Chapter 10
Change of Cloudiness

Janusz Filipiak

Abstract Cloudiness is an important element of the climate system as it strongly influences the global energy balance. On the basis of data from 57 stations, the most important features of spatial diversity and temporal variability of cloudiness, i.e. annual and seasonal mean and extreme values, number of clear and cloudy days and cloud type, were analysed. The mean annual cloud cover in Poland in the years 1951–2018 was 68.2%. The maximum value, equal to 73%, was recorded in 1966, whereas the minimum value of nearly 61% occurred in 1982. The lowest level of cloudiness occurs in summer, while the largest in winter. Generally, cloudiness in spring is lower than in autumn. In spring and summer, cloudiness decreases eastwards, while in autumn and winter it increases towards the north of the country. Additionally, the western part of Poland is cloudier than the east of the country. In the north, a negative tendency in annual cloudiness in the period 1951–2018 prevails, while in the south positive statistically significant changes occur. The amount of cloudiness in particular seasons also changes, however, stronger trends can be observed in subperiods: 1951–1984 and 1985–2018. In winter, in the later period, a statistically significant increase in cloudiness occurs with the coefficient increasing towards the south. Strong positive trends in spring were in the period of 1951–1984. In both remaining seasons, recorded changes of cloudiness are smaller, and, in the period of 1985–2018, a decrease of cloudiness was observed across the country. Overall, the frequency of cloudy days is much higher in Poland than clear ones. The number of clear days is decreasing considerably across the country, and, in case of cloudy days, negative changes concern only some regions. Atmospheric circulation plays a key role in shaping nephological conditions, however, processes of a local scale are also important. *Stratocumulus*, *Altocumulus* and *Cirrus* are the most frequent clouds among the low-level, middle-level and high-level clouds, respectively, in Poland, but its percentage ranges significantly in various regions. Coastlands are most favourable

J. Filipiak (✉)
Faculty of Oceanography and Geography, Institute of Geography, Department of Meteorology and Climatology, University of Gdańsk, Gdańsk, Poland
e-mail: janusz.filipiak@ug.edu.pl

Institute of Meteorology and Water Management—National Research Institute, Warszawa, Poland

M. Falarz (ed.), *Climate Change in Poland*, Springer Climate,
https://doi.org/10.1007/978-3-030-70328-8_10

in the country for the occurrence of both convective clouds and *Stratus* clouds. *Stratocumulus* clouds are most common in the whole country, particularly in areas with a diverse relief, and *Altocumulus* clouds are most observed in southwestern Poland. The frequency of occurrence of *Altostratus* decreases slightly from west to east. *Cirrostratus* clouds are the most frequent in western Poland, while *Cirrocumulus* clouds are very rare. In case of low-level clouds, excluding *Stratus*, a strong, statistically significant positive trend occurs. In addition, the number of *Stratus* observations is declining substantially. The frequency of occurrence of *Altostratus* and *Nimbostratus* is systematically decreasing, while in the case of *Altocumulus*, an increase may be observed. On the whole, high-level clouds can be observed more and more frequently in Poland.

Introduction

Cloudiness seems to be one of the most interesting among the meteorological elements. Clouds strongly influence the global energy balance: on the one hand, reflecting a large part of shortwave radiation, and, on the other, absorbing long-wave radiation and emitting the additional considerable own flux of energy (Norris and Slingo 2009; Siebesma et al. 2009; Boucher et al. 2013; Zhou et al. 2016). What is crucial is that their role in many regions of the Earth, particularly the most fragile ones, is still increasing—e.g. Vavrus et al. (2011) reported on the growing feedback on climate driven by clouds observed in the Arctic, and Schneider et al. (2019) presented the mechanism concerning how clouds can respond to greenhouse warming in the subtropical region.

Moreover, clouds greatly interact with other meteorological variables. There is a relation between the observed worldwide, long-term decrease in daily temperature range and the changes in cloud cover (Henderson-Sellers 1986), seasonal and regional variability of relative humidity and cloud cover (Cox et al. 2015), and sea ice and cloudiness (Jun et al. 2016).

Though visual observations at synoptic and climatological stations still remain the main source of information on the spatial and temporal variability of cloud cover and cloud type, the role of new methods, such as satellite observations (Hollmann et al. 2013) detecting clouds from a position above the atmosphere, is increasing. Such developments help in the discovery of new patterns of cloud changes as, e.g. increasing height of the highest cloud tops at all latitudes or poleward retreat of mid-latitude storm tracks (Norris et al. 2016). The drivers of all current changes in cloud amount and type appear to be related mostly to anthropogenic activity, specifically increasing greenhouse gas concentrations or human-induced aerosol optical depth (Charlson et al. 1992; Boers et al. 2017). The increasing analytical possibilities and growing volume of data constitute an important contribution to the enhanced analyses of long-term variability of cloud cover and cloud type (Eastman et al. 2011; Eastman and Warren 2013) as well as climate model simulations (Webb et al. 2017).

The increase in the spatial resolution of research brought to light important features of cloudiness variability in the smaller areas of special interest, as is presented in the analysis below.

Data and Methods

The structure of spatial and temporal variability of cloudiness in Poland was analysed for the period 1951–2018 using data derived from 57 observation stations located throughout Poland. The varied locations of the stations presents the variability of cloudiness in all geomorphological types of Polish landscapes (shores, lowlands, uplands, mountain foothill basins and mountains—low and high) (Solon et al. 2018).

The research material was derived mainly from manned synoptic stations, where measurements of cloud characteristics were made by visual observation. Initially, it included data on total cloud cover gathered during eight main and intermediate standard times (starting from 00 to 21 UTC).

Taking the specificity of the materials provided by the Polish National Hydrological and Meteorological Service (IMGW-PIB), the majority of data was available for the periods starting not earlier than in 1966. As for the period 1951–1965, the data available covers only three climatological times—morning, afternoon and evening. Moreover, during the 1990s, at some stations, 24/7 observation shifts were changed into a 12-h system of work, starting at 6 and finishing at 18 UTC. In 2000, some of the synoptic stations (more precisely the changes affected five stations) were fully automated. It was decided to delete these stations from the analysis due to insufficient temporal data coverage. In 2014, some more changes to the IMGW-PIB observation network were introduced, resulting in withdrawal of cloud observations from the observing practices at almost 20 stations (of total number of 63 synoptic stations in Poland). At the beginning of 2018, cloud observations were brought back in practice at approximately half of them. Currently (the end of 2019), observations of clouds are made at 48 Polish synoptic stations.

Additionally, three climatological stations were also added to the list of those analysed. The data on total cloud cover enriched the analysis concerning several physico-geographical regions. In Poland, climatological observations are carried out at times corresponding to the main morning, afternoon and evening synoptic observation times (i.e. 6, 12 and 18 UTC). Until 1970, meteorological observations in Poland had been made at 7, 13 and 21 of the local solar time.

As the analysis covered data obtained from the stations of different order (synoptic and climatological) and taking the above-mentioned changes in the observing practices under consideration, it was decided to use only the data gathered at three main standard times (06, 12 and 18 UTC), referring to the climatological ones.

Subsequently, it was necessary to standardise the unit used when assessing the total cloud cover. The one currently used—okta (covering the figures from 0 to 8 and, additionally 9 for an obscured sky), was introduced into observation practice on 1 January 1966 at the synoptic stations and on 1 January 1989 at the climatological ones. Before that time, cloud amount had been recorded in deciles (on a scale 0–10). Both units were converted into percentages in accordance with the WMO guidelines (WMO 2018). The cases with 9 oktas have been classified as situations of overcast sky (8/8). The number of such observations was very small and they constituted approximately 1% of all analysed cases. Exceptionally, at some stations located in the lakelands (Kętrzyn, Resko, Chojnice and Gorzów Wlkp.) and in the mountain regions (Zakopane—intramountain basin, Lesko—low mountains) such observations reached the value of approximately 2%. However, at two Polish high-mountain observatories, the percentage of full cloudiness cases was relatively high (Kasprowy Wierch—34%, Śnieżka—40%).

On the basis of the observation data, the mean daily total cloud cover was calculated for each analysed station. Then, the most important features of spatial diversity of mean annual and seasonal values of the element in the period 1951–2018 were determined. The aspects of temporal variability were analysed for the whole selected research period as well as its two subperiods: 1951–1984 and 1985–2018. Next, the annual frequency of clear and cloudy days was calculated. A clear day is one with a daily mean cloudiness lower than 20% of the cloud amount. Analogically, a cloudy day is the one with the daily mean cloudiness of more than 80% of the cloud amount.

Additionally, cloud type, i.e. estimate of sky fraction covered by a variety of ten cloud genera in the period of 1966–2018 for several dozen stations was analysed. The stations were selected using the criteria of observation material completeness, i.e. only from series with eight daily observations at main and intermediate standard times of cloud genera at all three levels were taken into account, which finally resulted in the number of 23 series. According to the regulations of FM-12 synoptic code (WMO 2018), results of cloud type observations are classified using a scale given in synoptic code: C_L, C_M or C_H. However, this specific way of coding does not always enable the assignment of a single genus of cloud to a particular code element, as Matuszko and Węglarczyk (2018) mentioned in their analysis. The regulations concerning the coding of C_L, C_M or C_H clouds in a situation when there is more than one genus of clouds in the sky which correspond to more than one code of clouds at particular level, put an obligation to select a proper code in accordance with the fixed priority hierarchy.

An easily noticeable example concerns low clouds—the appearance of the sky coded $C_L = 3$ and 9 means that *Cumulonimbus* is present, yet it may be accompanied by *Cumulus*, *Stratocumulus* or *Stratus*. Thus, it can be assumed that the accompanying clouds appeared in the sky in some part of the cases; in the remaining cases a huge *Cumulonimbus* completely obscured the other genera of clouds. A code of $C_L =$ 8 means coappearance of *Cumulus* and *Stratocumulus*, with their bases at different heights. Thus, all the cases were assigned to both clouds. In the case of middle clouds, a code of $C_M = 2$ means *Nimbostratus* or *Altostratus* sufficiently dense to hide the sun. The ratio of the occurrence of both clouds has to be, however, assigned. A code of $C_M = 7$ concerns both *Altocumulus* and *Altostratus*/*Nimbostratus*. Usually, observers code two genera of clouds—Ac As or Ac Ns. That is why, all observations coded that way were added to the number of *Altocumulus* cases, but part of them have to be added to the number of *Altostratus* and *Nimbostratus* ones. In the case of high clouds, a similar approach was implemented. The numbers 5 and 6 added to code of C_H mean not only *Cirrostratus*, but also the possibility of coappearance of *Cirrus* clouds. Similarly, in the case of $C_H = 9$, domination of *Cirrocumulus* does not exclude the existence of *Cirrus* and *Cirrostratus* clouds in the sky.

The above-mentioned short description explains why analysis of cloud type shall always be preceded by a detailed comparative analysis of data contained in synoptic reports and journal of synoptic observations. Nonetheless, the results of methodological analyses initially begun by the Polish National Meteorological and Hydrological Service, with the use of observation practices implemented at the Polish synoptic stations (IMGW-PIB 2013), further developed by the author for the purposes of the current paper, helped to indicate a simplified method of assigning a particular genus or genera of clouds to the code of C_L, C_M or C_H. The observation material for the years 2000–2018 collected for the current analysis helped to justify and improve the methodology. Its updated results are displayed in Table 10.1.

It is also worth emphasising that when analysing observation data concerning genera of clouds at levels higher than the low level it is important to keep in mind the fact that in some cases, the sky was completely obscured by the lower level clouds. As for the middle clouds, such a situation concerned approximately 30–40% of cases. However, the high clouds were not visible during approximately 50% of the observations. At the stations located in the north and in the mountain areas, this percentage was even higher.

Results

Total Cloudiness

The average annual total cloud cover in Poland during the period of 1951–2018 is 68.2%. The value of the variable recorded at particular stations varies from nearly 65% to more than 75% (Fig. 10.1a). Western and eastern peripheries of the Southern Baltic Coastlands belt (Świnoujście, Hel and Gdynia stations: 64, 65 and 65%, respectively) as well as the area of the Northern Subcarpathians (with value recorded at the Sandomierz station—64%) are the least clouded are in the country. The largest degree of cloud coverage is observed in the mountainous areas—the Sudety Mts. and the Carpathians, yet the average annual total cloud cover in the Karkonosze Mts. (the highest range in Sudety Mts.) is higher than in the Tatra Mts. (culmination of the Carpathians). The average annual total cloud cover at the top of Śnieżka Mountain in the Karkonosze Mts. reached almost 76%, while at Kasprowy Wierch it was 73%. Although cloudiness is predominantly dependent on the macro-scale situation (Ustrnul and Niedźwiedź 1994), there are a number of local factors affecting the forming clouds in the mountains (Trepińska 2002; Szyga-Pluta 2017). Among these, intensive dynamic and thermal turbulence can be listed as well the local convection

Table 10.1 Relation between coding of CL, CM or CH clouds as reported in synoptic reports and corresponding cloud genera reported in journals of synoptic observations[a]

Code of cloud reported in synoptic report		Corresponding cloud genus reported in journal of synoptic observations
C_L	1	*Cumulus*
	2	*Cumulus*, *Stratocumulus* (20% of cases)
	3	*Cumulonimbus*, *Cumulus* (75% of cases), *Stratocumulus* (50% of cases), *Stratus* (20% of cases)
	4	*Stratocumulus*
	5	*Stratocumulus*, *Stratus* (25% of cases)
	6	*Stratus*
	7	*Stratus*
	8	*Cumulus*, *Stratocumulus*
	9	*Cumulonimbus*, *Cumulus* (50% of cases), *Stratocumulus* (50% of cases), *Stratus* (10% of cases)
C_M	1	*Altostratus*
	2	*Nimbostratus* (80% of cases), *Altostratus* (20% of cases)
	3	*Altocumulus*
	4	*Altocumulus*
	5	*Altocumulus*
	6	*Altocumulus*
	7	*Altocumulus*, *Altostratus* (90% of cases)
	8	*Altocumulus*
	9	*Altocumulus*
C_H	1	*Cirrus*
	2	*Cirrus*
	3	*Cirrus*
	4	*Cirrus*
	5	*Cirrostratus*, *Cirrus* (75% of cases)
	6	*Cirrostratus*, *Cirrus* (75% of cases)
	7	*Cirrostratus*
	8	*Cirrostratus*, *Cirrus* (50% of cases), *Cirrocumulus* (10% of cases)
	9	*Cirrocumulus*, *Cirrostratus* (25% of cases), *Cirrus* (25% of cases)

[a]Numbers in parentheses indicate the percentage of cases when particular genera of clouds occur in relevant situation of coding. Lack of information in parentheses means that particular cloud occurs in each individual case

