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VARIATION OF CLOUDINESS IN THE MOUNTAIN REGION ON THE EXAMPLE OF THE SUDETES

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Abstract: The purpose of the study is to present a comparison of cloudiness at different levels of a mountain region and to emphasize the specific characteristics of cloud cover observed in valleys and on mountain summits, based on the example of the Sudetes. The analysis is based on cloudiness observations made in Jelenia Góra and on Mt Śnieżka in the years 1971–2015. The results obtained in the study demonstrate that the average cloudiness generally increases with altitude in the Sudetes. However, in the colder half of the year, in anticyclonic weather and thermal inversion conditions, this system may be inverted. There are more cloudless and clear days on average in the valleys and more overcast and cloudy days recorded at the tops of the Sudetes. The annual cloud cover amount is similar, due to atmospheric circulation. The diurnal pattern varies as an effect of the influence of local conditions. The increase in cloudiness during the period from 1971–2015 is more significant in Jelenia Góra than on Śnieżka.

Keywords: cloudiness, mountain, valley, Jelenia Góra, Śnieżka, Sudetes

INTRODUCTION

Cloudiness is considered an important factor which determines the radiation budget, thus influencing surface temperatures. The intense physical processes occurring in the atmosphere are the cause of highly variable cloud cover in mountain areas. These processes include intensive dynamic and thermal turbulence and local convection movements. Circulation conditions for the geographic area and the region in which the mountains are located affect cloudiness over the course of the year (Trepińska 2002). However, there are additional factors that govern the climate of mountains. Clouds in individual hypsometric layers also depend on the most frequently occurring cloud condensation level. Thus, regional studies in mountain areas are important in order to specify the nephological conditions.

The climate on Mount Śnieżka has been the subject of many studies (Głowicki 1998, 2000, 2001, 2003; Dubicka and Głowicki 2000a and 2000b; Wibig and Głowicki 2002; Migała et al. 2016; Urban and Tomczyński 2017); however cloudiness is not often analyzed. Dubicka and Limanówka (1994) described the variability of cloud cover and duration of sunshine in the Sudetes as well as on their foreland. The variability of the duration of sunshine on Śnieżka in relation

to atmospheric circulation and cloudiness has also been analyzed (Dubicka 1997). The relationship between air temperature and total cloudiness on Śnieżka in the 20th century was also looked at (Dubicka and Głowicki 2000a). Cloud cover in the wider area of the Karkonosze Mts. was described by Kwiatkowski and Hołdys (1985) and Sobik et al. (2014). This was also explored in an article concerning the bioclimatic conditions of the Sudetes (Miszuk 2008).

The purpose of this study is to present a comparison of cloudiness at different levels of a mountain region and to emphasize the specific characteristics of cloud cover observed in the valley and on the mountain summit.

MATERIAL, AREA AND METHODS

The source material used in this study consists of observations made during the climatological terms (0, 6, 12, 18 UTC) at the meteorological station of the Institute of Meteorology and Water Management National Research Institute (IMGW PIB) in Jelenia Góra and in the IMGW High Mountain Meteorological Observatory on the top of Śnieżka Mountain during the period 1971–2015. Jelenia Góra (50°54′N, 15°44′E H 342 m a.s.l.) lies on the River Bóbr in the northern part of the Jeleniogórska Valley in the foothills of the Karkonosze mountain range. Mt Śnieżka (50°44′N, 15°44′E) is the highest peak (1.603 m a.s.l.) in the Karkonosze range of the Sudetes. It is a highly exposed, summit situated in a sub-alpine climate. The climate in the Karkonosze is formed under the influence of general processes involving energy and water cycles in a temperate latitude. The local climate character is strongly modified by the influence of altitude and relief. The Karkonosze are mostly (64%) influenced by humid polar maritime air masses from the North Atlantic, relatively warm during the cold half-year, but relatively colder in the warm season causing high cloudiness all year round (Sobik et al. 2014). There are three climatic levels in the western Karkonosze Mts.: foot slope zone (< 850 m a.s.l.), slope zone (from 850 m a.s.l. to the upper tree line) and peak zone (above the upper tree line). The lowest cloudiness is observed in the slope zone. The two other zones demonstrate a higher amount of cloud cover (Kwiatkowski and Hołdys 1985).

Values of the average daily degree of cloudiness were converted from octant scale to a percentage scale and then used to calculate the following basic statistics: monthly, seasonal, annual and long-term averages, standard deviation and the linear trend of long-term changes in the degree of cloudiness on the basis of a 45 year observation series. Then, the number of cloudless and overcast days was determined. An indicator of nephological relationships is the number of clear and cloudy days, and so their number was determined as well. A clear day is one on which the average daily cloud cover is less than 20%. A day is defined as cloudy when total cloud cover is over 80%. Furthermore, days with overcast

sky in Jelenia Góra and a clear sky on Mt Śnieżka were chosen, to determine the pressure patterns on days with a sea of clouds. Use was made of average daily values of atmospheric sea level pressure (SLP) for the area of 25–75°N and 35°W–65°E obtained from the National Centre for Environmental Prediction/ National Center for Atmospheric Research Reanalysis (NCEP/NCAR) (Kalnay et al. 1996). The reanalysis data is grid-based (resolution of 2.5° x 2.5°) and is available in the files of the Climate Research Unit (CRU). Finally, a composite map of the sea level pressure (SLP) means for the selected days was constructed.

RESULTS

According to the data from 1971–2015, average annual cloudiness in Jelenia Góra is 68%, and 74% on Mt Śnieżka. The long-term course of mean annual values fluctuated similarly at both stations (Fig. 1A). The variability is relatively low and results in a standard deviation of only 3.6% in Jelenia Góra and 3.5% at Śnieżka (Tab. 1). Cloudiness in 1982 was the lowest in both stations. The years 2003, 1989, 1992 and 2011 also displayed very low cloudiness. The highest annual average cloudiness was observed in Jelenia Góra in 2013, and at the Śnieżka station in 1974. The long-term variability of cloudiness was estimated. There is an increasing tendency of total cloud cover in the research period, but it does not exceed the significance level (0.5% per decade in Jelenia Góra; 0.2%/10 years on Śnieżka).There are some differences in the deviation values; however, the periods with higher and lower cloudiness than the multiannual average can be clearly distinguished for both stations (fig. 1B).

