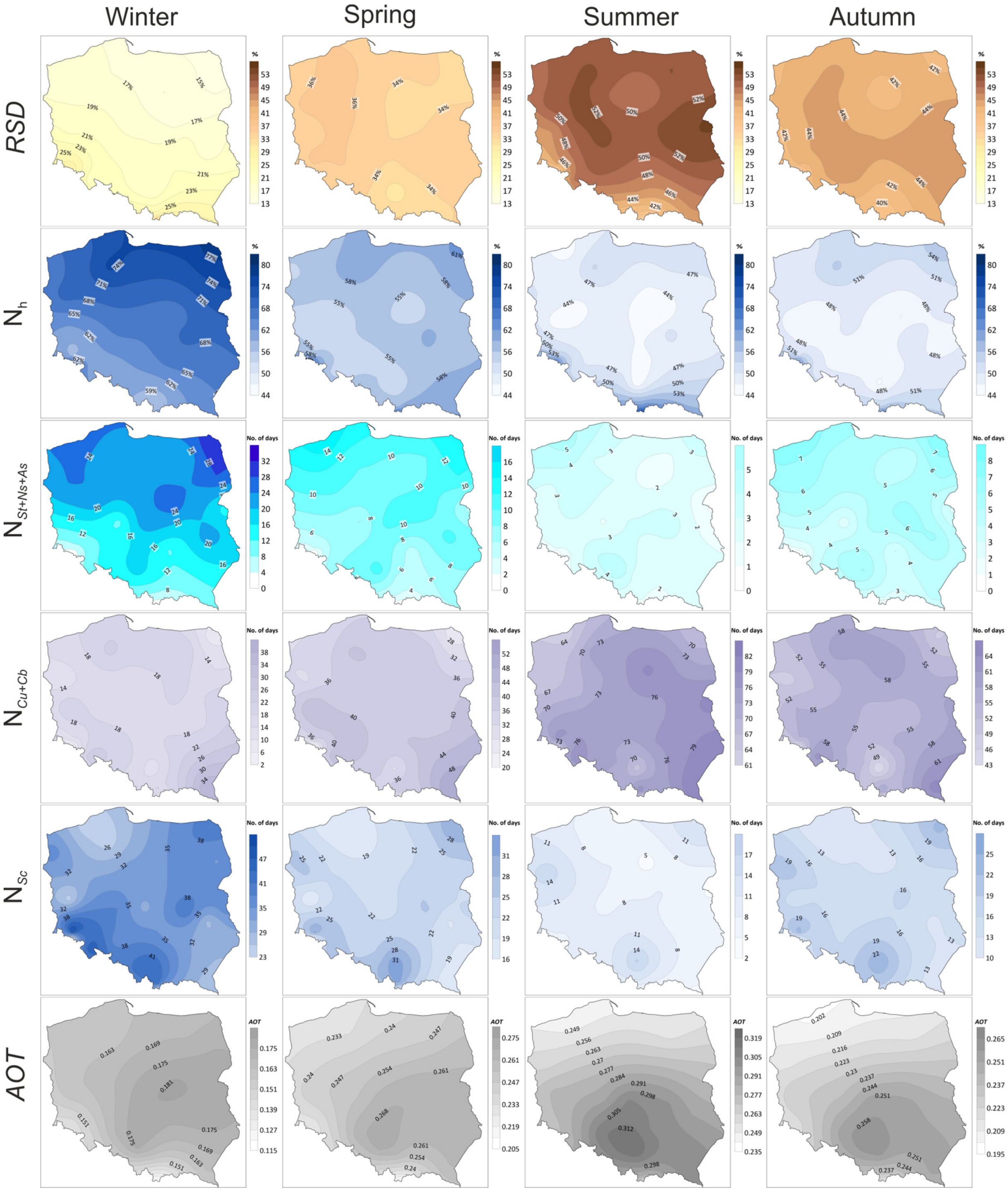

Fig. 2. The spatial diversity of seasonal-mean multi-annual values: relative sunshine duration, low-level cloudiness, number of days with stratiform clouds, number of days with cumuliform clouds, number of days with the *Stratocumulus* cloud, and AOT.

Table 2
The linear temporal trend slopes of area-average seasonal values of the analysed variables in Poland in the years 1980–2018.

	Trend	Winter	Spring	Summer	Autumn	Year
RSD	% / 10y	0.871	2.393**	3.012**	2.791**	2.202**
N_h	% / 10y	0.642	−0.442	−1.433	−1.302*	−0.602
$N_{St+Ns+As}$	days / 10y	0.009	−1.042**	−0.643**	−0.356	−1.598**
N_{Cu+Cb}	days / 10y	−0.842	0.996	0.998*	0.433	1.815
N_{Sc}	days / 10y	2.483**	1.682**	0.111	0.434	4.321**
AOT	AOT / 10y	−0.043**	−0.052**	−0.071**	−0.049**	−0.048**

* - statistically significant at the level of $p < .05$; ** - $p < .01$.