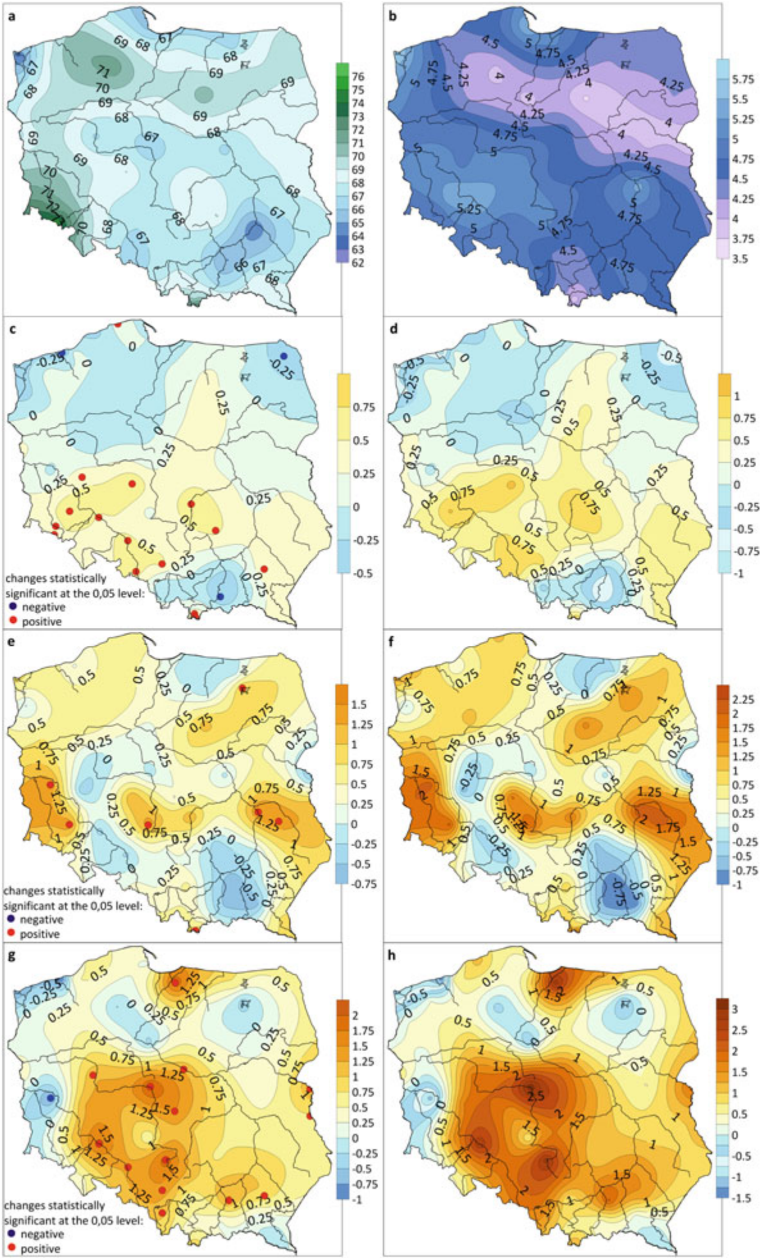

Fig. 10.1 Variability and change of annual total cloudiness: mean values (1951–2018; %; **a**), coefficient of variability (%; **b**), absolute trend for the whole period (1951–2018; %/10y; **c**), relative trend for the whole period (%/10y; **d**), absolute trend for the first half of the period (1951–1984; %/10y; **e**), relative trend for the first half of the period (%/10y; **f**), absolute trend for the second half of the period (1985–2018; %/10y; **g**), relative trend for the second half of the period (%/10y; **h**). Statistically significant (0.05) trends were shown in (**c**, **e**, **g**) as circles

movements. Cloud condensation level depends also on the vertical profile of water vapour.

Overall, total cloud cover in western Poland is greater than in the central and eastern parts of the country. A slightly higher level of cloudiness is also observed within the longitudinal belt stretching from the Sudety Mts., through the eastern part of the Central Poland Lowlands and Southern Baltic Lake Districts, and reaching the central part of the Southern Baltic Coastlands region. In the Lakelands, cloud cover exceeds 70% (at Chojnice station, it is 72%). Western Poland is more frequently, in comparison with other parts of the country, affected by the humid polar maritime air masses from the Atlantic Ocean. Their advection results in an increase in cloudiness, no matter the season.

It is also worth emphasising that the eastern part of the Lakelands region is characterised by higher degree of cloudiness than the neighbouring areas (slightly above 70% at Mława station or nearly 70% in Suwałki). The increased total cloud cover over the Polish lake districts correspond with the varied relief of this part of Poland, which in turn may be considered as an important factor fostering development of cloud coverage.

In the Polish Uplands region and in the eastern part of the Lowlands, cloud levels are below 70%, usually between 67 and 68%.

The average annual cloudiness in the Lakelands varies the least—the coefficient of variation at some stations does not exceed 4% (Fig. 10.1b). A similar stable situation is observed in the Tatra Mts. In the Uplands, the values of the coefficient reaches approximately 5%, and it systematically increases towards the west, finally exceeding 5%. Within the Coastlands, where the average annual total cloud cover is the lowest, the coefficient of variation comes to nearly 6%.

In a substantial part of the territory of Poland during the period of 1951–2018, there were no significant variations in cloudiness observed (Fig. 10.1c). However, in the north, a negative tendency in cloudiness predominates, while in the south—it is positive, with the exception of the Subcarpathians and Carpathians and excluding the Tatra Mts. Some statistically significant changes in total cloud cover were recorded in several dozen cases with domination of series presenting the positive trend in case of stations located in the southern part of Poland. Kalisz is the station at which the cloud cover develops at the fastest pace of 0.7%/10y. All in all, cloudiness decreased significantly only at three Polish stations (Kołobrzeg in the Coastlands, Suwałki in the Lakelands and Tarnów in Subcarpathians). The location of these stations seems to be random, therefore it suggests the impact of local factors. Spatial diversity in the relative trend (Fig. 10.1d) confirms the domination of positive tendencies in the development of annual total cloud cover in Poland.

The maximum of the average annual total cloud cover in Poland equalled 73% and was observed in 1966 (Table 10.2). At particular stations, the occurrence of maximum values was differentiated. It was observed most frequently in 1966 (11 stations, mostly in the northern part of Poland), 1980 (8 stations in eastern and southeastern Poland), 2013 (9 stations in central, southern and western parts of the country) and 2017 (6 stations located in central Poland). The cloudiest sky was in 2001 on Śnieżka Mt. (81%).

Table 10.2 Highest and lowest values of mean annual cloudiness [%] at stations taken into consideration (1951–2018)

Station	Highest		Lowest	
	Value	Year	Value	Year
Białystok	76.1	1980	62.3	1969
Bielsko-Biała	73.4	1952	59.8	1982
Chojnice	78.5	1966	65.8	1982
Częstochowa[a]	72.9	1952	55.8	1982
Elbląg	76.6	1962	60.7	1992
Gdynia[a]	73.3	1977	56.3	1982
Gorzów Wlkp.	77.4	1966	61.0	1982
Hel	71.9	1966	57.8	1989
Jabłonka[a]	72.6	1970	60.1	1982
Jelenia Góra	77.6	2013	62.6	1953
Kalisz	75.9	2013	60.8	1982
Kasprowy Wierch	78.8	2004	62.4	1953
Katowice	73.4	2016	58.6	1982
Kętrzyn[a]	72.8	2013	59.1	1982
Kielce	74.9	2013	59.0	1982
Kłodzko	76.5	2013	60.7	1982
Koło[a]	73.7	2013	57.8	1982
Kołobrzeg	74.6	1966	60.6	2018
Koszalin	76.8	1966	61.4	1982
Kraków Balice	71.0	1980	58.3	1982
Krosno[a]	77.7	1966	60.2	1982
Legnica[a]	78.9	2001	58.2	1953
Lesko[a]	74.8	1970	58.8	1982
Leszno[a]	76.8	2001	59.3	1982
Lublin	77.3	1980	59.0	1982
Łeba	74.3	1977	59.9	1953
Łódź	74.8	2017	59.1	1982
Mikołajki[a]	74.4	2017	60.6	1953
Mława[a]	75.4	2017	64.1	1964
Nowy Sącz[a]	72.8	1958	59.8	1982
Olsztyn[a]	73.1	1966	61.4	1982
Opole	74.5	2001	59.9	1982
Piła[a]	73.8	2001	61.4	1982
Płock[a]	74.1	1952	61.8	1956

(continued)

Table 10.2 (continued)

Station	Highest		Lowest	
	Value	Year	Value	Year
Poznań	74.0	2017	56.7	1982
Puławy	76.9	1980	58.4	1953
Racibórz[a]	71.9	2010	56.8	1982
Resko[a]	77.3	1977	61.9	2003
Rzeszów[a]	72.3	1980	56.8	1982
Sandomierz[a]	70.9	1980	56.1	1982
Siedlce	74.3	1980	62.1	1964
Słubice[a]	75.9	2013	59.8	1982
Sulejów[a]	75.0	2013	60.3	1982
Suwałki	76.6	1966	63.5	1951
Szczecin	74.2	1966	58.8	1992
Śnieżka	81.0	2001	66.0	1959
Świnoujście	72.7	1966	55.7	1982
Tarnów[a]	71.2	1958	56.4	1982
Terespol[a]	74.7	2017	61.8	1982
Toruń	74.3	1952	62.7	1982
Ustka	72.5	1966	59.3	1982
Warszawa	70.9	2017	57.8	1982
Wieluń[a]	75.1	1981	60.0	1953
Włodawa	76.5	1980	59.0	1953
Wrocław	75.1	2013	55.5	1982
Zakopane	74.6	2014	63.0	1982
Zielona Góra	75.9	1981	61.4	1953
Poland	73.0	1966	60.7	1982

[a]Period shorter than 1951–2018 (see details in Chap. 3 *Data and Methods of investigation*)

The minimum annual cloudiness, equalling 60.7%, was recorded in Poland in 1982 (Table 10.2). This year was characterised by very low value of cloud cover in the majority of stations in the country (37 stations of 56 analysed). In addition, very low value of cloud cover occurred also in 1953. The least cloudy sky was in 1982 in Wrocław (55.5%).

Periods of lower cloudiness levels were observed during the first half of the 1970s and at the turn of the 1980s and 1990s (Fig. 10.2). In fact, in the Coastlands, the minimum recorded at the turn of the 1980s and 1990s was even lower than in 1982. The sky over Poland was covered with the thickest layer of clouds at the beginning of the 1960s, in the second half of the 1970s and at the end of the twentieth century.

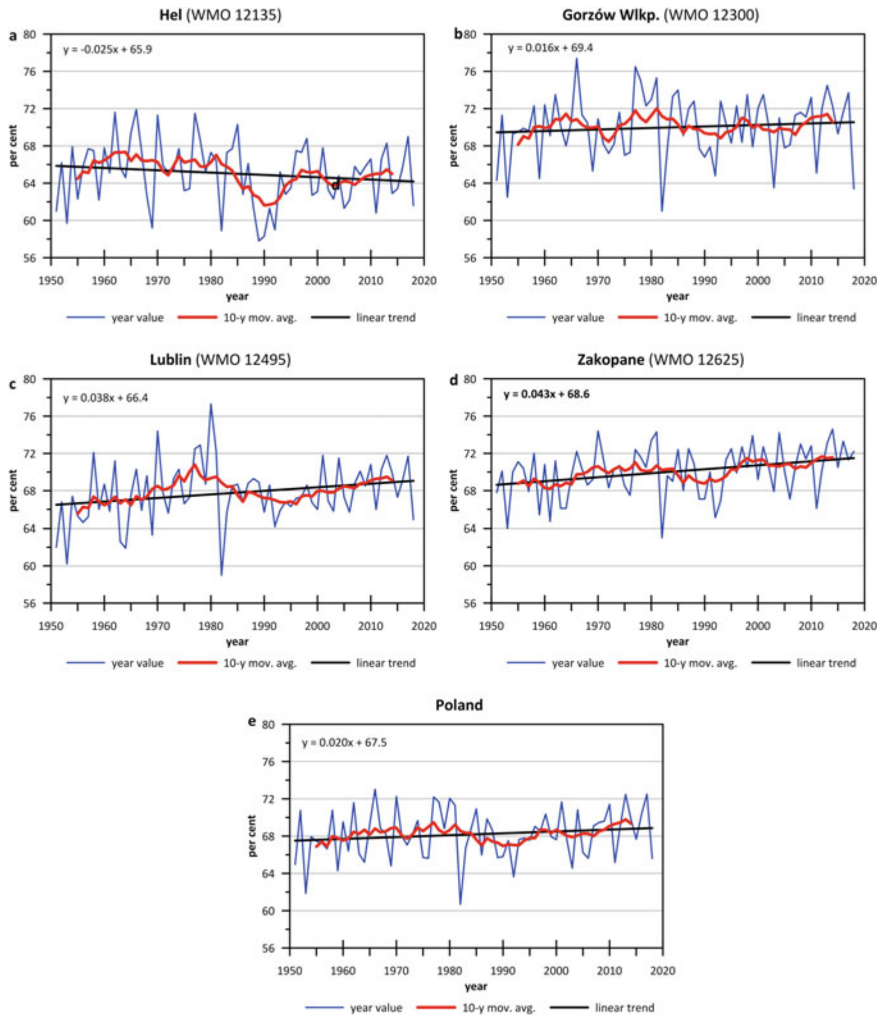

Fig. 10.2 Long-term variability of annual total cloudiness in the selected stations of: northern Poland (station Hel; 1951–2018; **a**), western Poland (station Gorzów Wlkp.; 1951–2018; **b**), eastern Poland (station Lublin; 1951–2018; **c**), southern Poland (station Zakopane; 1951–2018; **d**) and in Poland as a whole (the average, **e**). Mean annual value (*blue*), 10-year consecutive average (*red*) and line trend (*black*) are shown. The trend is statistically significant (0.05, in *bold*) in (**d**) and not significant in (**a**–**c**)

The last period of increased cloudiness began at the end of the first decade of the twenty-first century.

Temporal variability of cloudiness in Poland underwent a noticeable change in the analysed period. During the subperiod of 1951–1984, a statistically significant increase in cloudiness was observed at a relatively small number of stations (seven stations), mainly in the peripheral areas of the country (Fig. 10.1e). The increase of cloud cover was observed particularly in two pairs of stations—one located in western Poland (Legnica and Zielona Góra) and the second one in eastern Poland (Puławy and Lublin). During the later subperiod—in the years 1985–2018—the increase in cloudiness was already observed at a greater number of stations and, what is the most important, intensified and emerged as statistically significant at twice as many stations than in the previous subperiod (Fig. 10.1g). Positive trends are noticeable particularly at the stations located in the central and southern parts of the country. The values of relative trends revealed that cloudiness developed most intensively in Elbląg, Koło, Wrocław and Częstochowa, while areas with decreasing cloud cover were still in decline during the period of 1985–2018. Therefore, it can be stated that atmospheric conditions fostering cloudiness development were observed over the majority of Poland's territory. However, though the negative trends were not observed during the first subperiod, in the second they were recorded at one station (Zielona Góra, where in the years 1951–1984 cloudiness increased).

Winter is the season characterised by the highest value of total cloud cover (Fig. 10.3a). The average winter cloudiness in Poland reaches 75.7%. The values of total cloud cover decrease from north and northeast to the south. An exceptionally high level of cloudiness is observed over the Lakelands, especially those located in northeastern Poland. There, the level of cloudiness reaches approximately 80%. The lowest level of cloudiness, approximately 70%, is observed over the Carpathian Foreland and Carpathian basins (Zakopane, Nowy Sącz). Similarly, a relatively low level of cloudiness is observed in the Karkonosze Mountain Basins (Jelenia Góra station, located in a basin).

The coefficient of variation in winter is higher than the annual one. Its values increase towards the south, running almost parallel in the southern part of the country (Fig. 10.3b). The cloudiness varies the least in the lakeland areas of western Poland and in the central coast. In the Tatra Mts. the coefficient of variation is almost twice as high.

Largely, winter cloudiness gradually increases at the majority of considered stations (Fig. 10.3c, d). It is statistically significant at five stations located mostly in the southern part of the country (the western part of the Lowlands and the Uplands). Negative tendencies characterise the coastal region, the Lakelands in the northeastern part of Poland and the Subcarpathians. However, a statistically important decrease in cloudiness was recorded only in Kołobrzeg in the Coastlands.