Average annual total cloudiness at the Jelenia Góra station during the period 1971–2015 amounted to 68%. Higher mean cloudiness is observed in general during winter, but is also high in spring and autumn, with a maximum in November (73%) and December (72%). The lowest value of cloudiness was observed in summer, with a minimum in August (61%) (Fig. 2). The day-to-day variability of total cloud cover is highest in September and February in the valley, and results in a standard deviation of over 10%, and a coefficient of variation of over 14% (tab. 1). Annual total cloud cover at the Śnieżka station was higher, and amounted to 74%. Greater levels of cloudiness are observed generally in spring and autumn; however November is the cloudiest month (79%). Other very cloudy months on Mt Śnieżka are March and June. The lowest cloudiness is observed in August (69%) (Fig. 2). The maximum day-to-day variability on the mountain peak is highest in February and January, resulting in a standard deviation of 12% and 11% respectively, and coefficient of variation of 16.1% and 14.9% likewise (Tab. 1).

Cloudiness changes throughout the day. The diurnal pattern differs in the stations concerned (Fig. 2). From April to August, in Jelenia Góra the highest amount of cloud occurred at noon and the lowest at night, with a high daily

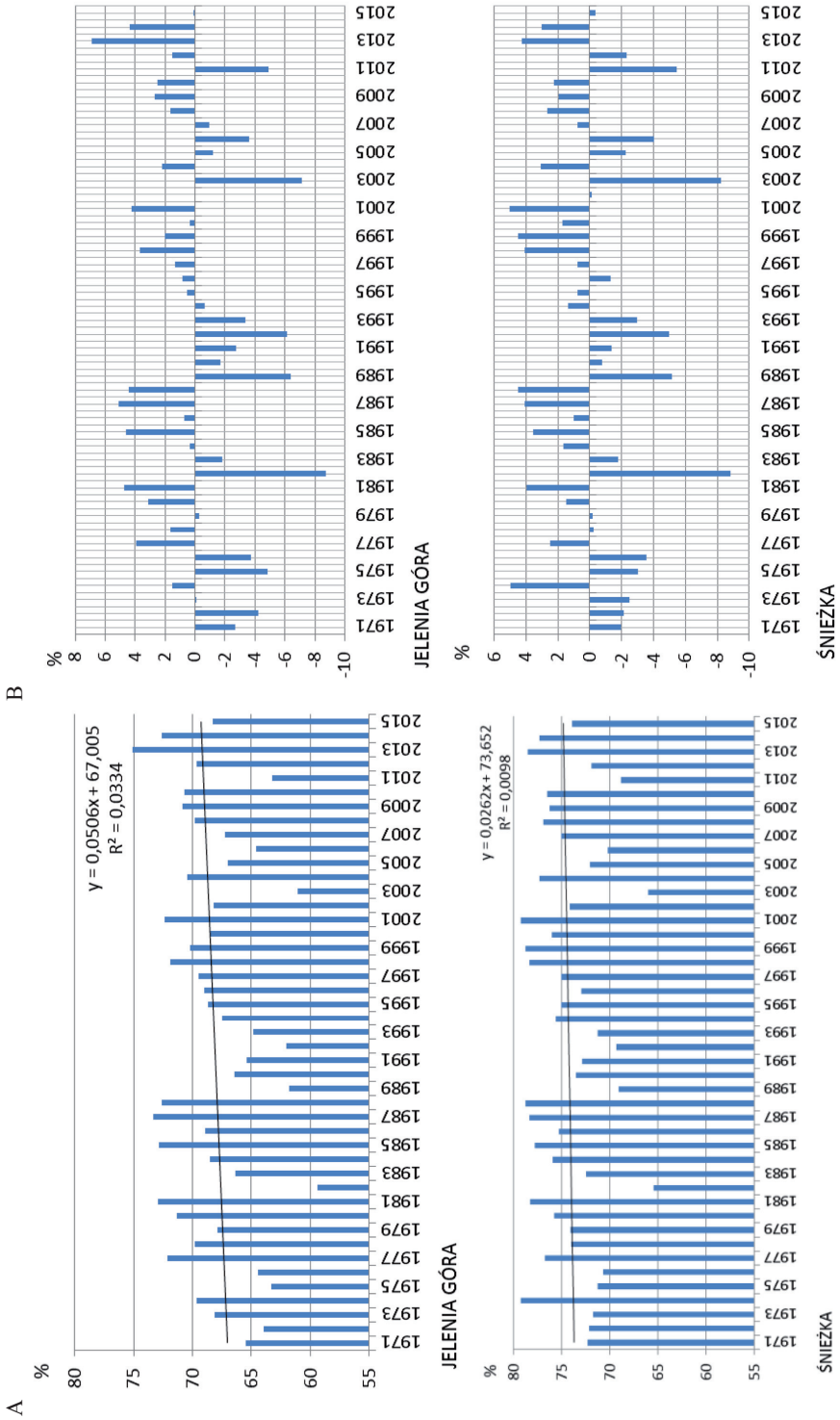

Fig. 1. Total cloudiness with linear trend and the coefficient of determination R^2 (A) and the annual deviation from the average of the period 1971–2015 (B) in Jelenia Góra and Mt Śnieżka