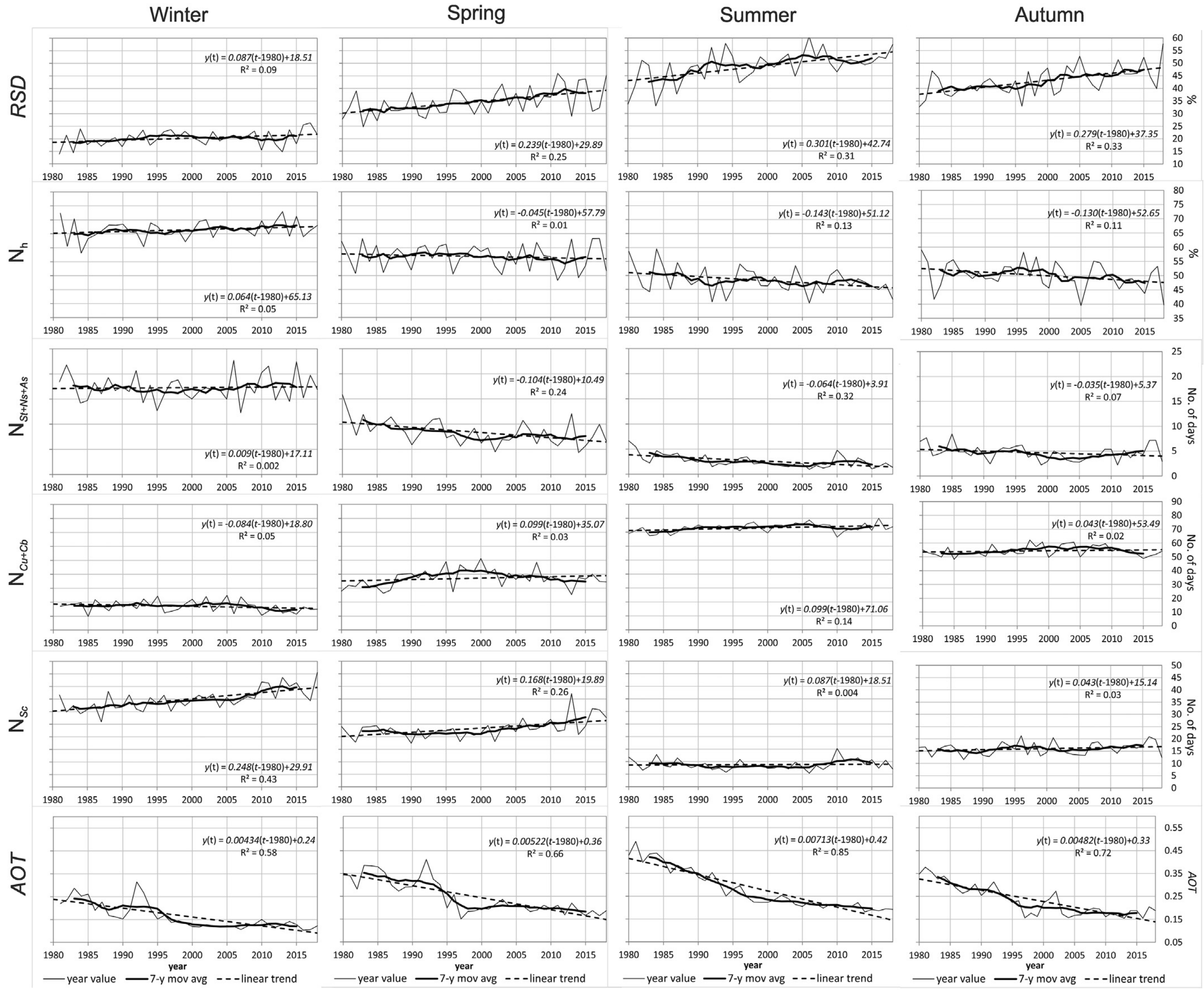

Fig. 3. The multi-annual variability of the area-average relative sunshine duration, low-level cloudiness, number of days with stratiform clouds, number of days with cumuliform clouds, number of days with the *Stratocumulus* cloud, and AOT in individual seasons in Poland.

The increase in the area-average relative sunshine duration in the years 1980–2018 was supported by the downward trend in the area-average low-level cloudiness (Fig. 3) from spring to autumn (Feb-Oct). The largest decrease in cloudiness (N_h down to about 40%) occurred in the summer of 1992, 1994, 2006 and in the autumn of 2005 and 2018. The decrease in cloudiness was accompanied by a decreasing trend in the number of days with stratiform clouds ($N_{St+Ns+As}$) in the spring, summer, and autumn, and with cumuliform clouds (N_{Cu+Cb}) in the winter. In turn, a clear increase in the number of days with the *Stratocumulus* cloud (N_{Sc}) was noted in winter and spring.

The increase in area-average relative sunshine duration in the years 1980–2018 in Poland was accompanied by a very clear decrease in the area-average aerosol optical thickness in each season of the year (Fig. 3; Table 2). The winter AOT values declined rapidly from the turn of the 1980/1981 to the early 1990s. In 1992 a significant increase in aerosol concentrations in the atmosphere (0.314) was associated with the 1991 eruption of a Philippines volcano, Mount Pinatubo (McCormick et al., 1995; Ansmann et al., 1997). From around 1995, the magnitude of AOT was clearly lower and remained at a similar level. In the first decade of the examined multi-annual period, the spring AOT values fluctuated between 0.281 and 0.385 in individual years and then, similarly as the winter AOT, they reached the highest value in 1992 (0.411). In subsequent years, the aerosol optical thickness decreased significantly, and in the 21st century it remained at a similar level (around 0.200). The summer AOT values dropped very quickly until around 1994, and since 1998 they have been below 0.250. The autumn aerosol optical thickness showed a slow decrease until 1997, followed by a temporary increase in the years 2000 to 2002, which was then followed by a decrease of AOT values below 0.200 by the end of the studied multi-annual period.