While analysing the long-term variability of values of average winter cloudiness, a minimum is clearly visible in all data series recorded at the beginning of the 1990s (selected examples presented in Fig. 10.4). At particular stations it was 1990–1991 or 1993. In some cases, especially at stations located in the Lakelands, the reduced cloudiness was observed until the end of the twentieth century and at the very beginning of the twenty-first century as well. Lower levels of cloudiness were also observed in the 1970s, yet this anomaly was visible mainly at the southern stations. At the upland stations deep minimums and periods with high levels of cloudiness were observed alternately in the 1960s. At the Lakeland stations, the lowest cloudiness level was observed during the winters of 1954 and 2003. The level of cloudiness

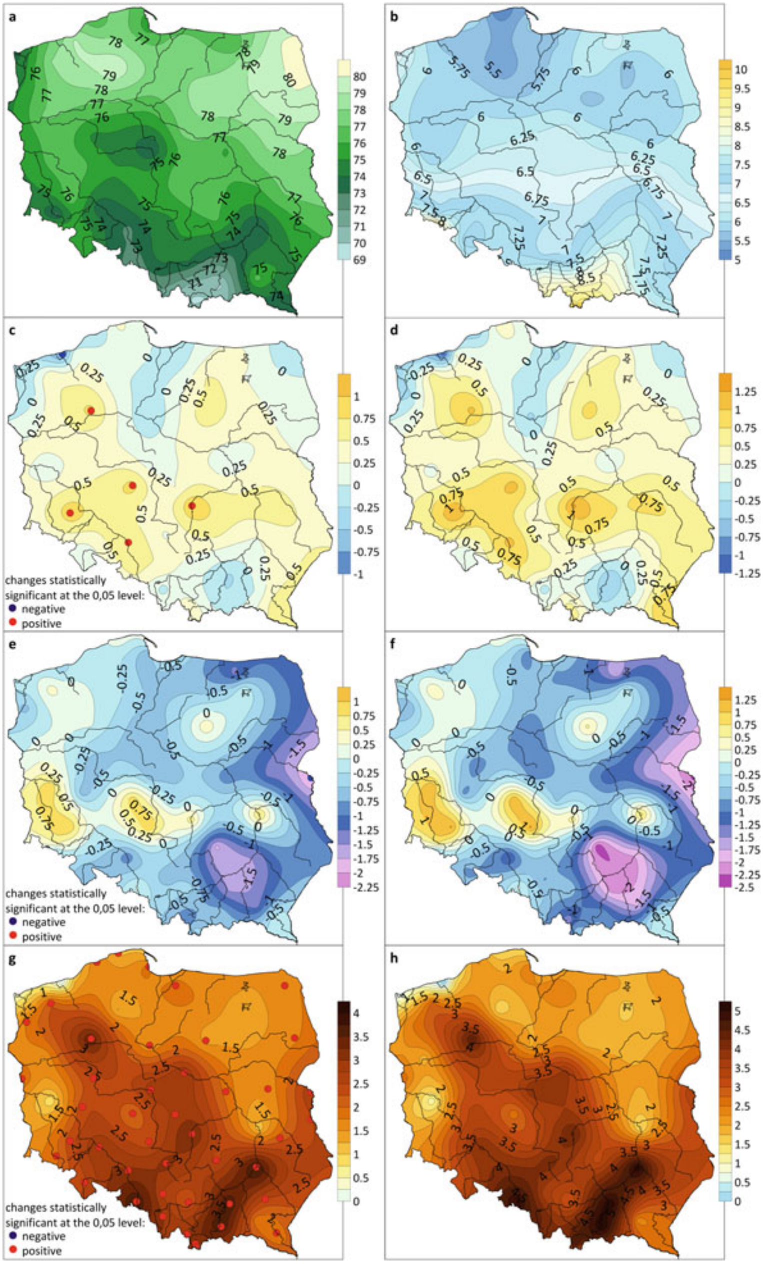

Fig. 10.3 Variability and change of total winter cloudiness: mean values (1951–2018; %; **a**), coefficient of variability (%; **b**), absolute trend for the whole period (1951–2018; %/10y; **c**), relative trend for the whole period (%/10y; **d**), absolute trend for the first half of the period (1951–1984; %/10y; **e**), relative trend for the first half of the period (%/10y; **f**), absolute trend for the second half of the period (1985–2018; %/10y; **g**), relative trend for the second half of the period (%/10y; **h**). Statistically significant (0.05) trends were shown in (**c**, **e**, **g**) as circles

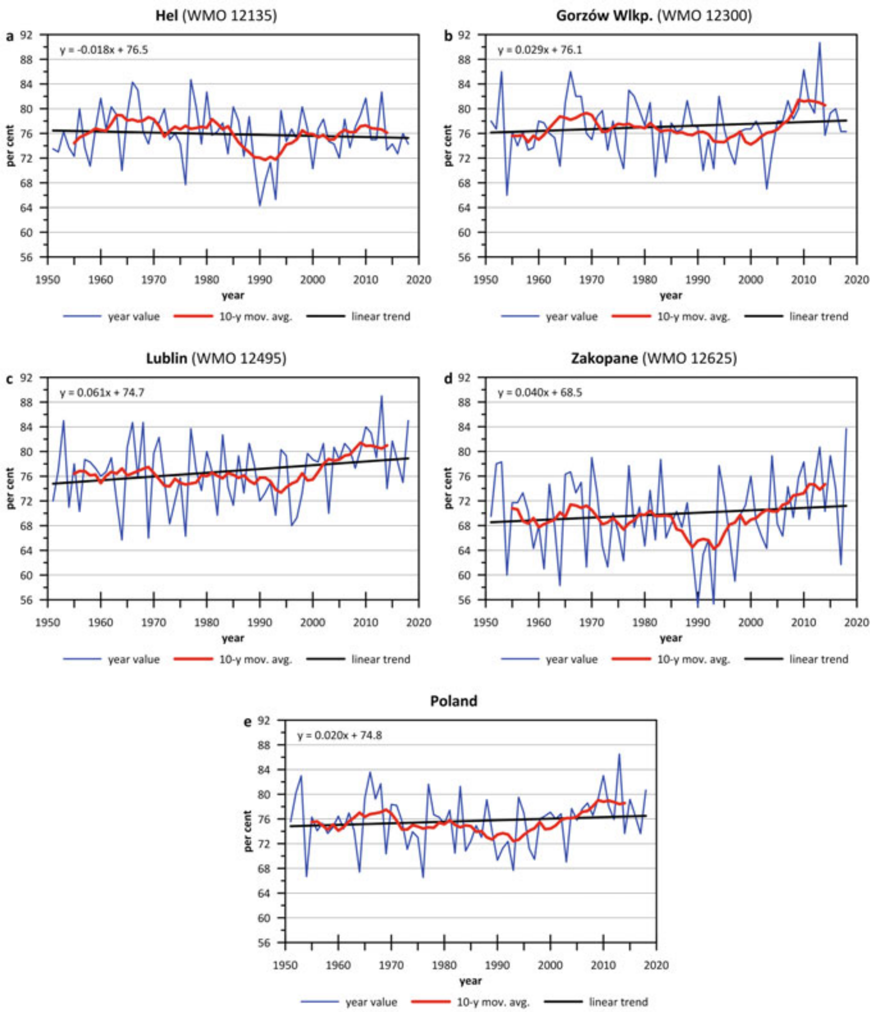

Fig. 10.4 Long-term variability of total winter cloudiness in the selected stations of: northern Poland (station Hel; 1951–2018; **a**), western Poland (station Gorzów Wlkp.; 1951–2018; **b**), eastern Poland (station Lublin; 1951–2018; **c**), southern Poland (station Zakopane; 1951–2018; **d**) and in Poland as a whole (the average, **e**). Mean seasonal value (*blue*), 10-year consecutive average (*red*) and line trend (*black*) were shown. The trend is statistically not significant (0.05) in (**a**–**d**)

visibly increased in the 1960s and this positive anomaly lasted for a decade. Another period of increased cloudiness started at the beginning of the present century and lasted until the end of the research period.

The highest winter cloudiness level in Poland occurred in 2013, when its value reached 86.5% (Table 10.3). At particular analysed stations it was most frequently also in 2013 (35 stations), 1953 (eight stations) and 1977 (four stations). At the

Table 10.3 Highest and lowest values of mean seasonal cloudiness [%] at stations taken into consideration (1951–2018)

Station	Winter				Spring				Summer				Autumn			
	Highest		Lowest		Highest		Lowest		Highest		Lowest		Highest		Lowest	
	Value	Year	Value	Year	Value	Year	Value	Year	Value	Year	Value	Year	Value	Year	Value	Year
Białystok	88.3	1955	65.7	1976	88.3	1955	65.7	1976	88.3	1955	65.7	1976	88.3	1955	65.7	1976
Bielsko-Biała	86.3	2013	58.3	1990	86.3	2013	58.3	1990	86.3	2013	58.3	1990	86.3	2013	58.3	1990
Chojnice	88.3	2013	69.7	1976	88.3	2013	69.7	1976	88.3	2013	69.7	1976	88.3	2013	69.7	1976
Częstochowa[a]	87.3	2013	63.7	1954	87.3	2013	63.7	1954	87.3	2013	63.7	1954	87.3	2013	63.7	1954
Elbląg	86.3	1977	67.0	1976	86.3	1977	67.0	1976	86.3	1977	67.0	1976	86.3	1977	67.0	1976
Gdynia[a]	85.5	2013	64.4	1976	85.5	2013	64.4	1976	85.5	2013	64.4	1976	85.5	2013	64.4	1976
Gorzów Wlkp.	90.7	2013	66.0	1954	90.7	2013	66.0	1954	90.7	2013	66.0	1954	90.7	2013	66.0	1954
Hel	84.7	1977	64.3	1990	84.7	1977	64.3	1990	84.7	1977	64.3	1990	84.7	1977	64.3	1990
Jabłonka[a]	84.3	1970	54.3	1990	84.3	1970	54.3	1990	84.3	1970	54.3	1990	84.3	1970	54.3	1990
Jelenia Góra	85.7	2013	58.7	1993	85.7	2013	58.7	1993	85.7	2013	58.7	1993	85.7	2013	58.7	1993
Kalisz	89.3	2013	63.3	1954	89.3	2013	63.3	1954	89.3	2013	63.3	1954	89.3	2013	63.3	1954
Kasprowy Wierch	80.3	2018	53.7	1964	80.3	2018	53.7	1964	80.3	2018	53.7	1964	80.3	2018	53.7	1964
Katowice	87.0	2013	63.7	1954,1990	87.0	2013	63.7	1954,1990	87.0	2013	63.7	1954,1990	87.0	2013	63.7	1954, 1990
Kętrzyn[a]	86.7	1988, 2013	61.3	1976	86.7	1988,2013	61.3	1976	86.7	1988,2013	61.3	1976	86.7	1988, 2013	61.3	1976
Kielce	88.8	2013	64.2	1976	88.8	2013	64.2	1976	88.8	2013	64.2	1976	88.8	2013	64.2	1976
Kłodzko	88.3	2013	62.7	1990	88.3	2013	62.7	1990	88.3	2013	62.7	1990	88.3	2013	62.7	1990
Koło[a]	87.3	2013	62.3	1996	87.3	2013	62.3	1996	87.3	2013	62.3	1996	87.3	2013	62.3	1996

(continued)

Table 10.3 (continued)

Station	Winter				Spring				Summer				Autumn			
	Highest		Lowest		Highest		Lowest		Highest		Lowest		Highest		Lowest	
	Value	Year	Value	Year	Value	Year	Value	Year	Value	Year	Value	Year	Value	Year	Value	Year
Kołobrzeg	86.7	1966	68.0	1976	86.7	1966	68.0	1976	86.7	1966	68.0	1976	86.7	1966	68.0	1976
Koszalin	89.4	2013	67.5	1976	89.4	2013	67.5	1976	89.4	2013	67.5	1976	89.4	2013	67.5	1976
Kraków Balice	86.3	1953	60.0	1990	86.3	1953	60.0	1990	86.3	1953	60.0	1990	86.3	1953	60.0	1990
Krosno[a]	88.1	1967	65.0	1990	88.1	1967	65.0	1990	88.1	1967	65.0	1990	88.1	1967	65.0	1990
Legnica[a]	88.7	2013	61.7	1954	88.7	2013	61.7	1954	88.7	2013	61.7	1954	88.7	2013	61.7	1954
Lesko[a]	84.7	1968	63.0	1976	84.7	1968	63.0	1976	84.7	1968	63.0	1976	84.7	1968	63.0	1976
Leszno[a]	87.9	2013	64.0	1984	87.9	2013	64.0	1984	87.9	2013	64.0	1984	87.9	2013	64.0	1984
Lublin	89.0	2013	65.7	1964	89.0	2013	65.7	1964	89.0	2013	65.7	1964	89.0	2013	65.7	1964
Łeba	88.7	2013	67.3	1954	88.7	2013	67.3	1954	88.7	2013	67.3	1954	88.7	2013	67.3	1954
Łódź	88.0	2013	66.3	1954	88.0	2013	66.3	1954	88.0	2013	66.3	1954	88.0	2013	66.3	1954
Mikołajki[a]	88.0	1988	65.0	1976	88.0	1988	65.0	1976	88.0	1988	65.0	1976	88.0	1988	65.0	1976
Mława[a]	87.0	1977	66.3	1976	87.0	1977	66.3	1976	87.0	1977	66.3	1976	87.0	1977	66.3	1976
Nowy Sącz[a]	85.3	2013	56.3	1990	76.7	1958, 1966	58.0	2000	74.3	1980	49.7	1992	76.3	1996	51.7	2011
Olsztyn[a]	88.3	2013	63.7	1976	75.3	1970	50.0	1953	72.2	1961	47.7	1992	84.2	1952	57.9	1951
Opole	88.0	2013	60.7	1954	75.0	2013	49.0	1953	71.8	1980	53.1	1973	84.6	1952	55.4	1982
Piła[a]	90.3	2013	68.3	1976	72.7	1983	54.3	2011	74.0	1980	50.0	1983	82.7	1978	57.3	2005

(continued)

Table 10.3 (continued)

Station	Winter				Spring				Summer				Autumn			
	Highest		Lowest		Highest		Lowest		Highest		Lowest		Highest		Lowest	
	Value	Year	Value	Year	Value	Year	Value	Year	Value	Year	Value	Year	Value	Year	Value	Year
Płock[a]	87.7	1953	65.7	1976	76.3	1970	54.3	1953	73.3	1980	46.3	1992	88.0	1952	57.3	1953
Poznań	88.7	2013	64.3	1954	73.7	1958	47.7	1953	74.7	1980	46.3	1983	83.3	1952	53.0	2005
Puławy	89.9	1977	63.3	1954	78.6	1958	47.1	1953	74.1	1977	46.8	1992	87.1	1952	50.6	1953
Racibórz[a]	85.3	2013	60.7	1964	73.7	1991	46.0	1953	72.3	1980	47.3	1983	78.7	1952	50.3	1982
Resko[a]	88.3	2013	67.3	1954	79.0	1970	54.3	1953,2007	76.3	1980	53.7	1983	85.1	1952	51.0	2005
Rzeszów[a]	87.0	1953	62.3	1976	75.0	1970	53.3	1953	71.0	1980	48.0	1992	78.0	1952	50.7	1982
Sandomierz[a]	87.0	1953	59.7	1976	71.7	2013	49.3	1953	73.8	1980	46.1	1971	80.0	1952	48.3	1982
Siedlce	88.3	2013	63.7	1976	77.0	1970	50.3	1953	77.7	1980	45.3	1992	86.0	1952	57.3	1953
Słubice[a]	88.7	2013	64.3	1954	77.0	2013	49.9	1953	72.0	1977	52.0	1983	82.9	1952	51.0	2005
Sulejów[a]	88.0	2013	62.0	1964	75.0	1970	57.4	1963	75.3	1980	51.3	1992	79.0	1996	55.0	1982
Suwałki	88.3	1967	65.0	1976	79.7	1966	51.3	1953	75.6	1980	45.0	1992	87.0	1952	60.7	2005
Szczecin	86.3	1953	65.3	1954	76.3	1970	48.3	1953	73.0	1987	48.0	1992	80.7	1952	56.3	2005
Śnieżka	88.0	1994	57.0	1964	86.0	1970	56.0	1953	83.3	1980	63.3	1983	90.3	1952	57.3	1959
Świnoujście	84.9	1953	61.5	1976	75.7	1970	46.1	1959	68.0	1987	43.3	2018	76.6	1976	53.6	2005
Tarnów[a]	88.2	1953	58.6	1990	73.5	1966	52.4	2000	71.9	1980	45.5	1992	79.8	1952	45.1	1982
Terespol[a]	88.7	2013	65.0	1976	75.7	1958	55.7	1986	76.7	1980	47.7	1992	83.7	2017	57.7	2011
Toruń	87.0	1953	67.0	1976	78.0	1970	51.3	1959	74.7	1980	49.3	1983	86.0	1952	55.3	2005
Ustka	87.7	2013	65.3	1954	78.3	1970	49.0	1990	67.3	1987	45.0	1992	82.0	1978	55.3	2005