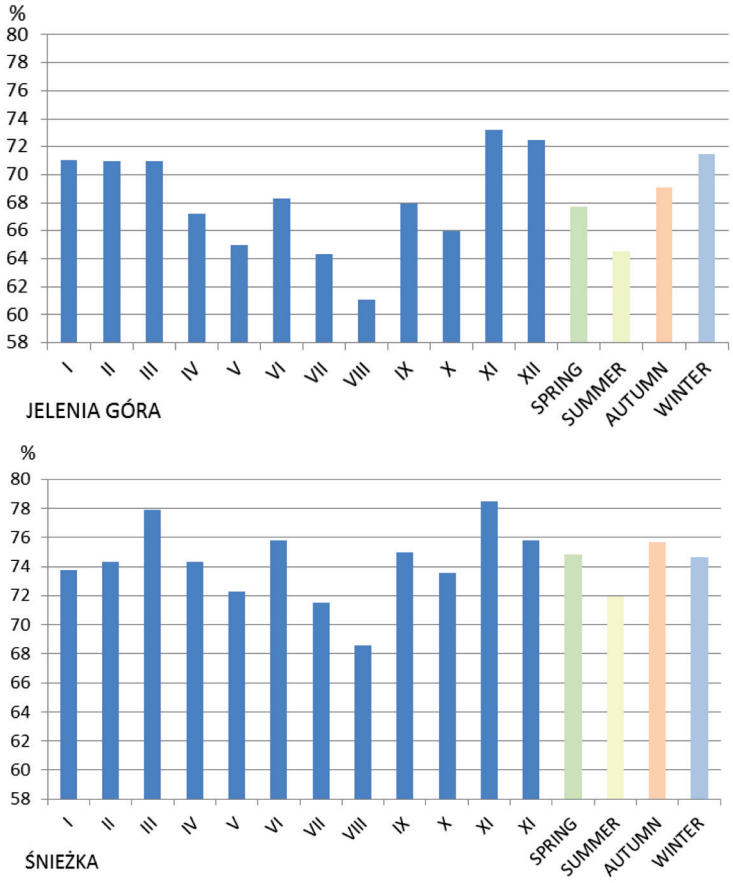

Fig. 2. Annual and seasonal course of total cloudiness in Jelenia Góra and on Mt Śnieżka, 1971–2015

amplitude. The greatest cloudiness at noon is observed both in December and January, but the daily amplitude is much lower then. In February and March, and from September to November, the greatest amounts of cloud appeared in the morning. On Śnieżka the highest cloudiness were observed at 18 UTC and the lowest at night, all year round. The amplitude of daily cloudiness changed in particular seasons. In the warm part of the year the amplitude is much higher than in the cold half-year.

A cloudless day was one in which a cloudless sky was observed during all four weather observations. The course of the number of cloudless days presents a high year-to-year variability (Fig. 3). They occur more often in Jelenia Góra than on Mt Śnieżka. The year with highest number of cloudless days at both stations was 2003. Other years characterized by a high number of cloudless days in the valley were: 1972, 1982, 1989, 1991 and 2006, and 1975, 1989, 1982, 1993

Table 1. Standard deviation (SD), coefficient of variation (CV) and extreme values of monthly, seasonal and annual total cloud cover [%] in Jelenia Góra and on Mt Śnieżka (1971–2015)

MONTH	JELENIA GÓRA						ŚNIEŻKA					
	SD	CV	MAXIMUM		MINIMUM		SD	CV	MAXIMUM		MINIMUM	
			VALUE	DATE	VALUE	DATE			VALUE	DATE	VALUE	DATE
I	9.0	12.6	89	2013	48	1971	11.0	14.9	89	1994	49	1989
II	10.2	14.3	93	1973	48	1982	12.0	16.1	92	2009	39	2003
III	8.1	11.4	87	2009	53	1972	8.3	10.6	93	1988	59	2011
IV	9.3	13.8	81	1972	36	2009	9.3	12.6	89	1972	42	2009
V	8.6	13.3	87	2010	49	1979	8.9	12.3	93	2010	54	1979
VI	6.9	10.1	78	1988	46	1976	7.1	9.4	87	1985	56	1976
VII	9.8	15.2	83	2000	43	2006	9.2	12.9	89	1980	50	2006
VIII	7.7	12.6	76	2006	41	1973	8.0	11.7	86	2006	45	1973
IX	10.7	15.7	88	1996	46	1975	9.4	12.5	93	1996	54	1982
X	9.4	14.2	84	2009	45	1979	10.4	14.1	95	1974	55	1977
XI	9.3	12.7	88	1987	45	2011	9.6	12.2	91	1987	46	2011
XII	9.4	12.9	88	1988	37	1972	10.4	13.8	95	1993	46	1972
spring	4.6	6.7	77	2013	56	2007	5.1	6.8	83	1985	64	2011
summer	5.3	8.3	73	1987	53	1976	5.1	7.0	81	1980	59	1983
autumn	6.5	9.4	81	1996	54	2011	6.0	7.9	87	1996	59	2011
winter	6.1	8.6	83	2013	53	1972	7.1	9.5	85	1999	59	1989
YEAR	3.6	5.3	75	2013	59	1982	3.5	4.7	79	1974	65	1982