3.3. *The spatial diversity of the magnitude of local trends of seasonal RSD, types of cloudiness, and AOT*

Series of local seasonal and annual values of all the studied variables were linearly regressed on time. The results (trend slopes) are shown in Fig. 4.

Statistically significant positive trends in winter relative sunshine duration occur only in south-western Poland (an increase by 3–5% in 10 years), the strongest occurring in the vicinity of Katowice and Opole, and on the Śnieżka Mt. (Fig. 4). The increase in sunshine duration in this area is accompanied by a negative trend in the number of days with stratiform clouds $N_{St+Ns+As}$ and cumuliform clouds N_{Cu+Cb} (a decrease by 2–4 days in 10 years), but positive with N_{Sc} clouds (an increase by

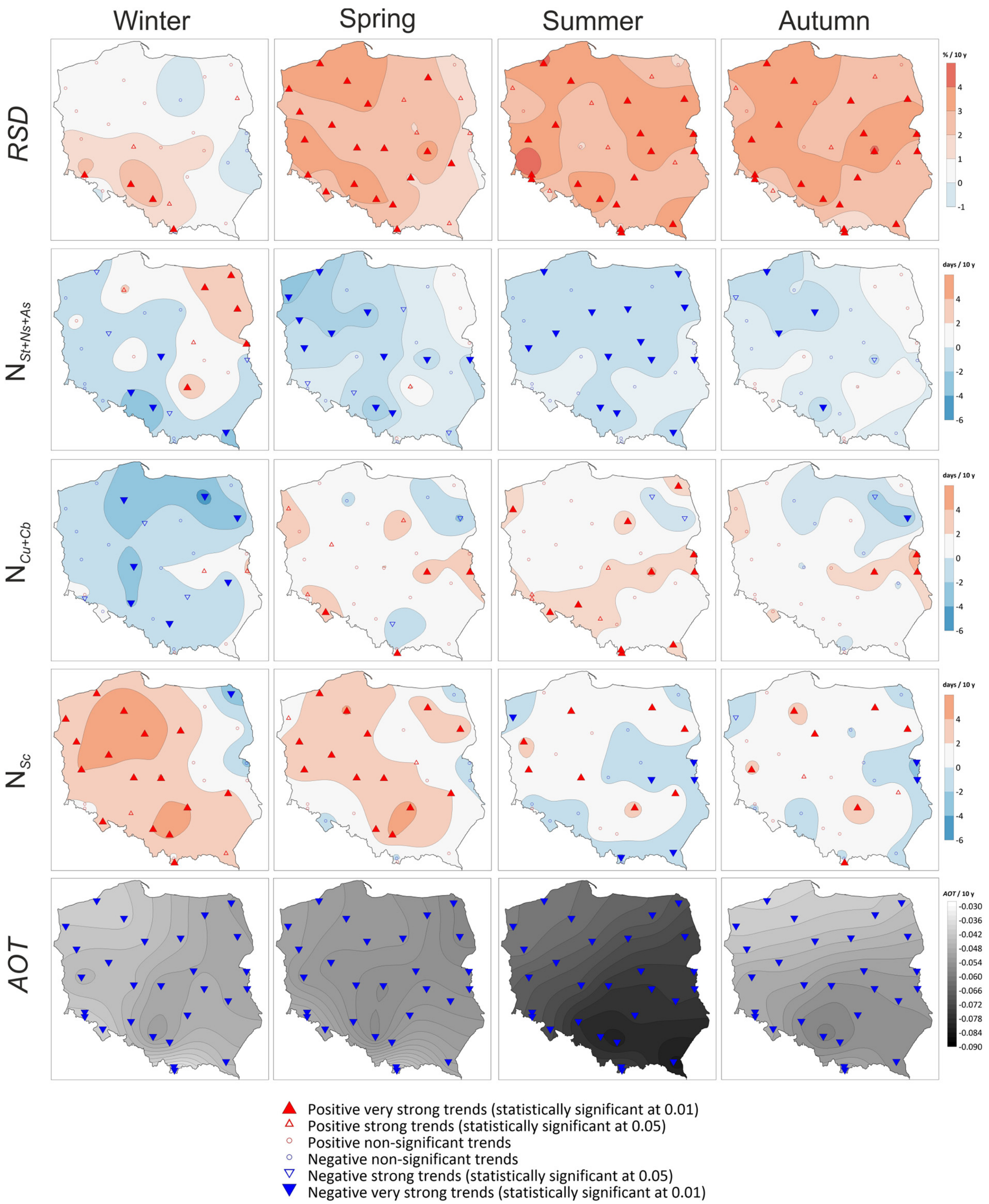

Fig. 4. The magnitude (slope value) and statistical significance of seasonal linear trends of relative sunshine duration, number of days with stratiform clouds, number of days with cumuliform clouds, number of days with *Stratocumulus* clouds, and AOT.

2–6 days in 10 years). The area that clearly stands out is the north-eastern part of the country, where together with a decrease in the frequency of *Stratocumulus* clouds and cumuliform clouds, the share of stratiform clouds has increased, which, however, does not affect the decrease in the RSD at this time of year.

The highest increase in the spring relative sunshine duration occurs in north-western and south-western Poland (4–6% per 10 years), which corresponds to a large decrease in the number of days with stratiform clouds in these regions (by 1–4 days in 10 years; Fig. 4). The cumuliform clouds trends throughout Poland are generally positive, with a more pronounced increase in frequency of *Stratocumulus* clouds.