(continued)

Table 10.3 (continued)

Station	Winter				Spring				Summer				Autumn			
	Highest		Lowest		Highest		Lowest		Highest		Lowest		Highest		Lowest	
	Value	Year	Value	Year	Value	Year	Value	Year	Value	Year	Value	Year	Value	Year	Value	Year
Warszawa	85.7	2013	65.3	1976	70.6	1962	47.9	1953	70.3	1980	44.7	1992	84.7	1952	52.7	1953
Wieluń[a]	89.0	2013	64.3	1954	76.0	1970,1977	47.0	1953	77.0	1980	49.7	1992	86.0	1952	52.3	1982
Włodawa	86.0	2013	66.0	1976	79.0	1970	46.3	1953	78.3	1980	45.7	1992	83.0	1952	56.3	2005
Wrocław	86.7	2013	60.7	1954	77.0	2013	48.0	1953	72.4	1980	49.7	1992	86.8	1952	51.5	1982
Zakopane	83.7	2018	55.0	1990	79.0	2017	55.7	1953	79.0	1980	55.0	1952	82.2	1952	53.3	2011
Zielona Góra	88.0	2013	63.7	1954	78.7	1983	49.9	1953	75.7	1980	53.3	1983	83.3	1952	52.3	2005
Poland	86.5	2013	66.6	1976	75.1	1970	50.4	1953	73.8	1980	50.5	1992	83.6	1952	57.2	1982

[a]Period shorter than 1951–2018 (see details in Chap. 3 *Data and Methods of investigation*)

remaining stations, the cloudiest sky in winter was observed in other years, i.e. in 1955, 1966 and 1967, 1970, 1988, 1994 and 2018. The highest total cloud cover at particular stations equalling 90.7% occurred in Gorzów Wlkp. in 2013.

The lowest total cloud cover in winter, 66.6%, in Poland occurred in 1976 (Table 10.3). At particular stations the years with the lowest cloudiness level in winter were: mentioned 1976 (23 stations), 1954 (17 stations) and 1990 (10 stations in the southern and southeastern part of the country). Furthermore, there were some additional years marked with very low levels of cloudiness: 1964 (minimum at five stations), 1984, 1993 and 1996. The clearest sky in winter occurred in 1964 at Kasprowy Wierch in the Tatra Mts; its value did not exceed 54% (53.7%). It should be underlined that the minima occurring in winter at stations located in mountains or mountain forelands were characterised by exceptionally low values, not exceeding 60% (e.g. Jabłonka and Zakopane—54.3 and 55%, respectively in 1990, Śnieżka Mt.—57% in 1964, Nowy Sącz—56.3% and Bielsko-Biała—58.3%, also in 1990, Jelenia Góra—58.7% in 1993). The minima recorded at the remaining stations did not drop below 60%, in the case of stations located in northern Poland these values were even close to 70%.

Both selected subperiods differ from each other in terms of sign of trend coefficients of cloudiness occurring in the country. During the first one, 1951–1984, decreases in the average seasonal cloudiness were common at stations all over Poland (Fig. 10.3e, f). The pace of decrease was higher than −1.5%/10y, and the value of the relative trend was even higher.

In the second analysed subperiod, 1985–2018, the trend completely reversed. At most stations, a strong, statistically significant increase in cloudiness was observed. The value of the trend increased towards the south, reaching 3%/10y at the Subcarpathian stations. The weakest observed changes were at the stations located along the western part of the Coastlands.

In spring, mean seasonal total cloud cover equals 65.7%, and cloudiness visibly decreases after the winter season, which is characterised by very high cloudiness levels (Fig. 10.5a). This change is the most apparent in the northern part of the country, where the cloudiness decreases from approximately 80% in winter to 65–67% in spring and even less in the coastal areas (Świnoujście and Hel—less than 60%, Ustka—61%, Łeba and Kołobrzeg—62%). In the Lakelands of northeastern Poland, which is usually mostly covered with a layer of clouds in winter in comparison with the rest of the country, clouds cover less than 65% of the sky in spring. Springs are also quite sunny in the Lowland area of central Poland. There the level of cloudiness is also less than 65% in spring. Both the Lowlands and Lakelands, located in the west, are characterised by the cloudiness reaching approximately 66–68%. In the Uplands, the total cloud cover is similar. In the Subcarpathian region, cloudiness drops to less than 65%, while in the mountains it is considerably higher. In the highest parts of the mountains—the Karkonosze Mts. and the Tatra Mts.—clouds cover more than 75% of the sky.

Spring variation of the cloudiness is also higher than in the winter (Fig. 10.5b). In the coastal areas and in the Lakelands of northeastern Poland, values of the coefficient of variation reach 9–10% and then slightly drop towards the south. The variability

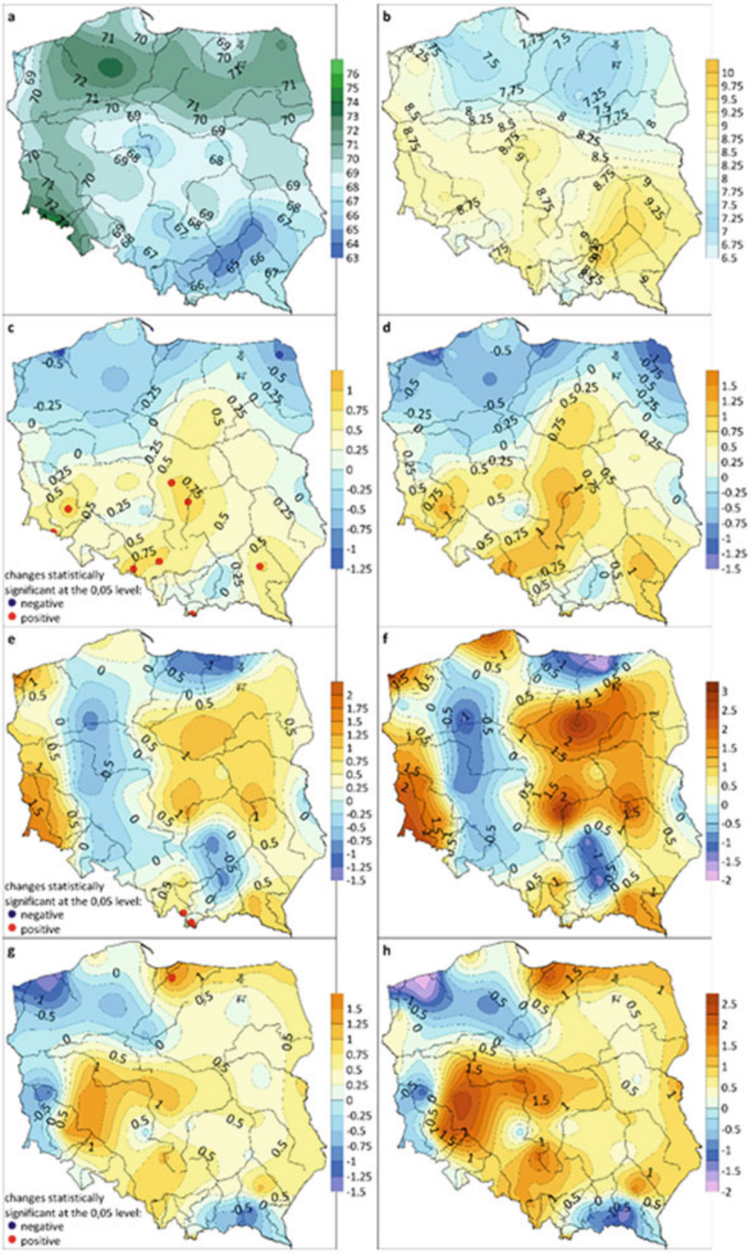

Fig. 10.5 Variability and change of total spring cloudiness: mean values (1951–2018; %; **a**), coefficient of variability (%; **b**), absolute trend for the whole period (1951–2018; %/10y; **c**), relative trend for the whole period (%/10y; **d**), absolute trend for the first half of the period (1951–1984; %/10y; **e**), relative trend for the first half of the period (%/10y; **f**), absolute trend for the second half of the period (1985–2018; %/10y; **g**), relative trend for the second half of the period (%/10y; **h**). Statistically significant (0.05) trends were shown in (**c**, **e**, **g**) as circles

is higher in the Lakelands and Lowlands of the western part of Poland and in the Upland areas in the east. In the submountainous areas and in the mountains, the cloud cover again varies slightly less.

By and large, there are not many stations in Poland which experienced statistically significant changes in spring cloudiness in the period 1951–2018 (Fig. 10.5c). In the Lowland areas of western Poland, the value of cloudiness rose; statistically significant values were recorded in Legnica and Kalisz. In the Subcarpathian region and in the Outer Western Carpathians (Beskidy Mts.), the cloudiness systematically decreased, which has been proved by the negatives values of the trend coefficient for stations in Tarnów and Nowy Sącz. In the remaining area of Poland—in the central and northern parts of the country—changes were insignificant, mostly negative and do not exceed 0.5%/10y. The strongest relative trend characterised the previously mentioned data series recorded in Nowy Sącz (approx. −1.5%) (Fig. 10.5d).

The beginning of the 1950s was particularly clear, especially the spring of 1953 when the absolute minimum cloudiness was recorded across the country (Fig. 10.6). After that, the value of total cloud cover gradually began increasing. From the 1960s to the very beginning of the 1980s, a clear positive anomaly in spring cloudiness was observed. At the turn of the 1980s and 1990s, the cloud coverage level did not change considerably. Then, in the north, a decrease in the average seasonal cloudiness was recorded. Subsequently, at the end of the last century, its value started to grow, and during the first decade of the twenty-first century, the average seasonal cloudiness dropped again. In the south, the turn of the centuries brought a negative anomaly of the element value, and, in the last few years of the research period, a slight increase in the cloud coverage was observed.

The cloudiest sky in spring in Poland, amounting to 75.1%, occurred in 1970 (Table 10.3). The minimum at particular stations was observed irregularly, however at many of them (23 stations) it was recorded in 1970. At nine stations, the minimum of spring cloudiness was observed in 1958, at another four in 1962 and at five in 1966. Additionally, the very low values of cloudiness were also recorded at the remaining stations in 1977, 1983, 1991, 2013 and 2017. The aforementioned minimum in spring cloudiness in Poland in 1953 was only 50.4% (Table 10.3). This absolute minimum was reflected in the course of series of 40 stations. The lowest cloudiness among all stations, equalling 44.8%, was then observed in Gdynia. At other stations the minimum cloudiness occurred in 1959, 1963 and 1974. In the Bieszczady Mts. (southeastern Poland), the lowest level of cloudiness was observed in 1982. At several individual stations, minima occurred at the turn of the century (at two stations in 2000) and in the twenty-first century (2007 and 2011).

Positive oscillation in the cloudiness of the 1960s resulted in the existence of strong positive trends throughout the country (Fig. 10.5e, f). More than ten stations recorded a statistically significant change in cloudiness in the period of 1951–1984, including the highest growths—approx. 3%/10y—recorded in the eastern Uplands. Although the observed trends in the south were stronger than in the north, there were a few stations in the Subcarpathian region at which slight decreases in the cloudiness were observed.

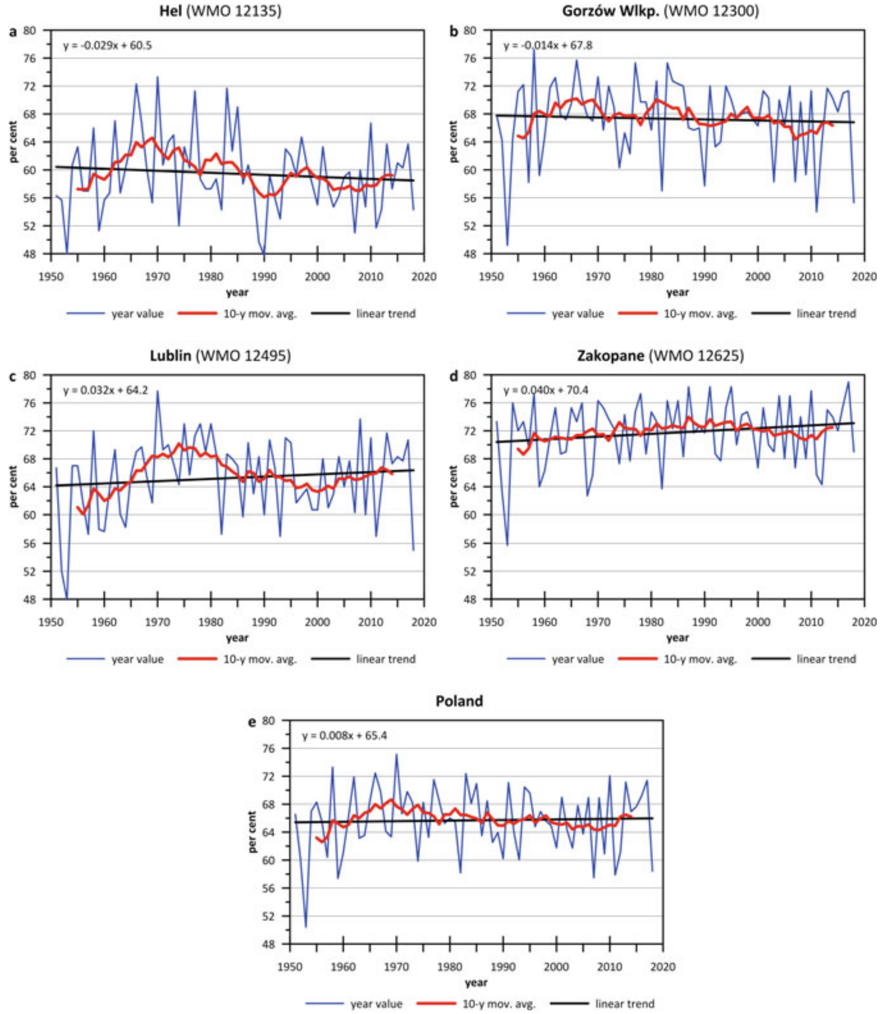

Fig. 10.6 Long-term variability of total spring cloudiness in the selected stations of: northern Poland (station Hel; 1951–2018; **a**), western Poland (station Gorzów Wlkp.; 1951–2018; **b**), eastern Poland (station Lublin; 1951–2018; **c**), southern Poland (station Zakopane; 1951–2018; **d**) and in Poland as a whole (the average, **e**). Mean seasonal value (*blue*), 10-year consecutive average (*red*) and line trend (*black*) were shown. The trend is not statistically significant (0.05) in (**a**–**d**)

In the subperiod of 1985–2018, the cloud coverage underwent changes in the opposite direction (Fig. 10.5g, h). In the northern and western regions, the cloudiness started to decrease and the station in Kętrzyn recorded statistically significant growth. A higher drop was observed in the whole Carpathian region along with the submountainous areas, and the decrease in cloudiness was even higher in Krosno than in the north. Some insignificant increases were observed in the central areas of

Lowlands. At the station located in Elbląg (northern Poland) the increase in cloudiness was extremely high during the analysed period, possibly due to the relocation of the station in the beginning of the second decade of the current century (the exposure of the station rose more than 100 m above sea level compared with the former location).