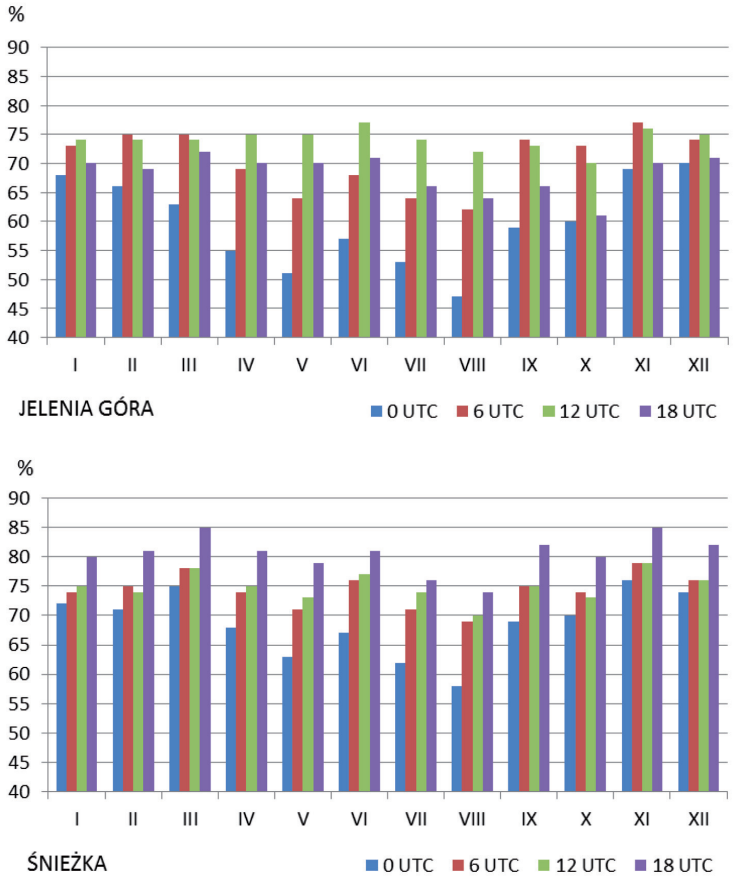

Fig. 3. Annual course of total cloudiness in particular observation periods in Jelenia Góra and on Mt Śnieżka, 1971–2015

and 2006 on the summit. The lowest number of cloudless days in Jelenia Góra fell in: 2008, 2010, 2013 and 2001. Cloudless days did not occur on Śnieżka in 1971, 1988 and 1998. The number of cloudless days in Jelenia Góra dropped over the research period (0.9 days per decade). This change is statistically significant at a level of 90%. On Mt Śnieżka, the number of cloudless days does not indicate any long-term changes.

Cloudless days, i.e. without clouds at all four times, are very rare (Tab. 2). They are observed more often in the valley than on the summit. On Mt Śnieżka these days occur only in winter. In Jelenia Góra they appear from October to March.

A cloudless sky is less frequently observed on Mt Śnieżka than in the Jeleniogórska Valley (Fig. 4), nevertheless, the daily course of occurrence is similar. Cloudless skies are recorded most often during the night, throughout the whole

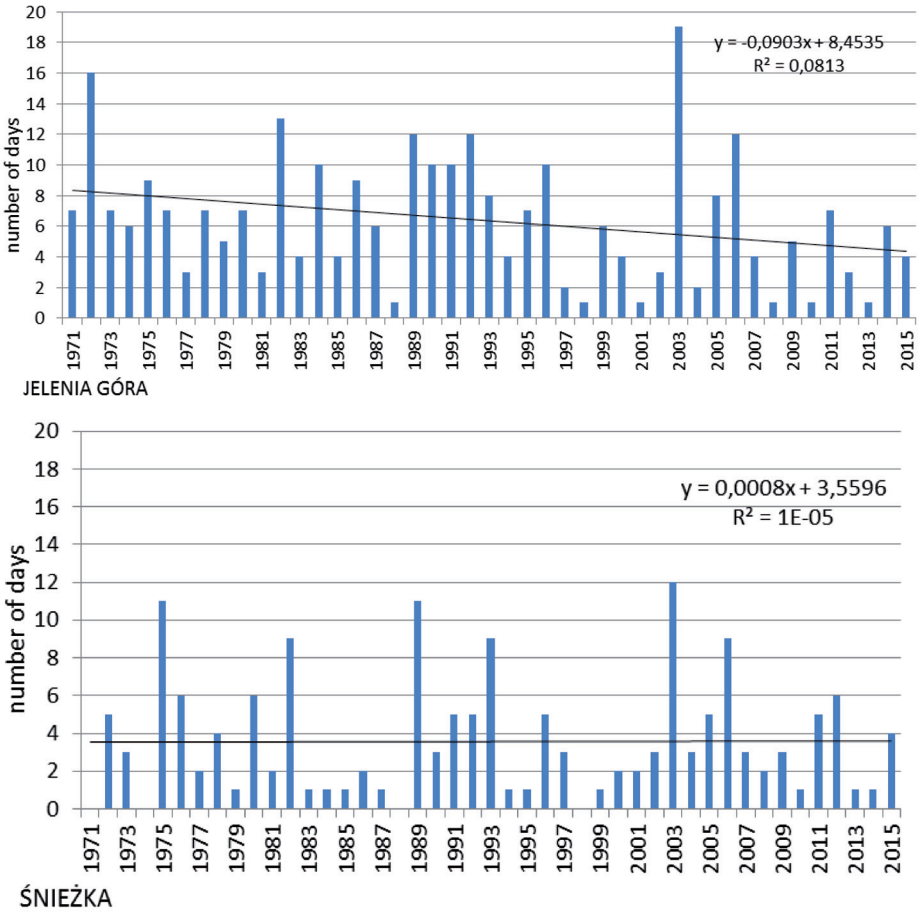

Fig. 4. Total number of cloudless days in Jelenia Góra and on Mt Śnieżka in 1971–2015 with linear trend and the coefficient of determination R^2

Table 2. Mean number of cloudless, clear, cloudy and overcast days in Jelenia Góra and on Mt Śnieżka (1971–2015)

Station	Days	Months												Year
		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	
Jelenia Góra	cloudless	1	1	1	0	0	0	0	0	0	1	1	1	6
	clear	3	2	2	3	2	1	3	3	2	3	2	2	28
	cloudy	16	14	15	12	11	12	11	9	12	12	15	16	155
	overcast	4	4	3	2	2	1	1	1	2	2	4	4	30
Śnieżka	cloudless	1	1	0	0	0	0	0	0	0	0	0	1	3
	clear	3	3	2	1	1	0	1	1	1	2	2	3	20
	cloudy	18	17	19	16	15	16	15	13	17	17	19	19	199
	overcast	8	8	8	5	4	4	3	3	5	7	8	9	72

year. Least frequent are cloudless skies at noon. The lack of clouds in daytime was more frequent in the cold half of the year, and at night in the warmer seasons.