The strongest positive trends in the summer relative sunshine duration (> 5% per 10 years) occur in western Poland (between Zielona Góra and Jelenia Góra). A fairly large increase is also seen in the rest of the country, especially in the northern half, corresponding to a clear decrease in the number of days with stratiform clouds (Fig. 4). In most parts of the country, the proportion of cumuliform clouds increases. In the case of *Stratocumulus* clouds, the direction of changes is different at different meteorological stations.

In clear increases in the autumn relative sunshine duration in Poland are associated with a decrease in the number of days with low-level clouds of various types (Fig. 4). The strongest positive trends occur in the western and central parts of the country, where at this time of year a decrease in the number of days with stratiform and cumuliform clouds is clearly noticeable.

In the studied multi-annual period, a significant decrease in aerosol optical thickness was clearly marked over the area of the whole country, regardless of the season. The strongest downward trends in the winter and spring occurred in central and eastern Poland, and in the summer and autumn in its southern part (Fig. 4).

4. The assessment of the impact of low-level cloudiness and AOT on relative sunshine duration

The relationship between area-average cloudiness and sunshine duration was studied taking into account only the cloud cover with low-level clouds and the *Nimbostratus* with *Altostratus*, because it is these clouds that most strongly modify local climate conditions and directly affect sunshine duration (Matuszko, 2012a, 2012b). A confirmation of the correctness of this selection are the higher values of the coefficients of determination (R^2) calculated for the relationship between relative sunshine duration and the size of cloud cover with low-level clouds (N_h) in comparison with the amount of general cloud cover (N) for each season (Table 3). To determine the coefficients of determination, simple linear regression models (1) were used, in which area-average values of the studied variables for the period 1980–2018 were used:

$$RSD_s(x) = B_{0,s} + B_{1,s}x + \in_s,\ s = \{1, 2, 3, 4\} = \{\text{winter, spring, summer, autumn}\} \qquad (1)$$

where:

$RSD_s(x)$ - area-average relative sunshine duration in the season s in %, $x = N_s$, N_{hs}.

$B_{0,s}$, $B_{1,s}$ - regression coefficients.

N_s - area-average total cloud cover in the season s in %.

N_{hs} - area-average low-level cloud cover in the season s in %.

$\in_s$ - uncorrelated model residuals, $N(0,\sigma_s)$ distributed.

To conduct more detailed studies, daily N_h, AOT, $N_{St+Ns+As}$, N_{Cu+Cb}, and N_{Sc} values from all meteorological stations were used, then averaged over the country (daily area-average values), and then their raw interrelationships were analysed separately for each season. Based on the performed analysis, it was found that in the year and in all seasons, relative sunshine duration depends significantly on the degree of cloud cover with low-level clouds (Fig. 5 ab). The highest values of relative sunshine duration in corresponding intervals of low cloudiness N_h occur in the summer, and the lowest in the winter. The reason is the clear advantage of the share of stratiform clouds and *Stratocumulus* in the winter (Table 1), which block the inflow of solar radiation to the earth's surface much more than the vertical clouds that prevail during the summer. In the case of occurrence of *Stratus*, *Nimbostratus,* and *Altostratus* clouds, average daily relative sunshine duration values, and 4% in the summer (Fig. 6). However, in the case of occurrence of *Cumulus* and *Cumulonimbus* clouds, the values of relative sunshine duration are generally higher than average, regardless of the season.

Table 3

The coefficient of determination of the linear simple regression model of area-average relative seasonal sunshine duration in Poland on the total (N) and low-level cloud cover (N_h).

Type of cloud cover	Coefficient of determination (R^2)			
	Winter	Spring	Summer	Autumn
N	0.57	0.67	0.67	0.65
N_h	0.62	0.81	0.88	0.84

For the most part of the year (except for winter), only a moderate decrease in low-level cloudiness was responsible for a large increase in relative sunshine duration, because the decrease in the frequency of stratiform clouds was balanced by an increase in the frequency of *Cumulus*, *Cumulonimbus,* and *Stratocumulus* clouds. However, owing to their vertical structure, such clouds, if they do not cover the solar disk, do not limit the inflow of radiation to the earth's surface (Matuszko, 2012). Analysing the daily values of relative sunshine duration in the days with $N_h < 20\%$, one can note their gradual increase over the multi-annual period studied (Fig. 7). The differences between the 1980s and the second decade of the 21st century ranged from 4 percentage points in the summer, to 13 in the winter. At the same time, during this period, in the days with $N_h < 20\%$, there was a significant reduction in aerosol optical thickness, particularly pronounced in the summer and autumn (Fig. 8). This is significant because the content of aerosols in the atmosphere is clearly negatively correlated with sunshine duration (Fig. 9).

Based on the above observations, the magnitude of the total and individual impact of stratiform clouds, vertical clouds, *Stratocumulus* clouds, as well as aerosol optical thickness on the variability of relative sunshine duration in individual seasons was assessed. To determine the interrelationship between the variables on the basis of eq. (2), multiple linear regression models were determined (Table 4):

$$RSD_s = B_{0,s} + B_{1,s}AOT_s + B_{2,s}N_{St+Ns+As_s} + B_{3,s}N_{Cu+Cb_s} + B_{4,s}N_{Sc_s} + \in_s,\ s = \{1, 2, 3, 4\} = \{\text{winter, spring, summer, autumn}\} \qquad (2)$$

where:

RSD_s - area-average relative sunshine duration in the season s in %.