In comparison to spring, cloudiness in Poland continues to decrease in summer (Fig. 10.7a), even in the mountains where it has reduced by 2–3%. Less than 60% of the summer sky over the coastal areas is covered by clouds: 55% in Świnoujście, 56% in Hel and 58% in Gdynia and Ustka. There is a visible difference between the value of total summer cloud cover over the east and west parts of Poland; usually it is higher by 5% in the west. There is also a belt of low cloudiness across the Subcarpathian region and the Uplands of eastern Poland, along the Vistula River—the average cloudiness does not exceed 60% there; in Sandomierz it drops to 58%.

Summer is the season with the least average cloudiness, equalling 62.1%, and with the highest total cloudiness variability (Fig. 10.7b) when comparing to the other seasons. The coefficient of variation in the north exceeds 10%, which indicates great dynamics of cloud conditions. However, the value decreases towards the south reaching 6–7% in the submountainous areas and less than 6% at Zakopane station, located at the foot of the Tatra Mts. High values of the coefficient of variation were also observed in Uplands of the eastern areas of the country.

The only statistically significant changes in the summer cloudiness during the period of 1951–2018 were observed at a few stations in the south of Poland (Fig. 10.7c). An interesting situation can be observed in the mountains. In the Tatra Mts. and the Sudety Mts., cloudiness increased systematically, while at stations located in the lower parts of the mountains, in the Outer Western Carpathians (Beskidy Mts.), the cloudiness gradually decreased. However, when compared to the previously described season, in summer there are more regions where a positive tendency in cloudiness development over the long-term period of research can be observed. Taking the decrease of the average seasonal cloudiness into consideration, the relative trend is higher in summer than in spring; it exceeds 1% in the southern belt and in the northernmost edge of the country (Fig. 10.7d).

When analysing the whole long-term period 1951–2018, some significant year-to-year anomalies in total summer cloudiness are observed (Fig. 10.8). Most of the analysed data series are characterised by the existence of alternate positive and negative anomalies of cloudiness value. Total cloud cover increased at the turn of the 1950s and 1960s as well as at the turn of the 1970s and 1980s, at the end of the last century and the beginning of the present one. In 1980, clearly visible cloudiness maximums were observed at most of the stations throughout the country. However, it is noticeable that it is not observed for the data series gathered at the stations located in the north. In the case of coastal stations, the highest cloudiness was recorded in 1987 as well as in 1961 and 1963. A period of decreased cloudiness was observed in the whole country in the last decade of the twentieth century. This was the period when most stations recorded minimum cloudiness levels (1992). The former negative oscillation of cloudiness in northern Poland was observed at the turn of the 1960s and 1970s, while in the south it had been observed a few years earlier. The last several

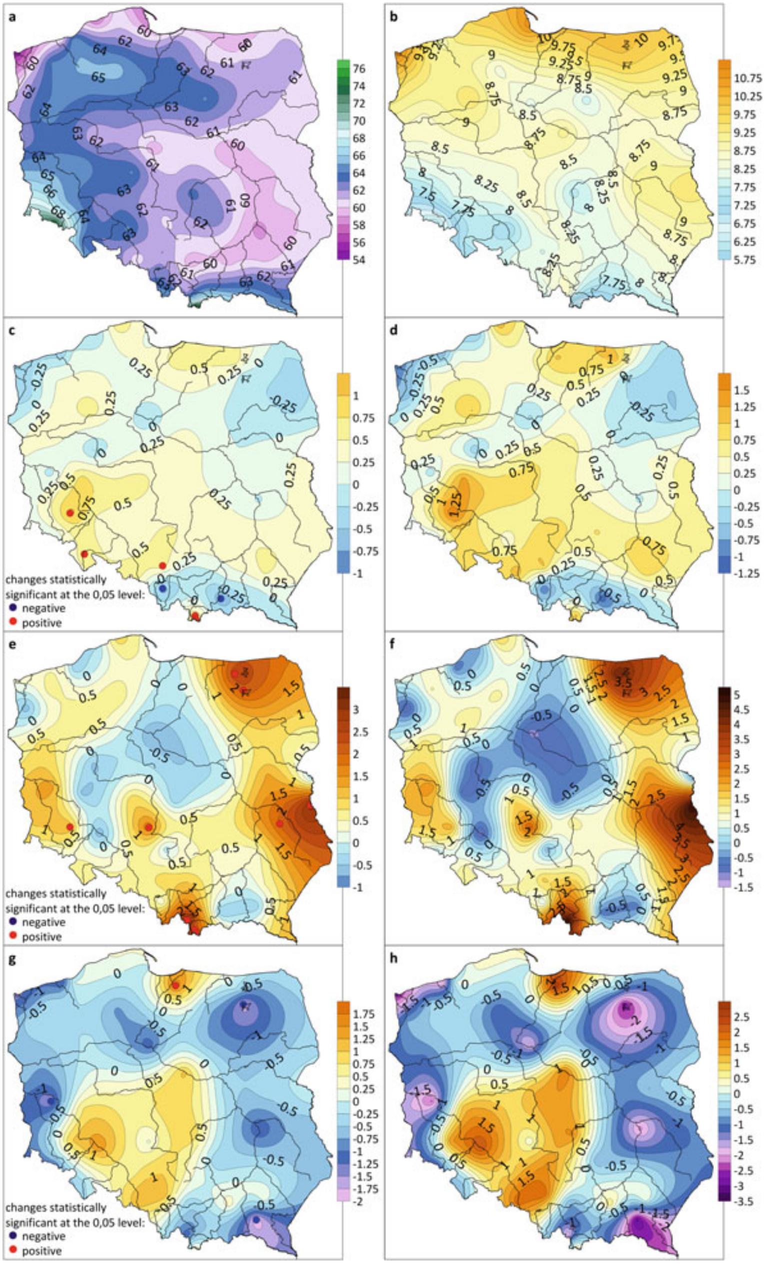

Fig. 10.7 Variability and change of summer total cloudiness: mean values (1951–2018; %; **a**), coefficient of variability (%; **b**), absolute trend for the whole period (1951–2018; %/10y; **c**), relative trend for the whole period (%/10y; **d**), absolute trend for the first half of the period (1951–1984; %/10y; **e**), relative trend for the first half of the period (%/10y; **f**), absolute trend for the second half of the period (1985–2018; %/10y; **g**), relative trend for the second half of the period (%/10y; **h**). Statistically significant (0.05) trends were shown in (**c**, **e**, **g**) as circles

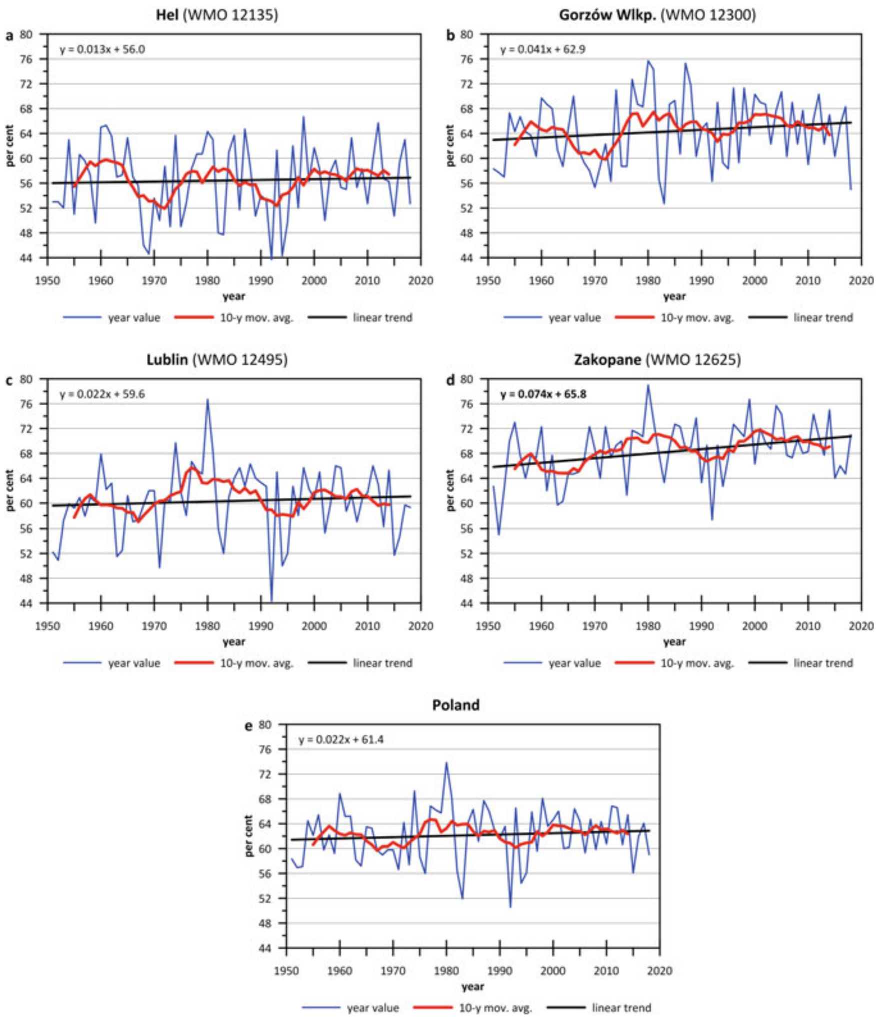

Fig. 10.8 Long-term variability of total summer cloudiness in the selected stations of: northern Poland (station Hel; 1951–2018; **a**), western Poland (station Gorzów Wlkp.; 1951–2018; **b**), eastern Poland (station Lublin; 1951–2018; **c**), southern Poland (station Zakopane; 1951–2018; **d**) and in Poland as a whole (the average, **e**). Mean seasonal value (*blue*), 10-year consecutive average (*red*) and line trend (*black*) were shown. The trend is statistically significant (0.05, in *bold*) in (**d**) and not significant in (**a**–**c**)

dozen years of the analysed period were characterised by a slight, yet continuous, drop in cloudiness.

The cloudiest sky in summer in Poland was observed in 1980, with a mean total cloud cover equal to 73.8% (Table 10.3). The indicated year was also marked with the occurrence of maximum value at 43 stations. However, particularly at coastal stations, the highest values did not occur in summer of said year. This is the region where maxima occurred irregularly, depending on the station. In western part of the Coastlands (from Świnoujście and Szczecin to Ustka) the highest level of cloudiness was observed in 1987. In Łeba and Koszalin, it was in 1961, and in Gdynia, located in western part of the Coastlands, in 1981. In Hel, the maximum occurred in 1998. At a few stations located in interior of the country, the highest values of cloudiness were also recorded irregularly—in 1961 (Olsztyn in Masurian Lakeland), 1974 (Kłodzko in the Sudety Mts.), 1977 (Słubice am Oder in the western part of Lakelands and Puławy in the Masovian Lowland), 1982 (Legnica in the Silesian Lowland) and 2012 (Kętrzyn in the Masurian Lakeland). The absolute maximum cloudiness in summer in Poland occurred on Kasprowy Wierch Mt. in 1980 and equalled 84%, at Śnieżka Mt. it was only slightly smaller and amounted to 83.3%.

The least cloudy sky in summer in Poland occurred in 1992, with the value amounting to 50.5% (Table 10.3). This absolute minimum was marked also in the course of cloudiness series of 30 stations. In the Lakelands and Lowlands of western Poland and in the Sudety Mts., the lowest level of cloudiness in summer was recorded in 1983. In addition, there are a few stations where the minimum occurred at another time, e.g. in Legnica and in the Tatra Mts. in 1952, in Łeba in 1959, in Gdynia in 1969, in Krosno (Outer Western Carpathians) and Sandomierz (Northern Subcarpathians) in 1971, in Opole (Silesian Lowland) in 1973, in Lesko (Outer Western Carpathians) in 2015 and in Kołobrzeg and Świnoujście in 2018. Exceptionally low total cloud cover of only 42.3% occurred in Cracow in the summer of 1992, and in Gdynia in 1969, the value of mean summer cloudiness was only higher by 0.2%.

During both subperiods, only a few stations recorded statistically significant changes of cloudiness. In the case of the first subperiod, beginning in 1951 and ending in 1984, there were more such stations (nearly ten) than in the latter one and all the data regard cases of increases in total cloudiness (Fig. 10.7e, f). Those stations are most often located in eastern Poland and in the highest parts of the Beskidy Mts. and Tatra Mts. For those stations the value of the relative trend reached 5%. On the whole, some drops in cloudiness were recorded only in the central part of the country.

The decrease in cloudiness dominated in the period from 1985 to 2018 (Fig. 10.7g, h). Yet, there are only four cases of statistically significant cloudiness changes—at three stations (Legnica, Mikołajki and Krosno) the cloud cover showed a tendency to decline, while in Elbląg the value of total cloud cover increased—this is the second time this station has stood out in comparison to other stations located in the same region. However, it is worth mentioning that some weak positive tendencies were also observed in Hel and Łeba in the coastal region. All in all, the values of the relative trends usually do not exceed $\pm 1.5\%$.

The mean seasonal total cloud cover in autumn amounts to 69.2%, and the cloud cover over Poland visibly transforms (Fig. 10.9a) comparing to spring and summer. Clouds cover more than 70% of the sky over the northern part of the country, with culmination reaching 74% over the Lakelands (Chojnice station). However, the highest level of autumn cloudiness is observed in the high-mountain ranges: the Karkonosze Mts. and Tatra Mts., reaching approximately 76%. In general, the central areas of the country are not particularly cloudy as of yet. Within the region as a whole,

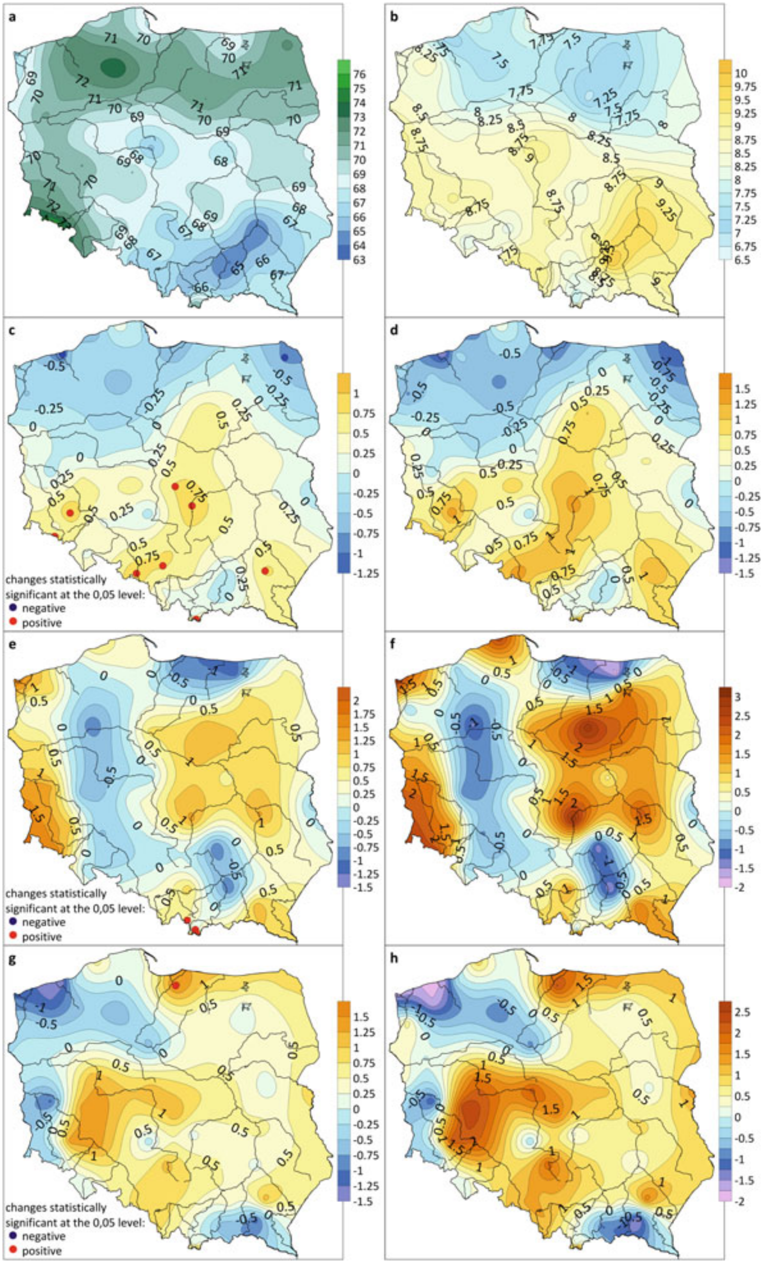

Fig. 10.9 Variability and change of autumn total cloudiness: mean values (1951–2018; %; **a**), coefficient of variability (%; **b**), absolute trend for the whole period (1951–2018; %/10y; **c**), relative trend for the whole period (%/10y; **d**), absolute trend for the first half of the period (1951–1984; %/10y; **e**), relative trend for the first half of the period (%/10y; **f**), absolute trend for the second half of the period (1985–2018; %/10y; **g**), relative trend for the second half of the period (%/10y; **h**). Statistically significant (0.05) trends were shown in (**c**, **e**, **g**) as circles

an increase in cloudiness is observed towards the west, just as during the rest of the seasons. The lowest cloudiness level in autumn is observed in the Subcarpathian region, where less than 65% of the sky is covered with clouds. Transformations of cloud cover towards the structure typical for the cold half of the year also include a decrease in variation of the element, visible especially in the north (Fig. 10.9b). Only in the region with the lowest cloudiness, i.e. the Northern Subcarpathians, the coefficient of variation reaches approximately 10%, in the remaining areas of the country it oscillates around 7–9%.