Overcast days, when clouds fully cover the sky all day long, are recorded much more frequently at the summit of the Karkonosze Mts than in the valley (Fig. 5). The number of such days at both stations is characterized by high year-to year variability. There is a downward tendency in overcast days over the research period. The number of these days in Jelenia Góra dropped during the research period (5 days per decade). This change is statistically significant at a level of 99%. On Mt Śnieżka, there is a downward tendency, but it does not exceed the significance level.

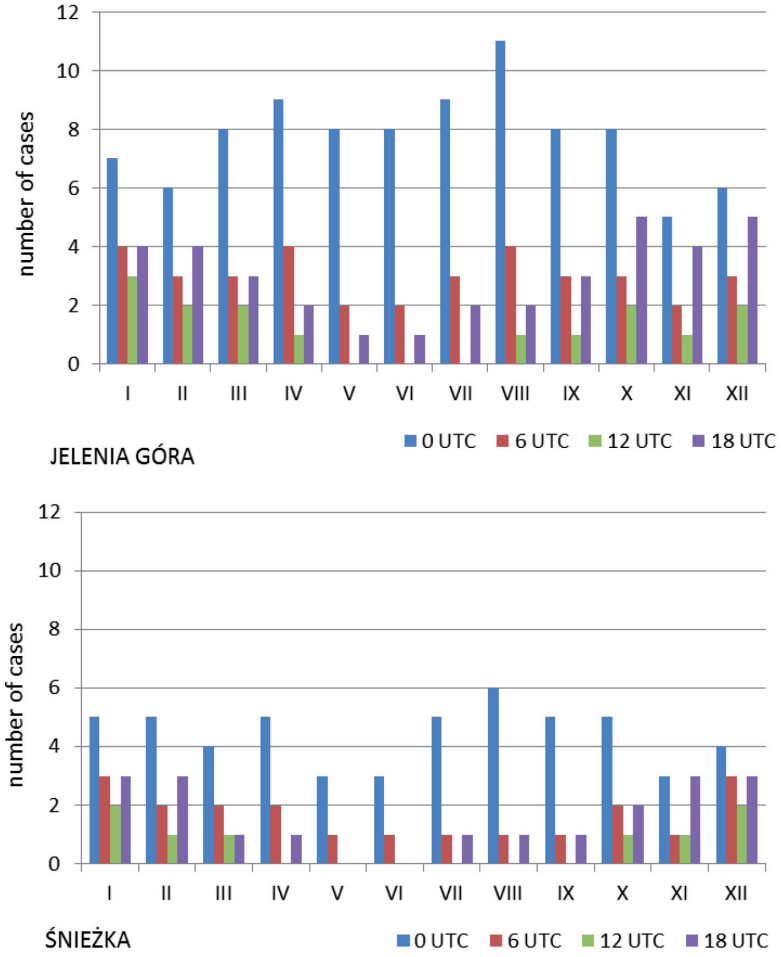

Fig. 5. Total number of cloudless skies at particular observation times in Jelenia Góra and on Mt Śnieżka in 1971–2015

Overcast skies are observed more often on Mt Śnieżka than in the Jeleniogórska Valley (Fig. 6). The annual course of the occurrence is similar in both places. The highest frequency is in winter, the lowest in summer. The transitional seasons are characterized by a systematic fall or increase of cases of overcast sky. The lowest frequency of fully obscured skies is observed at noon at these stations. Overcast sky in Jelenia Góra occur most often in the morning or at night, while on Śnieżka, from November to April – at night, and from May to August equally often at night and in the morning.

Overcast days appear on average 30 days per year in the valley, and 72 days per year on the summit of the Sudetes (Tab. 2). The mean number of overcast days occurs least frequently in the summer at both stations. The highest number

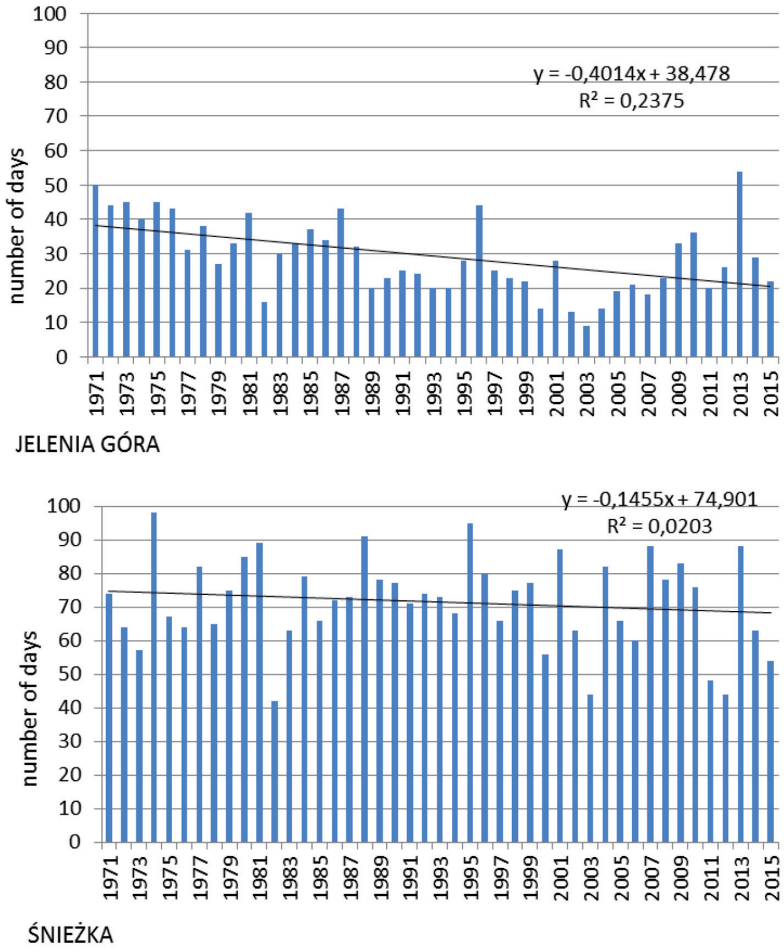

Fig. 6. Total number of overcast days in Jelenia Góra and on Mt Śnieżka in 1971–2015 with linear trend and the coefficient of determination R^2

of such days is recorded in Jelenia Góra from November to February, while on Mt Śnieżka this is in December.