$B_{0,s}$, $B_{1,s}$, $B_{2,s}$, $B_{3,s}$, $B_{4,s}$ - unstandardized B regression coefficients.

AOT_s - area-average values of aerosol optical thickness in the season s.

$N_{St+Ns+As\ s}$ - area-average number of days of stratiform clouds at 1200 UTC in the season s.

$N_{Cu+Cb\ s}$ - area-average number of days of vertical clouds at 1200 UTC in the season s.

$N_{Sc\ s}$ - area-average number of days of *Stratocumulus* clouds at 1200 UTC in the season s.

$\in_s$ - uncorrelated model residuals, $N(0,\sigma_s)$ distributed.

Statistical analysis showed all predictors explain from 64% (in the winter) to 76% (in the spring and summer) of the variance of relative sunshine duration in Poland (Table 5). All the variables selected for the model are statistically significant ($p < .05$) in any season of the year. *Stratocumulus* clouds are the strongest predictors of winter and summer RSD (*Beta* $= -0.764$ and -0.561), cumuliform clouds - for spring RSD (*Beta* $= -0.713$), and aerosol optical thickness for autumn RSD (*Beta* $= -0.542$).

5. Discussion and conclusions

This study is part of research on the complex relationship between cloudiness, aerosols, and the inflow of solar radiation to the earth's surface. In the 5th IPCC Report (Boucher et al., 2013), one of the chapters was devoted to aerosols and clouds because these elements were considered to be the main source of uncertainty, both in attribution (i.e. determining the causes of past climate change) and forecasts of future global warming. The direct impact of aerosols on the amount of solar radiation caused by its scattering and absorption by air suspended solids and liquids is theoretically explored (though not fully parameterized) (i.a. Rosenfeld et al., 2014; Boers et al., 2017). However, it is much harder to assess their indirect effects. One of the first described mechanisms of the indirect influence of aerosols on clouds was the so-called Twomey effect (Twomey, 1977), which leads to an increase in cloud albedo. Other effects concern changes in the life expectancy of clouds, their altitude, or the intensity of precipitation (i.a. Ramanathan

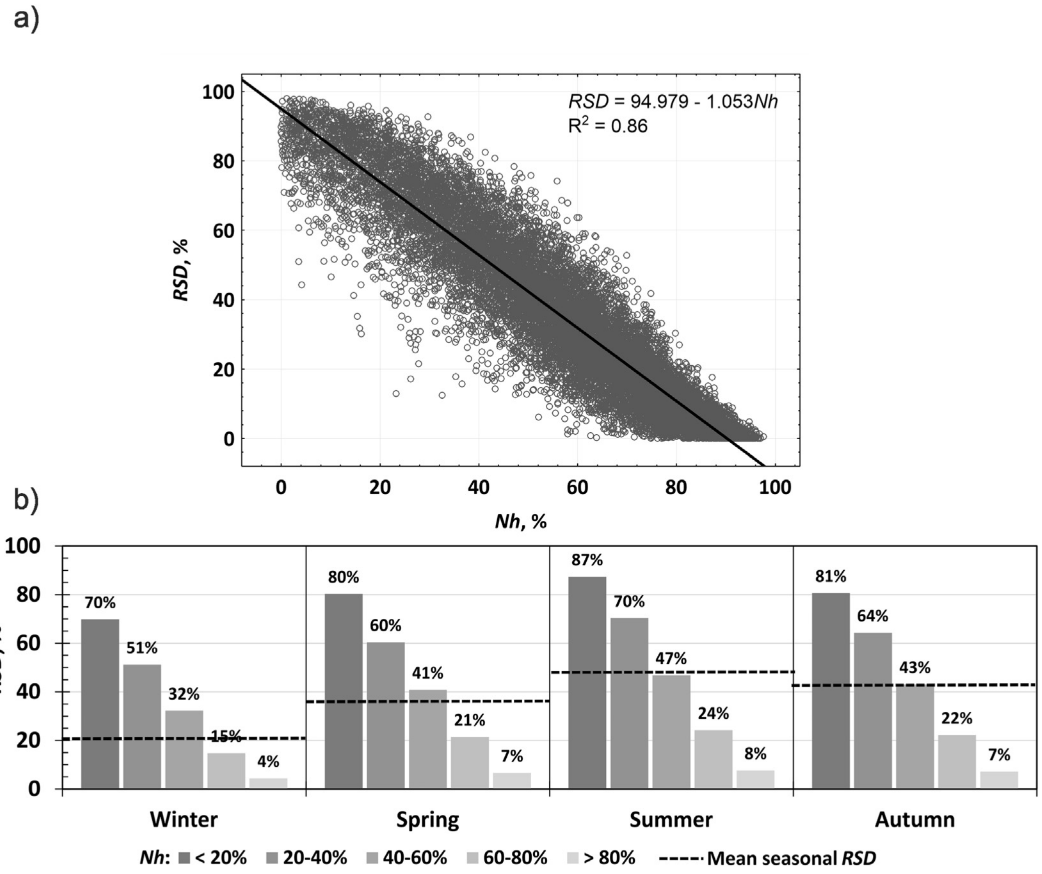

Fig. 5. Mean daily area-average values of relative sunshine duration in Poland depending on the Nh cloudiness in a year (a), and in individual seasons (b).

et al., 2001; Rosenfeld et al., 2014; Sherwood et al., 2014). Unlike greenhouse gases, which remain in the atmosphere for a long time and mix well in it, the concentration of aerosols is very heterogeneous and depends on the sources of emissions and atmospheric circulation (Rosenfeld et al., 2014). An additional difficulty in assessing the impact of anthropogenic aerosols on the climate system is the lack of knowledge of the “base”, pre-industrial level of the content of various types of aerosols in the atmosphere, which makes it impossible to accurately estimate their change.