The country is visibly divided into areas opposite in signs of the long-term tendency of total cloudiness during the period from 1951 to 2018. This division is more or less latitudinal (Fig. 10.9c). Generally, total cloud cover systematically decreased in the north but increased in the south; statistically significant data series were gathered at ten stations. As for the decline of cloudiness in autumn, the trend was statistically significant only for three stations: Hel and Kołobrzeg in the coastal region and Suwałki in the northeastern Lakelands. Values of the relative trend rarely reach 1%, even at stations where significant changes are observed.

The positive and negative phases of total autumn cloudiness in Poland were consistently observed in series of almost all analysed stations during the period of 1951–2018 (Fig. 10.10). After two decades of a relatively stable year-to-year values of autumn cloud cover, a period of increased cloudiness started in the 1970s. However, it should be emphasised that there were three consecutive years (1951–1953) with alternate very high and low cloudiness seasons (at most stations the absolute maximum of average autumn cloudiness was observed in 1952). During the 1980s, a negative anomaly of cloudiness was recorded with a minimum in 1982. It is also worth mentioning that at some coastal stations the least cloudy sky was observed in 1988. Generally, in the 1990s the cloudiness was higher than usual and then during the next decade it dropped again. The last few years of the research period were characterised by relatively high year-to-year cloudiness variability.

As mentioned above, the highest autumn cloudiness level was observed in Poland in 1952. Its value amounted to 83.6%. That year the absolute maximum was recorded at a majority of stations. At the stations found along the coast, the maximum typically occurred in 1978. In the case of stations with observations beginning after 1952, the culmination of autumn cloudiness was observed, respectively: in 1996 (Sulejów, Nowy Sącz and Krosno), 1998 (Leszno and Legnica), 2002 (Lesko) and 2017 (Mława and Terespol). The highest cloudiness in autumn, amounting to 90.3%, was recorded on Śnieżka Mt. in 1952.

The least cloudy sky in autumn was observed in Poland in 1982, when total cloud cover amounted to 57.2%. At particular stations, the occurrence of minimum values was differentiated. Most frequently it was observed in 1982 (17 stations, mostly in central and southern Poland) and 2005 (16 stations in northern and western Poland). There was also a number of stations where the least cloudy sky in the described season was observed in 1950s (1951, 1953 and 1959, summarising 13 stations) and in 2005 (six stations in southern and southeastern Poland). The remaining cases concerned the singular stations with minima in other years. The least cloudy sky was in 1982 in Tarnów in the Northern Carpathians, where it was recorded as 45.1%.

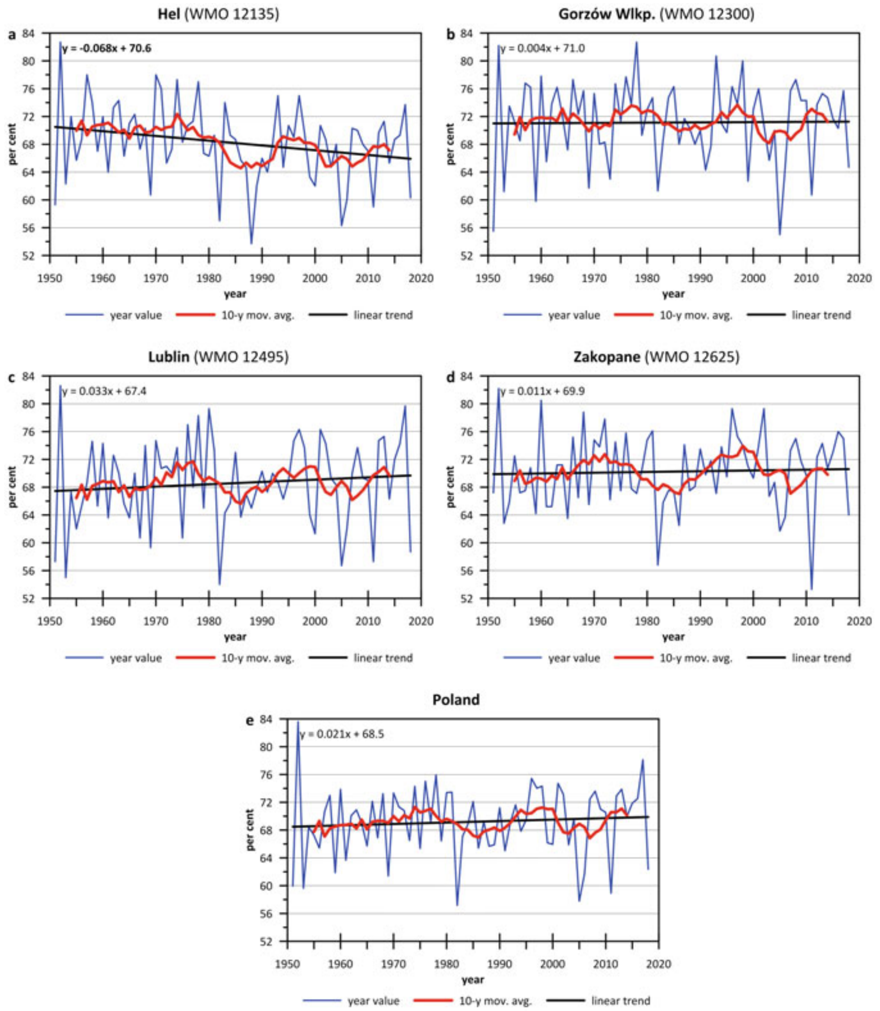

Fig. 10.10 Long-term variability of total autumn cloudiness in the selected stations of: northern Poland (station Hel; 1951–2018; **a**), western Poland (station Gorzów Wlkp.; 1951–2018; **b**), eastern Poland (station Lublin; 1951–2018; **c**), southern Poland (station Zakopane; 1951–2018; **d**) and in Poland as a whole (the average, **e**). Mean seasonal value (*blue*), 10-year consecutive average (*red*) and line trend (*black*) were shown. The trend is statistically significant (0.05, in *bold*) in (**a**) and not significant in (**b**–**d**)

Overall, there were very few significant changes in cloudiness during both subperiods. In the years 1951–1984, cloudiness slightly increased on the western edges of the country as well as in the central and northeastern parts of Poland (Fig. 10.9e, f). The region with the most intensively developing cloud cover was the Carpathians. however, statistically significant variability of the element was observed only at three stations located in this region: Jabłonka (Beskidy Mts.), Zakopane and Kasprowy Wierch Mt. in the Tatra Mts. Some insignificant declines in cloudiness were observed at less than half of the stations. The relative trend reached approximately 2% at a few stations (in western Poland).

After 1985, the structure of long-term autumn cloudiness variability significantly changed (Fig. 10.9g, h). At a greater part of the stations, increases in cloudiness were observed, but statistically significant data series come from only one station located in Elbląg. In western and central Poland, a decrease in cloudiness is observed as well as in the Karpaty Mts., while in the northern and eastern parts of the country values of the element increased.

Clear Days

Certainly the sky over Poland is more often cloudy than cloudless, as confirmed by data on the number of clear and cloudy days.

In Poland, clear days were recorded at least several dozen times a year during the period of 1951–2018 (Fig. 10.11a). On average, the number of clear days in Poland amounts to 32 days. The highest number of clear days occurred in the Subcarpathian region: in Tarnów there were 43 such days a year and a slightly lower result was noted in Sandomierz—nearly 40. Both the Polish Uplands and the Carpathians Mts. are also regions where the sky without clouds or with low levels of cloudiness can often be observed: 32–34 clear days a year, on average. More than 30 such days are recorded in the western part of the Lakelands and Coastlands (Świnoujście and Słubice: 33–34 clear days annually) as well as in the central part of the Lowlands (Wieluń—35 cases, Opole—32 cases). Generally, western Poland, except for the aforementioned regions, is characterised by a lower average annual number of clear days (less than 30 cases a year) than the rest of the country. The Karkonosze Mts. is the region with the lowest annual number of clear days—25, on average.

On the whole, the sky over Poland usually becomes clear in spring. However, this is true especially for areas by the Baltic Sea and at lower altitudes, in general. In the Uplands and in the upper part of Odra River basin, the maximum number of clear days is usually recorded in autumn. In the Subcarpathians, the number of clear spring days equals the number of such days observed in autumn. In the high-mountain regions, the highest number of clear days is recorded in winter.

In spring, the number of clear days amounts to 9, on average. Clear days are usually the most frequently noted in the coastal region (from 10 days in Kołobrzeg to 12 days in Hel and Świnoujście). The eastern part of the Lakelands is also clear—on average 10 such days a year are recorded there in spring. From 9 to 10 clear days occur in the Uplands and Lowlands of eastern Poland while in the Subcarpathians—11. In the low-mountain regions (the Beskidy and Sudety Mts.; excluding the Karkonosze Mts.) from 6 to 8 clear days are noted in spring, while in the highest mountains (the Tatra Mts. and above-mentioned Karkonosze Mts) only 5.

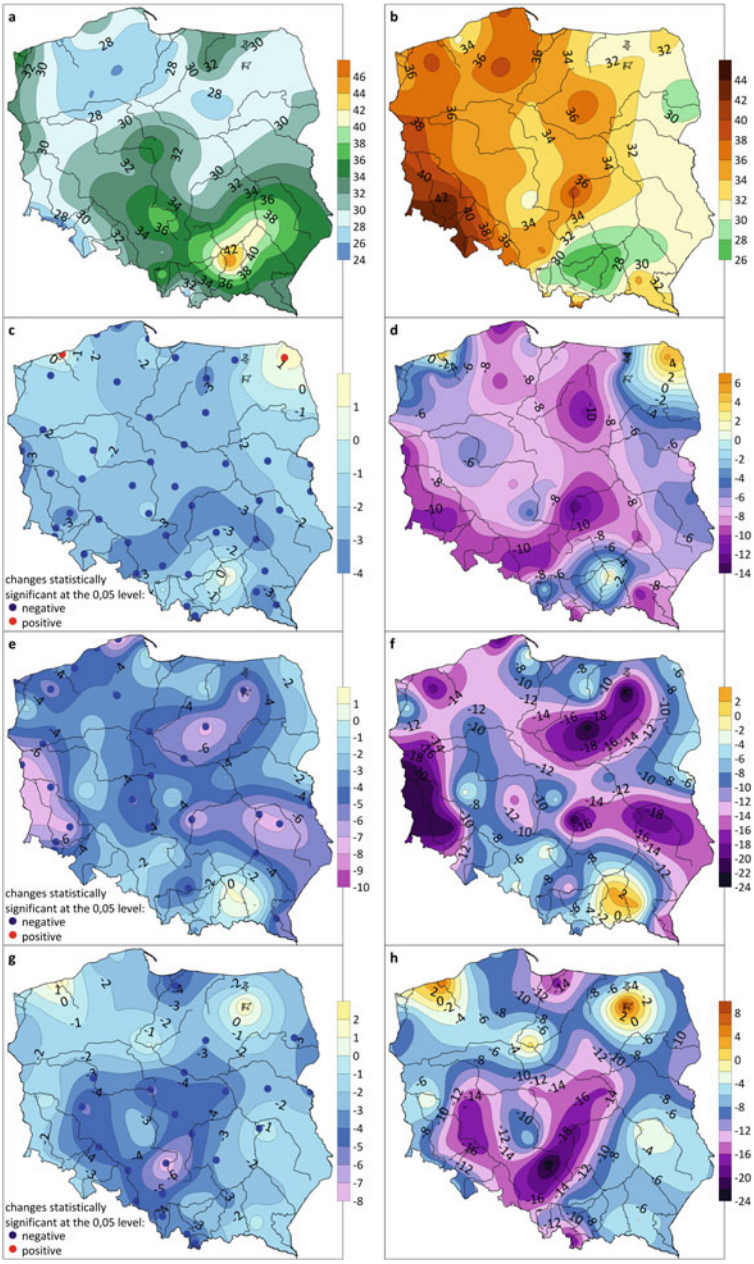

Fig. 10.11 Variability and change of annual number of clear days: mean values (1951–2018; %; **a**), coefficient of variability (%; **b**), absolute trend for the whole period (1951–2018; %/10y; **c**), relative trend for the whole period (%/10y; **d**), absolute trend for the first half of the period (1951–1984; %/10y; **e**), relative trend for the first half of the period (%/10y; **f**), absolute trend for the second half of the period (1985–2018; %/10y; **g**), relative trend for the second half of the period (%/10y; **h**). Statistically significant (0.05) trends were shown in (**c**, **e**, **g**) as circles

The Subcarpathian region is the one where the largest number of clear days is recorded in summer: 11–12 cases on average in Tarnów and Sandomierz. In the coastal areas, at least 9 clear days occur in summer and this number reaches up to 12 in Hel. In most of the country, approximately 8–9 clear days are recorded in summer, yet in the Lakelands there are usually only 6–8 such days (for instance, only 6 clear days in summer are observed in Piła and Chojnice). The lowest number of clear days are noted in the mountains (approx. 5 cases in the Tatra Mts., 3 cases in the Karkonosze Mts.). The mean seasonal number of clear days amounts to 8 days.

The numbers of clear days in autumn and winter amount to 8 and 6, respectively. In autumn, the lowest number of clear days is recorded in northern Poland, especially in the coastal areas—only 6 cases by the Gdańsk Bay (Gdynia and Hel), 6–7 cases in the remaining coastal areas, with the exception of Świnoujście, where 8 clear days are recorded. In the Lakelands, the number of clear days in autumn is also low, no more than 7–8 days, and, in the case of stations located at higher altitudes (Chojnice), only 6 clear days are noted. In the Lowlands, at least 8 such days are recorded in autumn and in the Uplands at least 9–10. In the Subcarpathian region, around 11–12 clear days occur in autumn. However, this number is slightly lower in the Karpaty Mts. In the Sudety Mts., only 7–8 autumn clear days are recorded and 6 in the Karkonosze Mts.