Days with cloud cover of less than 20% occurred in Jelenia Góra 28 times per year during the research period. On Mt Śnieżka it is a little lower. There are 20 clear days a year on average (Fig. 7, Tab. 2). The lowest mean at both stations falls in June . On the peak, they occur mainly in the winter months. These days are characterised by high year-to year variation at these stations, together with the downward tendency of the number of clear days in the period from 1971–2015. There is a drop of ca. 3 days per decade, with statistical significance at a level of 95% in Jelenia Góra. On Mt Śnieżka, the downward tendency does not exceed the significance level.

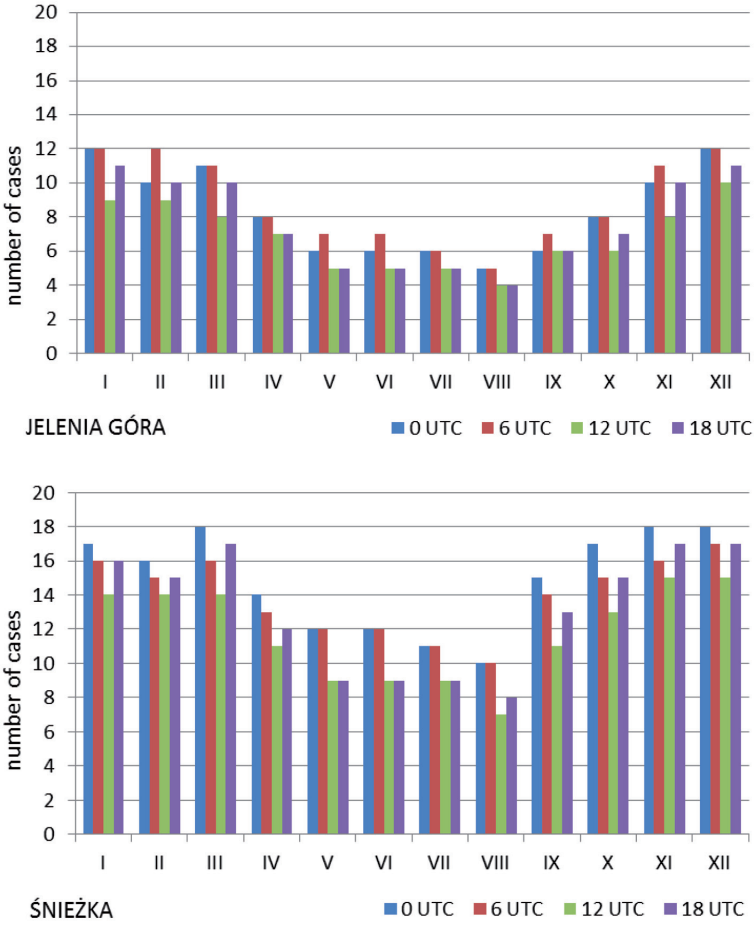

Fig. 7. Total number of overcast days in Jelenia Góra and on Mt Śnieżka in 1971–2015 with linear trend and the coefficient of determination R^2

Cloudy days (> 80%) appear on average 155 days a year in the valley and 199 days a year on the summit of the Sudetes (Fig. 8, Tab. 2). The lowest mean falls in August at both stations. In Jelenia Góra they occur most frequently in January and December, and on Mt Śnieżka - in March, November and December. The number of cloudy days has a slight upward tendency over the research period on Mt Śnieżka and a downward tendency in Jelenia Góra. This is not statistically significant for either station.

The variation in cloudiness across the year between the lower and higher parts of the mountains is very clear both in summer and winter. Summer is generally less cloudy on the lower levels, and the peaks are then at low clouds. In winter, radiation or advection fog occurs, and the level of condensation falls.

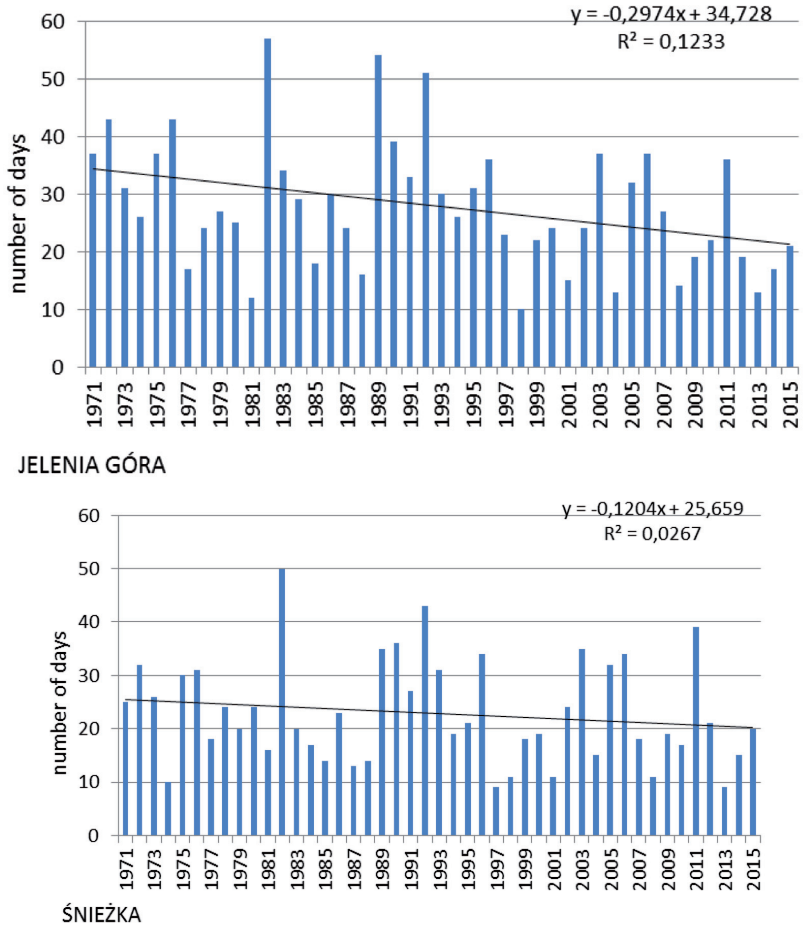

Fig. 8. Total number of clear days in Jelenia Góra and Mt Śnieżka in 1971–2015 with linear trend and the coefficient of determination R^2