In the present study, in contrast to the theoretical works in the field of atmosphere physics mentioned above, climatological and statistical analyses were carried out on the basis of the measurement data from the years 1980–2018 from the area of Poland. The basic characteristics taken into account in the work were relative sunshine duration, the size and types of low-level clouds, and the size of aerosol optical thickness (AOT).

As a result of the conducted research, a growing trend in area-average values of relative sunshine duration in each season of the year was found in Poland, the highest being in the spring and the smallest in the winter. The magnitude of the trend, the periods of increase and decrease, and spatial differentiation were different, and extreme values usually occurred in other years. The highest increase in sunshine duration occurred in the south-western part of Poland, from the last decade of the 20th century to the end of the studied period. It was shown that a reduction in aerosol optical thickness and a decrease in the incidence of low-level clouds, including mainly stratiform clouds, had the greatest impact on the changes in sunshine duration. Owing to the vertical construction of cumuliform clouds, the increase in their share in the summer was not an obstacle to the increase in sunshine duration at this time of year. *Cumulus* and *Cumulonimbus* clouds, if they

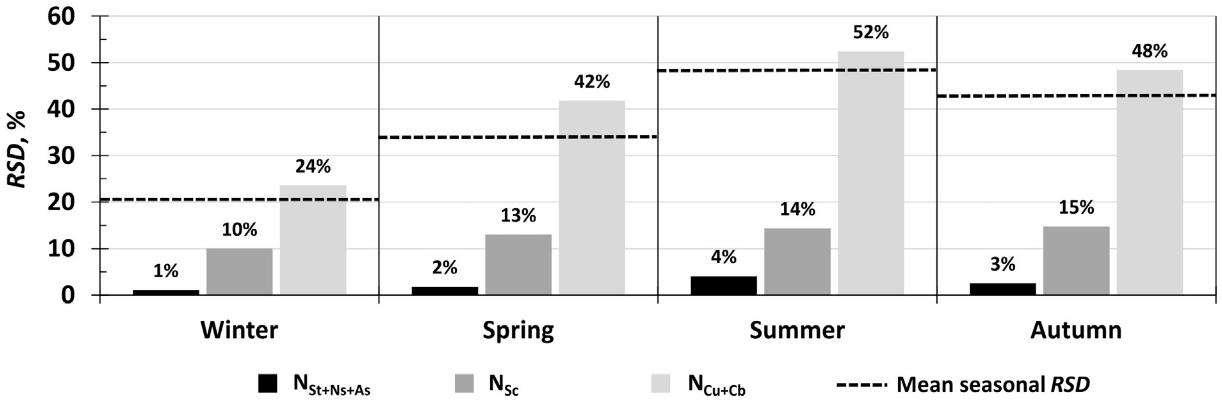

Fig. 6. Mean daily area-average values of relative sunshine duration (%) in individual seasons, during the occurrence of a specific type of clouds at 1200 UTC.

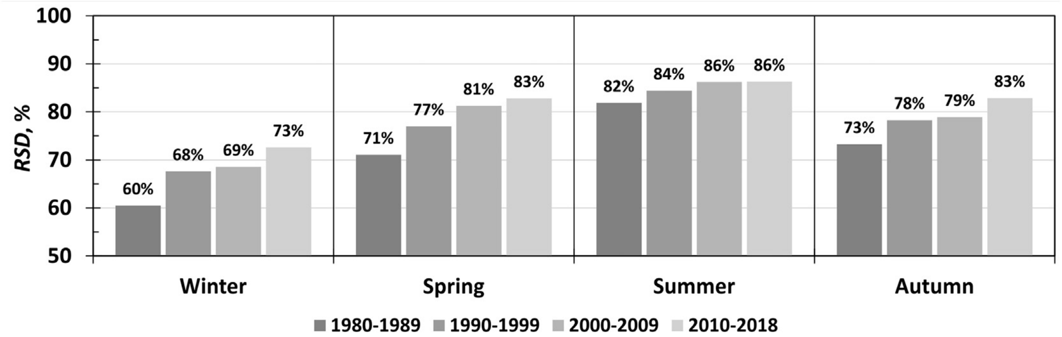

Fig. 7. Mean daily area-average relative sunshine duration (%) on the days when the area-average size of low-level cloudiness in Poland was below 20% in the subsequent decades of the period 1980–2018.

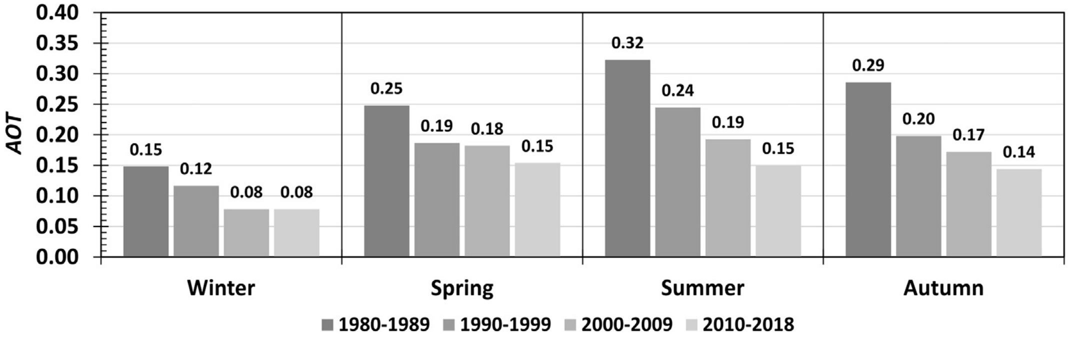

Fig. 8. Mean daily area-average AOT values in Poland when the area-average size of low-level cloud cover was below 20%. The values were compiled for 4 time intervals in the years 1980–2018.