Furthermore, only 3 clear days are noted in winter in areas by the Gulf of Gdańsk. In the remaining coastal regions, about 4–6 cases are usually recorded. In the Lakelands, 5–6 clear days occur in winter. Further to the south, this number increases—in the Lowlands of western Poland and in the Uplands from 6 and 7 cases are noted. In the Lowlands of eastern Poland, only 5–6 clear days are noted in winter. The Carpathians can be divided into several parts: in the eastern one, 7 clear days are recorded. There are 9 cases in the western part and 12 in the Tatra Mts. In the Karkonosze Mts., 9 winter clear days are usually recorded.

Both large year-to-year fluctuations and long-term decreases in the number of clear days are common phenomena in Poland (Fig. 10.11b, c). The coefficient of variation is between 30 and 40% and it increases from east to west, which is especially visible in the Sudety Mts., where the value of this coefficient is the highest. This value is the lowest in the Subcarpathians and in the Lakelands of eastern Poland. In the country as a whole, with the exception of three small regions, the number of clear days is decreasing considerably. A vast majority of the analysed data series are characterised by statistically significant decreases. The pace of decline is 3 days/10y, and the Uplands is the region with the highest value of this rate. The only exceptions include data series taken from the stations in Kołobrzeg, Suwałki and Tarnów. In the case of Kołobrzeg and Suwałki, statistically significant increases in the number of clear days can be observed. Taking the relative scale into consideration, the reductions reach up to a dozen or so percentage points (Fig. 10.11d). The frequency of clear days decreased at majority of the analysed stations during the earlier of the two established subperiods (Fig. 10.11e, f). Statistically significant drops in the variable were a distinctive feature of the data series collected from the stations located in the central and northern parts of the country. The relative drops in the number of clear days were also considerable, reaching more than 20%. During the subperiod of 1985–2018, statistically significant decreases in the number of clear days were recorded for the data series obtained from the stations located in the central and southern parts of Poland (Fig. 10.11g, h). However, in this case, the relative scale of the decreases is smaller than the one for the earlier subperiod.

The largest annual number of clear days in the period 1951–2018 occurred in Poland, on average, in 1953, as an effect of a spring with an exceptionally low level of cloudiness (particularly in the south of the country) as it was mentioned in preceding Section Total Cloudiness. It is worth noting that summer and autumn 1953 were also among seasons with low cloudiness levels. Other years characterised by great number of clear days were 1964 and 1982, in northern Poland also 1959. The absolute maximum number of clear days was 89 and occurred in 1964 in Sulejów in the central part of Poland. In the same year, 79 clear days were recorded in Sandomierz, and in 1959, another 79 clear days occurred in Świnoujście.

The fewest clear days in Poland were recorded, on average, in 1998. It was the smallest value of the variable at 14 stations. Additionally, at particular stations, minima also occurred in 2001, 1977 and 2008 at 9 stations, 5 stations and another 5 stations, respectively. The smallest annual number of clear days came to only 6 cases at Śnieżka Mt. in 1998 and in Resko (Lakelands in western Poland) in 1978.

In the scale of seasons, the reduction in the number of clear days is strongly visible in spring and summer. The spring maxima were most often recorded at the analysed stations in 1953, 1959, 1982, 2007 and 2018. The most frequently clear days in spring occurred in Świnoujście in 1959 (31 cases) and Włodawa and Puławy in eastern Poland in 1953 (29 cases). Clear days were the least frequent in 1970 and 1983 (at five stations there were no clear days at all in this year). In the case of summer, the following years were especially clear: 1959, 1964, 1982–1983 (particularly 1983 as a summer season with the clearest sky in the analysed period 1951–2018) and 1992. In the Coastlands, clear days were also frequent in 1969. In the Uplands in Częstochowa, in the summer of 1983, there were 31 clear days, which is the absolute maximum value of the considered variable. Furthermore, in Puławy there were 30 such days noted in the same season, and 28 clear days occurred in Hel in summer of 1968. It is worth noting that at the same station 27 clear days were recorded also in 1959 and 1969, which underlines the exceptional position of Hel as the station with clearest sky in the summer in Poland, most probably due to its location—at peninsula, in the indirect vicinity of deep sea basin of Gulf of Gdańsk, which effectively reduces the likelihood of development of clouds in summer. At more than half the stations, at least one summer season with a complete lack of clear days occurred in the period 1951–2018. Among such seasons were the summers of 1980 and 2014, and in northern Poland in 1998. At high-mountain stations: Kasprowy Wierch Mt. and Śnieżka Mt., the number of such seasons reached 14 and 9 cases, respectively.

The number of clear days also decreases in autumn, yet the trend rate is lower. This was mainly caused by the high frequency of autumn seasons with frequent clear days in the beginning of the research period—in the 1950s (1951, 1953 and 1959) and in 1961. What is more, a high frequency of clear days was noticeable in Poland in 1982 and 2005–2006. The maximum numbers of clear days noted at particular stations increases from 16 to 22 cases (in 1951 in Gdynia and in 2005 in Ustka) in the north to 25 cases or more in the south (27 cases in 1959 in Kłodzko, 26 cases in Zakopane and at Kasprowy Wierch Mt., both in 1962). Again, at all 30 stations, at least one season with the lack of clear days occurred. This situation was most frequently recorded in autumn 1997, when at 12 stations no clear days occurred. In winter, the number of clear days remains relatively stable throughout the research period. However, a strong positive anomaly was observed in the 1960s and 1970s. The high numbers of clear days occurred, respectively in 1964 and 1969 and in 1973 and 1976. Other positive, but slightly weaker anomalies of the analysed variable were noted in 1993 and 2003. The highest maxima of the number of clear days at particular stations were recorded at high-mountain stations—at Kasprowy Wierch Mt. and Śnieżka Mt. In the Tatra Mts. in 1964, 30 clear days occurred during winter and in the Karkonosze Mts. 26 clear days were noted in 1993. The lowest number of clear days occurred in the winters of 1966 and 2013. In 1966, at 17 stations, there were no clear days recorded. Some strictly local minima also occurred. In 1968, the central area of the country experienced very small number of clear days, whereas in 2007 such situation occurred in the Lakelands of western part of Poland.

The presented long-term course of seasonal data series is partially reflected in the course of annual values (Fig. 10.12). In the 1950s, there were numerous clear days in Poland, and their annual number decreased over the next decade. Despite the aforementioned significant increase in the frequency of winter clear days in the 1970s, a strong negative anomaly in the variable was a distinctive feature of this decade across the country. Another visible increase in the annual number of clear days took place in the late 1980s and early 1990s. Subsequently, the number of clear days started to decrease systematically.

Cloudy Days

All in all, the mean number of cloudy days in Poland amounts to 157 days. Spatial diversity of the annual number of cloudy days recorded at selected Polish stations during the period of 1951–2018 was considerable (Fig. 10.13a). It can generally be stated that the structure of the variable changes latitudinally. In the north, especially in the coastal regions, the lowest values of this variable are usually recorded. In Świnoujście, only 110 cloudy days occur, which is the lowest value recorded in Poland. At the remaining coastal stations, the frequency of cloudy days varies from approx. 130 days in Hel and 140 days in Ustka and Łeba to approx. 160 cloudy days in Kołobrzeg. In the Lakelands, the number of cloudy days is higher, varying usually from 155 to 165, with the culmination in the areas located at the highest altitude: Chojnice—173 days and Suwałki—166 days. In the Lowlands of central and eastern Poland, and in the areas of the Lakelands located at a lower altitude and at a greater distance from the Baltic Sea coast, the number of cloudy days is lower—150 cases or less. Moving south, the number of cloudy days increases again. In the Lowlands of western Poland and in the Uplands, there are typically 160 cloudy days a year or more. In the Subcarpathian region, the number of cloudy days is much

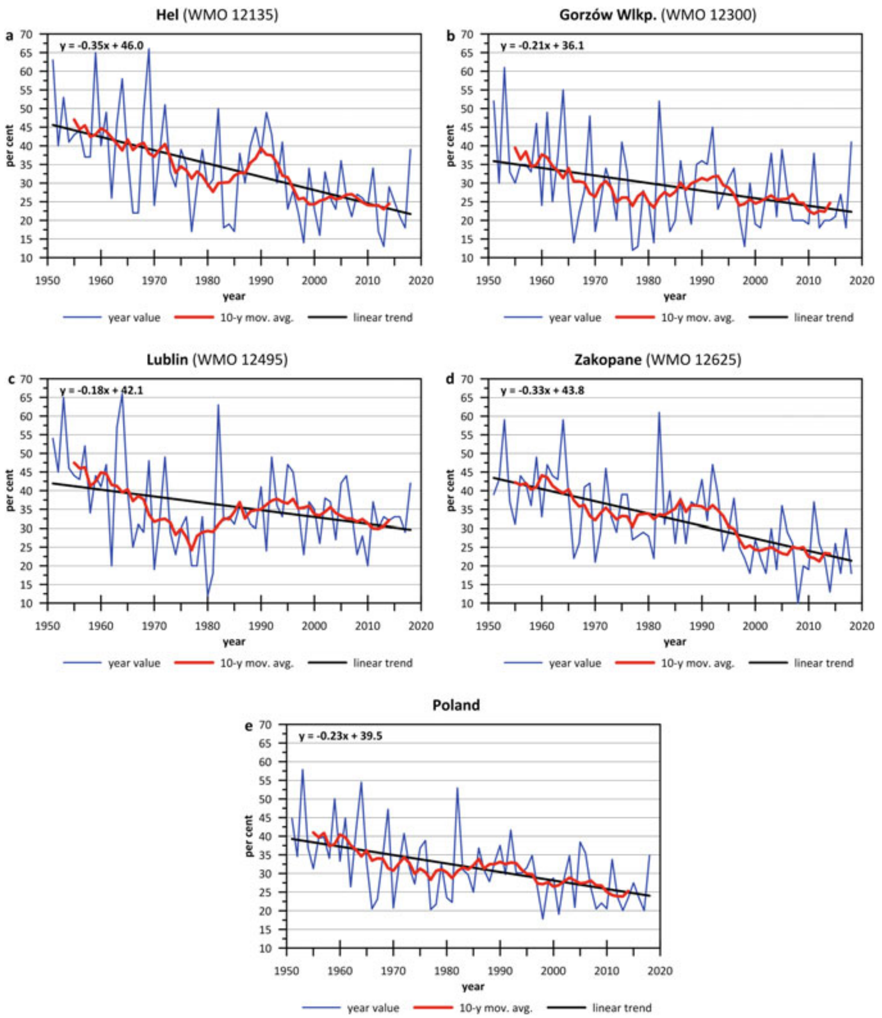

Fig. 10.12 Long-term variability of the annual number of clear days in selected stations of: northern Poland (station Hel; 1951–2018; **a**), western Poland (station Gorzów Wlkp.; 1951–2018; **b**), eastern Poland (station Lublin; 1951–2018; **c**), southern Poland (station Zakopane; 1951–2018; **d**) and in Poland as a whole (the average, **e**). Mean seasonal value (*blue*), 10-year consecutive average (*red*) and line trend (*black*) were shown. The trend is statistically significant (0.05, in *bold*) in all cases

lower, reaching 140–145 cases. In the mountains, the variable value increases again by a dozen cases or so. In the highest parts of the mountains, the number of cloudy days reaches nearly 200 (Kasprowy Wierch—192 days) or even more (Śnieżka—207 days). The variability in the number of cloudy days in Poland during the period 1951–2018 is significantly smaller than the fluctuations in the number of clear days (Fig. 10.13b). The coefficient of variation value is less than 10% in eastern Poland

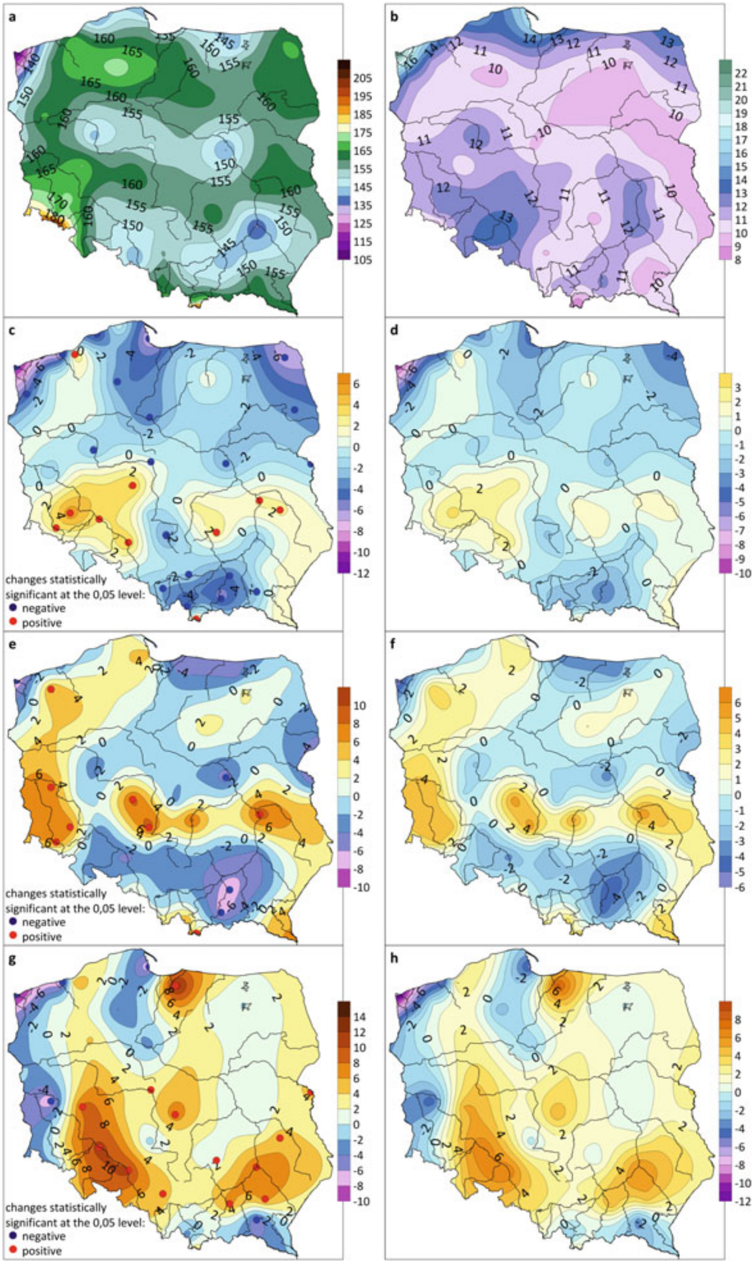

Fig. 10.13 Variability and change of annual number of overcast days: mean values (1951–2018; %; **a**), coefficient of variability (%; **b**), absolute trend for the whole period (1951–2018; %/10y; **c**), relative trend for the whole period (%/10y; **d**), absolute trend for the first half of the period (1951–1984; %/10y; **e**), relative trend for the first half of the period (%/10y; **f**), absolute trend for the second half of the period (1985–2018; %/10y; **g**), relative trend for the second half of the period (%/10y; **h**). Statistically significant (0.05) trends were shown in (**c**, **e**, **g**) as circles

and almost 20% in Świnoujście. The rate for Świnoujście is exceptionally high as a typical range of values for this variable in Poland is between 10 and 13%.

The seasonal frequency of cloudy days follows a simple pattern: summer is the season with the lowest number of cloudy days (28 cases), then spring (36 cases), autumn (41 cases) and winter when the number is the highest (52 cases).

In summer, the number of cloudy days varies from almost 20 in Świnoujście and Hel, 21 in Ustka and Łeba to more than 30 days in the lower mountains, e.g. the Beskidy Mts. Generally, the number of cloudy days is higher in the western parts of the country than in the eastern regions. In the highest mountains, there are approx. 47 cloudy days observed. Kasprowy Wierch is the only station where there are more cloudy days in summer than in autumn.