In the valley, ventilation is limited, the cool air flowing from the slopes quickly fills in such a depression, which results in faster and more frequent thermal inversion and reversal of the thermal profile. Therefore, in autumn and winter, the higher parts of the mountains are more often free of cloud cover, because they are above the so-called sea of clouds. In 1971–2015, in the research area the phenomenon was recorded 1.226 times which is 7.5% of all observations (Tab. 3). It occurs mostly at night and in the morning in the cold half-year, with a maximum in January. It was observed least frequently at noon, with a minimum in June. From May to August in the evening, and from May to July at noon, it did not occur at all.

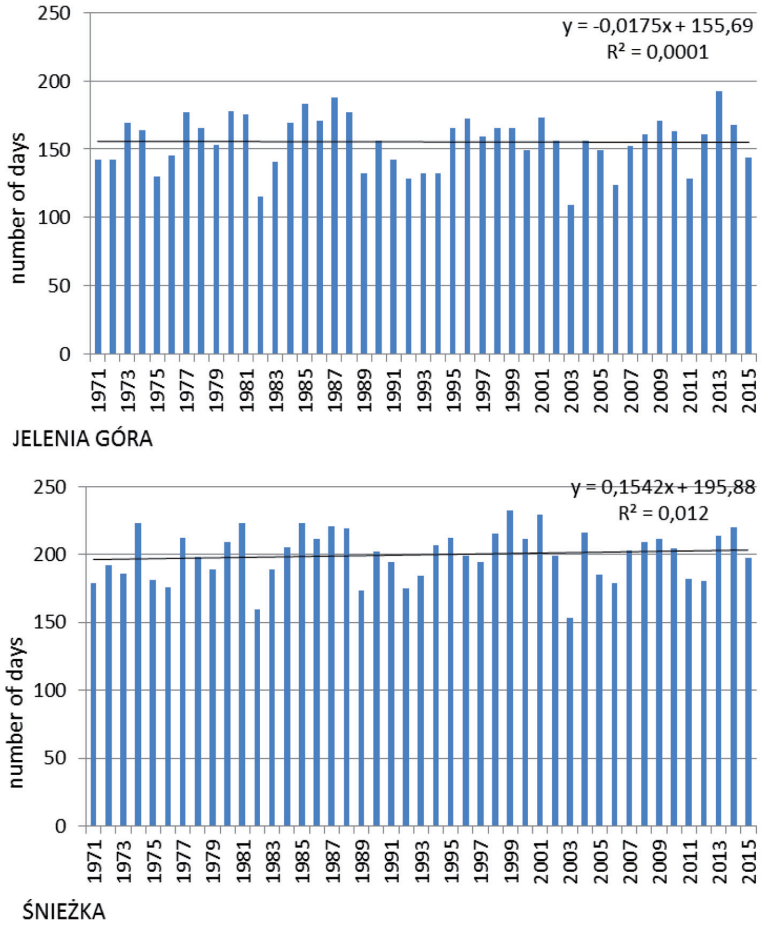

Fig. 9. Total number of cloudy days in Jelenia Góra and on Mt Śnieżka in 1971–2015 with linear trend and the coefficient of determination R^2

Table 3. Number of cases of the occurrence of ≤ 20% cloudiness on Mt Śnieżka and ≥ 80% cloudiness in Jelenia Góra simultaneously in the four periods (1971–2015)

Months	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
0 UTC	78	72	21	19	15	11	15	24	46	73	62	63	499
6 UTC	61	54	21	20	9	3	8	8	49	67	48	57	405
12 UTC	32	24	6	1	0	0	0	0	2	12	14	26	117
18 UTC	43	42	9	3	0	0	0	1	1	17	39	50	205
Total	214	192	57	43	24	14	23	33	98	169	163	196	1226

In the research period, there were 54 days with an all-day sea of clouds phenomenon. These occurred mainly in winter: the most frequently in December (18 days), February (13 days) and in January (10 days). They were observed quite often in October (6 days) and November (5 days), and only once a month in each of March and September. In the composite SLP map constructed for the selected days, a distinct anticyclone spreads over Central Europe with its center over western Poland (Fig. 10). The pressure gradient is large. That indicates a stable air mass over the area of Poland influencing the advection in winter of cold arctic or polar continental air masses. Such a pressure pattern enhances thermal inversion, which causes the flow of cold air into the Jeleniogórska Valley. Clouds form when the air under the inversion layer is very humid and is not sufficiently heated by the sun during the short day. Above the inversion layer, the weather is sunny, dry and relatively warm.