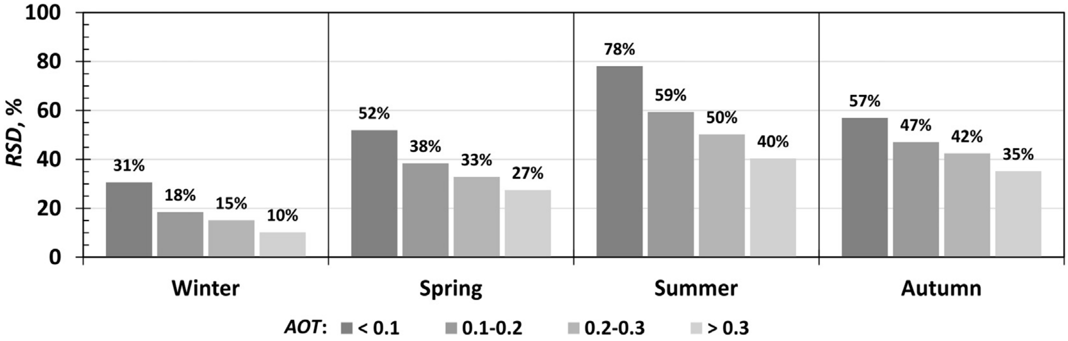

Fig. 9. Mean daily area-average values of relative sunshine duration (%) in Poland depending on the magnitude of AOT on a given day, when the area-average size of low-level cloudiness was below 20%.

do not cover the solar disk, do not limit the inflow of solar radiation (Matuszko, 2012a, 2012b). A similar tendency concerning cloudiness (a decrease in the incidence of stratiform clouds and an increase in the incidence of cumuliform clouds and *Stratocumulus*) was observed in many countries (i.a. Clement et al., 2009; Sherwood et al., 2014) and was explained by the increase in the temperature of the active surface, especially the surface of the oceans. A decrease in aerosol optical thickness (AOT) has been observed since the 1980s in many cities around the world (Provençal et al., 2017; Mukkavilli et al., 2019).

Trends in the inflow of solar radiation based on terrestrial and satellite data on the Iberian Peninsula in the years 1985–2015 are similar to the trends of relative sunshine duration in Poland, and are also explained by the changes in cloudiness and a decrease in AOT (Montero-Martín et al., 2020). Also in Spain, the largest increase in solar radiation occurred in the spring, which is mainly explained by the decrease in cloudiness at this time of year (Trigo et al., 2002; Sanchez-Lorenzo

Table 4
Linear multiple regression models (2) of area-average relative seasonal sunshine duration in Poland in the years 1980–2018.

Season	Model equation
Winter	$RSD_1 = 68.78 - 35.51AOT_1 - 0.71\mathrm{N}_{St+Ns+As1} - 0.49\mathrm{N}_{Cu+Cb1} - 0.64\mathrm{N}_{Sc1}$
Spring	$RSD_2 = 92.64 - 41.03AOT_2 - 1.29\mathrm{N}_{St+Ns+As2} - 0.62\mathrm{N}_{Cu+Cb2} - 0.59\mathrm{N}_{Sc2}$
Summer	$RSD_3 = 132.24 - 34.53AOT_3 - 1.73\mathrm{N}_{St+Ns+As3} - 0.74\mathrm{N}_{Cu+Cb3} - 1.73\mathrm{N}_{Sc3}$
Autumn	$RSD_4 = 102.11 - 45.17AOT_4 - 1.13\mathrm{N}_{St+Ns+As4} - 0.53\mathrm{N}_{Cu+Cb4} - 0.93\mathrm{N}_{Sc4}$

Table 5

The coefficients and results of the linear multiple regression models of area-average relative seasonal sunshine duration in Poland.

Season		Unstandardized Coefficients		Standardized Coefficients	t	*p*-value	R^2	Bootstrap 95% confidence interval for RSD (%)	
		B	Standard Error	*Beta*				Lower bound	Upper bound
Winter	Intercept	68.779	6.098	·	11.280	0.000**	0.64	18.8	21.6
	AOT	−35.504	6.897	−0.594	−5.148	0.000**			
	$N_{St+Ns+As}$	−0.706	0.160	−0.515	−4.420	0.000**			
	N_{Cu+Cb}	−0.492	0.108	−0.563	−4.573	0.000**			
	N_{Sc}	−0.636	0.103	−0.764	−6.199	0.000**			
Spring	Intercept	92.637	6.447	·	14.369	0.000**	0.76	32.5	37.1
	AOT	−41.027	8.550	−0.558	−4.798	0.000**			
	$N_{St+Ns+As}$	−1.289	0.259	−0.570	−4.974	0.000**			
	N_{Cu+Cb}	−0.623	0.087	−0.713	−7.199	0.000**			
	N_{Sc}	−0.593	0.146	−0.412	−4.064	0.000**			
Summer	Intercept	132.236	19.336	·	6.839	0.000**	0.76	46.1	51.2
	AOT	−34.531	8.666	−0.492	−3.984	0.000**			
	$N_{St+Ns+As}$	−1.733	0.695	−0.358	−2.491	0.018*			
	N_{Cu+Cb}	−0.739	0.227	−0.363	−3.253	0.003**			
	N_{Sc}	−1.730	0.387	−0.561	−4.468	0.000**			
Autumn	Intercept	102.103	10.276	·	9.936	0.000**	0.67	40.7	45.1
	AOT	−45.170	9.439	−0.542	−4.785	0.000**			
	$N_{St+Ns+As}$	−1.125	0.541	−0.309	−2.080	0.045*			
	N_{Cu+Cb}	−0.525	0.157	−0.348	−3.335	0.002**			
	N_{Sc}	−0.929	0.289	−0.415	−3.219	0.003**			