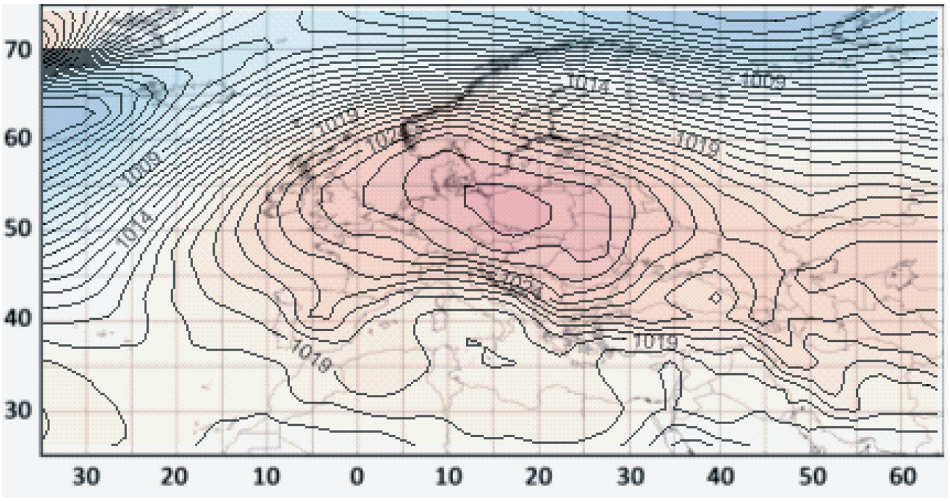

Fig. 10. Mean SLP in hPa during the occurrence of days of ≤ 20% cloudiness on Mt Śnieżka and days of ≥ 80% cloudiness in Jelenia Góra simultaneously (1971–2015)

CONCLUSIONS AND DISCUSSION

In 1971–2015, the average total cloud cover in Jelenia Góra (68%) was lower than on Śnieżka (74%). The lowest cloudiness occurred in 1982 at both stations. The highest was in 1974 on Śnieżka and in 2013 in Jelenia Góra. The results obtained on the basis of earlier observations for the research area show lower values. Kwiatkowski and Hołdys (1985) stated that the average annual cloudiness in the Karkonosze varies from 62 to 65% at the foot of the slope to 74–78% in the peak zone. Sobik et al. (2014) received values from 68% in Jelenia Góra to 73% on Śnieżka. The increase of total cloud cover in Jelenia Góra was greater than on Śnieżka in 1971–2015. The increase of total cloudiness is confirmed by the general trend observed in Europe (Henderson-Sellers 1986). On the other hand Dubicka and Limanówka (1994) stated that in the earlier period, from 1901–1980, there was a decrease of total cloud cover on Śnieżka. Fluctuations in long-term cloudiness and its upward tendency from 1983 were recorded in Kraków (Matuszko 2003). A downward trend of total cloud cover was observed in Łódź in the second half of the XX century but varied at different times of the day (Wibig 2008). An upward tendency was also recorded in the western part of the Sudetes – on Szrenica in 1961–1990 (Pereyma et al. 1997). Statistical co-variability analysis of temperature and cloudiness time series carried out by Dubicka and Głowicki (2000a) showed the existence of a significant dependence between these variables, but only in the summer season.

Winter in the Jeleniogórska Valley was described by the highest cloudiness among all seasons. On Mt Śnieżka, spring and autumn were the cloudiest seasons on average. The lowest cloud cover, based on the research, occurred in summer, with a minimum in August at both stations. According to the other results, the lowest cloud cover was observed at Szrenica in September (Szczepankiewicz-Szyrka and Mielcarek 1997) and on Śnieżka in September and October (Kwiatkowski and Hołdys 1985; Sobik et al. 2014). Kwiatkowski and Hołdys (1985) also recorded a minimum in August in the foothill area of the Sudetes. The cloudiest month was November at both stations, and this is confirmed by other studies (Szczepankiewicz-Szyrka and Mielcarek 1997; Sobik et al. 2014). According to Żmudzka (2007), in the period 1951–2000, the highest cloud cover in Poland occurred the most frequently from November to January and fluctuated from 79–84%. The lowest cloudiness appeared most often in September, May and August with an average of between 46 and 52%. The high cloud cover in the cold half-year is due to the greater frequency of polar-sea air advection from the SW-W sector and the reason for the lower cloudiness is anticyclonic weather complexes and the dry continental air flow from the E–SE–S sector (Sobik et al. 2014).

There are more cloudless and clear days in Jelenia Góra, while on Śnieżka overcast and cloudy days occur more frequently. In Jelenia Góra and on Śnieżka

the least cloudiness appeared at night. Cloudless nights make it possible to carry out astronomical observations. According to the research by Kreiner and Trepińska (1991) the best conditions in the Polish mountains are in September and October, due to the length of the night and the least cloudiness. Less favorable night-time nephological conditions occur in the highest parts, as radiation fogs rise up from the valleys (Trepińska 2002).

The cloudiest time of day varied at different altitudes. Overcast skies in Jelenia Góra occur the most often in the morning or at night, while on Śnieżka, from November to April – they occur at night, and from May to August they occur at night as often as in the morning. The diurnal differences are due to regional factors, hence there are some differences from the types of daily cloudiness distinguished by Olszewski (1990).

As the research showed, the reversal profile of cloudiness is related to the anticyclonic conditions in the cold half-year, mainly when thermal inversion forms over the valley. In Karkonosze Mts, the most persistent and intense inversions come from settling, especially in the winter season (Zipser-Urbańska 1964). In hypsometric cross-section, inversions occur most frequently at the foot of the slopes. Their average ceiling is 750–800 m, which corresponds to the average level of the Kaczawskie and Rudawy Janowickie Mountains, which hinder the free flow of cool air from the bottom of the Jeleniogórska Valley (Kwiatkowski and Hołdys 1985; Urban et al. 2017). The results of research into the factors responsible for the formation of inversions in mountain valleys obtained by Wibig (1997) confirmed the thesis that the main reason is anticyclonic circulation.

So, the results obtained in the study demonstrate that average cloudiness generally increases with altitude in the Sudetes. However, in the cold half of the year, with anticyclonic weather and thermal inversion, this system may be inverted. There are more cloudless and clear days on average in the valley, and more overcast and cloudy days recorded at the summit of the Sudetes. The annual course of cloud cover amount is similar, which is due to the atmospheric circulation. The diurnal pattern varies as an effect of the influence of local conditions. The increase in cloudiness during the period from 1971–2015 is more significant in Jelenia Góra than on Śnieżka.

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