* - statistically significant at the level of $p < .05$; ** - $p < .01$. Bootstrap results are based on 1000 bootstrap samples.

et al., 2009, 2017; Tzallas et al., 2019).

The results of the analyses carried out in this study showed that changes in AOT thickness and in the structure of low-level cloudiness ($N_{St+Ns+As}$ and N_{Cu+Cb} and N_{Sc}) do not fully explain (especially in the winter) the amount of increase in the area-average values of relative sunshine duration in recent decades. There can be several reasons for this. They can be associated with both the existence of feedback in the climate system and can be of a methodical nature. As is commonly known, in addition to aerosols, water vapour has an impact on atmosphere transparency and cloud formation. Its importance as a feedback initiator is clear in large-scale processes. On the other hand, in local and mesoscale processes, these feedbacks often coexist, making individual factors difficult to isolate (Hall and Manabe, 1999). The results of the studies conducted in India and China indicate a positive correlation between AOT and water vapour content (Srivastava et al., 2008; Che et al., 2016). It can be explained by the condensation mechanisms of growth of aerosol particles. In the atmosphere over Poland in the years 1973–2005, a statistically significant decrease in the rainwater content was found based on radio sounding measurements and reanalyses (Wibig and Siedlecki, 2007), which corresponds to the decrease in AOT since the 1980s.

An important factor not analysed in this paper is the height of the sun above the horizon, which has a major impact on the scattering of solar radiation by aerosols, water vapour, and clouds (Boers et al., 2017). In Poland, from the last ten days of May to the beginning of the third decade of July, the sun is in the highest position above the horizon (above 60^{o} at actual solar noon), therefore, despite the highest AOT values, aerosols have little effect on the magnitude of sunshine duration. Also in other European countries, the highest AOT values fall in the summer (Zhao et al., 2018; Che et al., 2019). An important reason for higher AOT in the summer is that higher solar radiation intensity and higher air temperature accelerate secondary aerosol formation (Timonen et al., 2014). Moreover, it is possible to transport primary aerosols into higher troposphere layers as a result of more intense air mixing; what is more, a higher content of water vapour in the atmosphere promotes the hygroscopic growth of aerosols (Liu et al., 2012; Zheng et al., 2017).

One of the methodological reasons hindering the full explanation of sunshine duration trends may be the imperfection of the AOT indicator for estimating the content of aerosols in the air. This problem is indicated by the research of Karlsson et al. (2017); Pfeifroth et al. (2017), Pfeifroth et al. (2018) who note that satellite measurements do not take into account all types of aerosols (Karlsson et al., 2017; Pfeifroth et al., 2017) with the exception of high concentrations of pollutants, such as those caused by sandstorms (Müller et al., 2015; Provençal et al., 2017). The use of satellite measurement results is also associated with a number of restrictions related to, among other things, the ageing and, thus, frequent replacement of instruments, and errors resulting from the algorithms necessary to process the data (McCarthy and Toumi, 2004; Trenberth et al., 2005; Wagner et al., 2006).

An important aspect of the research presented in this article is methodological issues. It seems that the development of a method of using data on the types of clouds from the SYNOP message to analyse cloud types may be of great importance for further research. Knowledge about the role of cloudiness in the climate system is still insufficient. For this reason, further research with the use of nephological data should be expected, and cloud recording in the form of SYNOP messages is a considerable difficulty. It is worth noting that the global observation system is used rather for weather monitoring than for climate research (Norris and Slingo, 2009). It also seems right to take into account in this paper only low and medium level stratiform clouds, because the use of general cloudiness would hinder the interpretation of results. High-level clouds have a reverse trend in the multi-annual course, i.e. an increase in their incidence is observed (including Henderson-Sellers, 1986; Stordal et al., 2005) and, moreover, they let in the solar radiation reaching the earth's surface (Matuszko, 2012a).

It seems that the research methods used in the work (both traditional and modern, satellite) have fulfilled their role, making possible the demonstration of the spatial diversity and temporal variability of relative sunshine duration, cloudiness, and aerosol optical thickness in Poland. They also made it possible to determine the mutual dependencies and conditions between these elements. The climatological analysis carried out for the whole country using uniform methods seems to be an important starting point for further research on the relationship between the inflow of solar radiation and air temperature, the content of water vapour and aerosols, and the formation of clouds and their impact on the radiation balance. A good exploration and parameterization of these interactions based on measurement and observational data would certainly contribute to the improvement of the quality of forecasts and scenarios regarding the increase in temperature and changes in the magnitude and type of precipitation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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