While in summer the lowest frequency of cloudy days is observed (with the one already-mentioned exception), an interesting relation has been discovered between the number of cloudy days in spring and autumn.

In the north, especially in the coastal areas, there are far more cloudy days in autumn than in spring—at least 20% (30–35 cases in spring and 8–10 cases more in autumn). The greater the distance from the sea, the lower the disproportion: the number of spring cloudy days starts to grow, while the number of autumn cloudy days remains unchanged or only slightly increases. In the Lowlands of western Poland and in the Uplands, the number of spring cloudy days (35–40 cases) is only slightly lower than the number of cloudy days observed in autumn (38–42). Fewer cloudy days, both in spring and autumn, are observed in the Subcarpathians: 30–35 and 35–37, respectively. In the Carpathians and Sudety Mts. almost the same numbers of spring and autumn cloudy days are recorded by all stations (38–41 in the Carpathians; 38–42 in the Sudety Mts.); except for Śnieżka—52 cloudy days in spring as well as in autumn and Kasprowy Wierch—52 cloudy spring days and 45 cloudy autumn days. At several stations located in the Carpathians the number of cloudy days in spring is larger than the number in autumn. Thus, in autumn the Karkonosze Mts. are the region with the largest number of cloudy days in Poland.

By and large, in winter the number of cloudy days in Poland is higher than in the remaining seasons of the year. The lowest number of cloudy days (less than 50) is recorded in the western part of the Coastlands and at some selected stations located in western Poland in the Subcarpathians and the Carpathians. The highest number of cloudy winter days is observed in the Lakelands: from 55 to almost 60 cases.

Similarly to the case of clear days, the annual number of cloudy days in Poland during the period of 1951–2018 decreased at majority of the stations (Fig. 10.13c). The decrease is especially visible in the north: in Suwałki the pace of the decrease exceeds 7 cases/10y; in Świnoujście it is even faster—12 cases/10y. The drops are also observed in the Subcarpathians and in the lower ranges of the Carpathians (the Beskidy Mts.) and the fastest pace of decrease is observed in Nowy Sącz—5 cases/10y. Yet, in many analysed stations located within this region, the negative trend is statistically significant. However, there are two regions in Poland where considerable increases are observed. The first one is the Lowlands of western Poland and the Sudety Mts. and the second is the central and eastern parts of the Uplands. The pace of increase reaches 4 cases/10y in Legnica. The number of cloudy days also increases in the Tatra Mts. The relative decreases or increases in the number of cloudy days range from −10 to +3% (Fig. 10.13d).

There were a few years in the period 1951–2018 with very high annual numbers of cloudy days. Its temporal distribution is somewhat interesting. First of all, a high frequency of such cases was characteristic for the first three decades of the analysed period (with maxima in years: 1952, 1958, 1962, 1966—the highest value in the whole research period, 1970, 1977 and 1980—the second highest one). During the next three decades, negative anomalies of the considered variable were recorded, which means the occurrence of potentially more sunny years with relatively low total cloud cover: 1982, 1989, 1992, 2003, 2006 and 2011. The minimum number of cloudy days occurred in 1982. In the last decade of the analysed period, again years with large amount of cloudy days occurred. The long-term course of the number of days without sun (Chap. 6) confirms that 1980 was characterised by a very high number of days without sun and, on the contrary, during 1982 the fewest number of such days was noted.

The greatest numbers of cloudy days were noted at mountain stations: 243 days at Śnieżka Mt. in 2016 and 223 days at Kasprowy Wierch Mt. in 2003. The smallest number of the considered days, equalling only 49, was recorded in Świnoujście in 2003.

In winter, the drops in the number of cloudy days are observed only in the north, yet some disparities were observed within the regions. The winter seasons of 1953, 1966, 2010, 2013 and 2018 were the ones with an exceptionally large number of cloudy days. Particularly frequent cloudy days were in 2013, when, at greater part of analysed stations, the maximum number of cases was recorded. In Leszno (Lowlands in western areas of Poland) there was 76 cloudy days noted then. In Białystok and Suwałki, 74 and 73 cloudy days, respectively occurred in 1959—in north and north-eastern Poland, an increase in winter cloudiness was observed that year. In 1954, 1976 and 1984, the number of cloudy days was extremely low. Furthermore, between 1990 and 2000, a considerable decrease in the number of cloudy days occurred in Poland with minima in the years: 1990–1991, 1993, 1997 and 2000. The fewest cloudy days (22 cases) were recorded in Świnoujście in 2000. Overall, spring is the season when the number of cloudy days usually considerably decreases in Poland and there are only a few stations that do not match this pattern. Thus, the spring seasons exceptionally abundant in cloudy days in spring occurred in the first two decades of the research period: 1958, 1962, 1970 and 1972. A strong maximum was recorded in the Masurian Lakeland in the northeastern part of Poland in 1966, and the largest amount of cloudy days was noted at mountain stations. At both locations, 71 such days occurred—at Śnieżka Mt. in 1958 and at Kasprowy Wierch Mt. in 2017. The lowest minimum occurred in 1953 and the number of cloudy days noted at more than 20 stations did not decrease in the subsequent years. However, it is worth noting that cloudy days were not frequent after the beginning of the current century. Minima occurred in 2007, 2011 and 2018, which means that the spring seasons of the twenty-first century have been rather sunny. Among the considered stations, the lowest values of the variable are characteristic at coastal stations. The cold water of the Baltic Sea in the spring effectively limits the development of clouds in this region. The minima recorded at coastal stations did not exceed 20 cases in spring: seven cloudy days in Świnoujście in 2011, 13 such days in Hel in 1990 and 14 days in Łeba, also in 1990. In Ustka in 1974, only 15 cloudy days occurred. In summer, the number of cloudy days decreases in Poland. The coast and Lakelands are among the regions where the drops are considerable. Thus, during the first half of the research period, the high frequency of the seasons with a large number of cloudy days occurred in Poland: 1960–1961, 1974, 1980–1981 and 1985. In 1980, the lowest number of cloudy days occurred at 34 stations. At Kasprowy Wierch Mt., 74 cloudy days were then recorded. However, in the summer of 1974 at Śnieżka Mt., an even larger amount of cloudy days was noted—79 cases. Since the 1980s, the negative anomalies of the variable frequently occurred: 1982–1983, 1992, 1994, 2003 and 2015. The summer of 1992 was characterised by a particularly low number of cloudy days at half the stations. At stations located in the Coastlands and Lakelands of eastern Poland, less than 10 cloudy days were then noted. In 2003 in Świnoujście, only four such days occurred. In autumn, the number of cloudy days decreases only in northern Poland. The decade of 1950s was characterised by a great multi-year variability in the number of cloudy days in Poland. In 1951, 1953 and 1959 a very low number of cloudy days occurred in Poland, whereas in 1952 and 1958 this number rose considerably. Absolute minima and maxima occurred year by year—in 1951 (minimum) and in 1952 (maximum). In autumn of 1952 at Śnieżka Mt., 73 cloudy days, 69 such days in Płock and 68 in Warsaw were recorded. Other negative anomalies in the amount of cloudy days occurred in 1982, 2005–2006 and 2011. In autumn of 2003, only 8 cloudy days occurred in Świnoujście. On the whole, substantial increases were noted in 1978, 1996 and 2017. Additionally, in the Coastlands the autumn of 1993 was also very cloudy.

The first subperiod (1951–1984) was characterised by a relatively low number of drops in the variable (including some statistically significant changes recorded at four stations) and by some more increases (statistically significant at 10 stations) (Fig. 10.13e). The number of cloudy days decreased mainly in the south, including the Subcarpathians. In turn, in western Poland and at several stations located in the Uplands, the analysed variable increased. Nonetheless, the relative changes in the variable were rather unnoticeable (Fig. 10.13f).

During the second subperiod (1985–2018), the pace of the increase in the number of cloudy days was visibly faster in the whole country (Fig. 10.13g). At the majority of stations, the number of cloudy days systematically increased. It is particularly visible in the upper part of Odra River basin: more than 10 cases/10y. The number of cloudy days also increased in the Subcarpathians and in Elbląg in northern Poland. In western Poland, the variable decreased, which was especially visible in Świnoujście. The range of relative changes strongly relates to the highly diversified absolute values and it varies from −12 to 8% (Fig. 10.13h).

The long-term analysis of changes in the number of cloudy days recorded by the selected stations in Poland showed that this variable is diversified (Fig. 10.14). In the north, the number of cloudy days was rather high from the beginning of the research period until the 1980s. However, there was a short-term drop in the variable recorded at the stations located in the Lakelands in the late 1960s and early 1970s. In the central

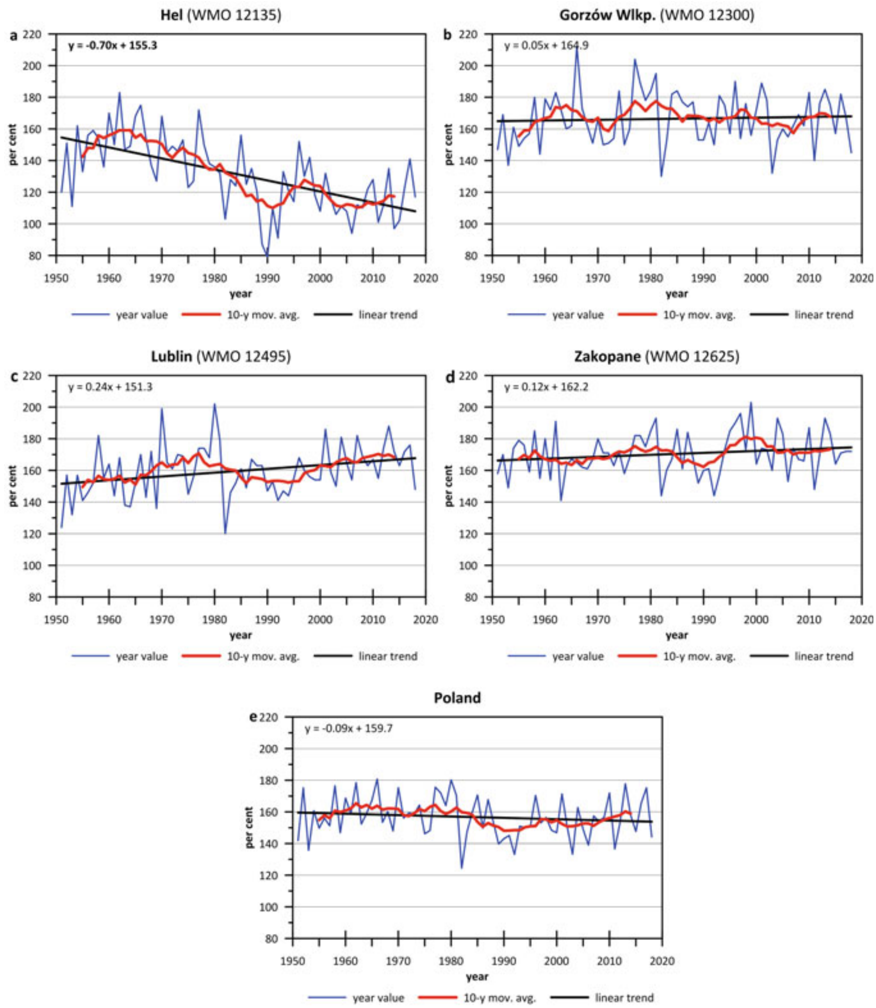

Fig. 10.14 Long-term variability of the annual number of overcast days in: northern Poland (station Hel; 1951–2018; **a**), western Poland (station Gorzów Wlkp.; 1951–2018; **b**), eastern Poland (station Lublin; 1951–2018; **c**), southern Poland (station Zakopane; 1951–2018; **d**) and in Poland as a whole (the average, **e**). Mean seasonal value (*blue*), 10-year consecutive average (*red*) and line trend (*black*) were shown. The trend is statistically significant (0.05, in *bold*) in (**a**) and not significant in (**b–d**)

part of the country and in the south, there were short-term increases in the 1970s. In the late 1980s and early 1990s a strong negative anomaly of the variable value was observed. At the beginning of the twenty-first century, the number of cloudy days in Poland increased again and now it is relatively stable at the majority of the stations.

Cloud Type

While analysing spatial and temporal variability of cloud type, i.e. cloudiness divided into 10 cloud genera, it is important to be aware of the fact that data series obtained from visual observations conducted at synoptic stations are imperfect. Occurrence frequency of a particular genera of clouds is largely affected by actual possibilities of its observation. It is a significant hindrance in the case of medium- and high-level clouds, as they may be obscured by some low-level clouds. Any clouds may be obscured by a thick layer of fog. Moreover, the specific coding requirements for synoptic observations, however, designed to give an optimum characteristic of cloudiness, may partially limit the possibility to register all genera of clouds that are present in the sky at a particular moment. Another impediment is the way the data are coded at some stations. Although National Hydrological and Meteorological Services provide trainings on proper methods of observing and recording cloudiness, there are still cases when some observers use techniques learnt from their predecessors, frequently their teachers. The above-mentioned situation does not apply to the way particular genera of clouds are recognised, but rather to the way of their subdivision into species and varieties, as well as classification in terms of coding them to report the specific state of the sky.

The data series obtained from 25 stations were analysed according to the methodology described in Chap. 3. The analysis made it possible to calculate the frequency of all ten cloud genera with a reference to the number of observations at particular levels.

On the assumption that has already been mentioned, frequency (in per cent) of low-level clouds was determined with regard to the number of their observations and the fact that in some cases the weather conditions made it impossible to carry out observations. The percentage of such cases varies from almost 0.4% in Ustka and Warszawa, 0.6% in Hel, Świnoujście, Białystok, Wrocław, Lublin and Rzeszów to 2% in Koszalin, Gorzów Wielkopolski, Kielce and Zakopane. At two other stations—in Zielona Góra and Chojnice, the weather conditions made it impossible to identify low-level clouds in 4% (Zielona Góra) and 5% (Chojnice) of all observations. Typically, results of low-level clouds observations are unsatisfactory in 1.4% of cases.

Medium-level clouds are not visible in less than 30% of all observations made at stations located in the Coastlands, Lowlands and Uplands (e.g. Ustka, Świnoujście, Warszawa, Wrocław and Kraków), while at the stations located in the Lakelands (Suwałki and Chojnice) and in the Carpathians (Zakopane and Lesko) these genera of clouds are invisible in more than 40% of all observations. The average for all the stations is 35%.

Świnoujście is a station where high-level clouds are well observable—in only 39% of cases these genera of clouds were not visible. At the remaining stations, except for ones located near the large civil airports (Warszawa and Kraków), the percentage of observations during which it was impossible to record any high-level clouds varies from 47 to 52%. In Warsaw and Kraków, it was approximately 42%. The average for all the station is 49%.

Stratocumulus is the most frequently observed cloud in Poland (Fig. 10.15a), especially at stations located in the regions with diverse orography and at high altitudes (in the Lakelands, Uplands and in the mountains). There, the *Stratocumulus* frequency exceeds 40% of all observed low-level clouds. On the coastline, this genus of clouds is observed with a frequency lower than 33%. In the remaining regions of the country, the frequency of *Stratocumulus* reaches approximately 33–35% or more. By and large, the frequency of *Stratocumulus* in Poland is 40%.

Cumulus is the second most frequently observed low-level cloud in Poland (Fig. 10.15b). On average, *Cumulus* is observed in one of every five observations of the sky in Poland. The highest frequency is recorded in the Coastlands—from nearly 20% in Kołobrzeg to more than 30%, with a maximum in Hel (33%). However, at several stations located inland (Gorzów Wlkp., Suwałki and Kraków), the frequency of *Cumulus* decreases to 15% of the observable low-level clouds and then towards the south it increases again reaching 20% in Lesko (the Carpathians). In Zakopane,

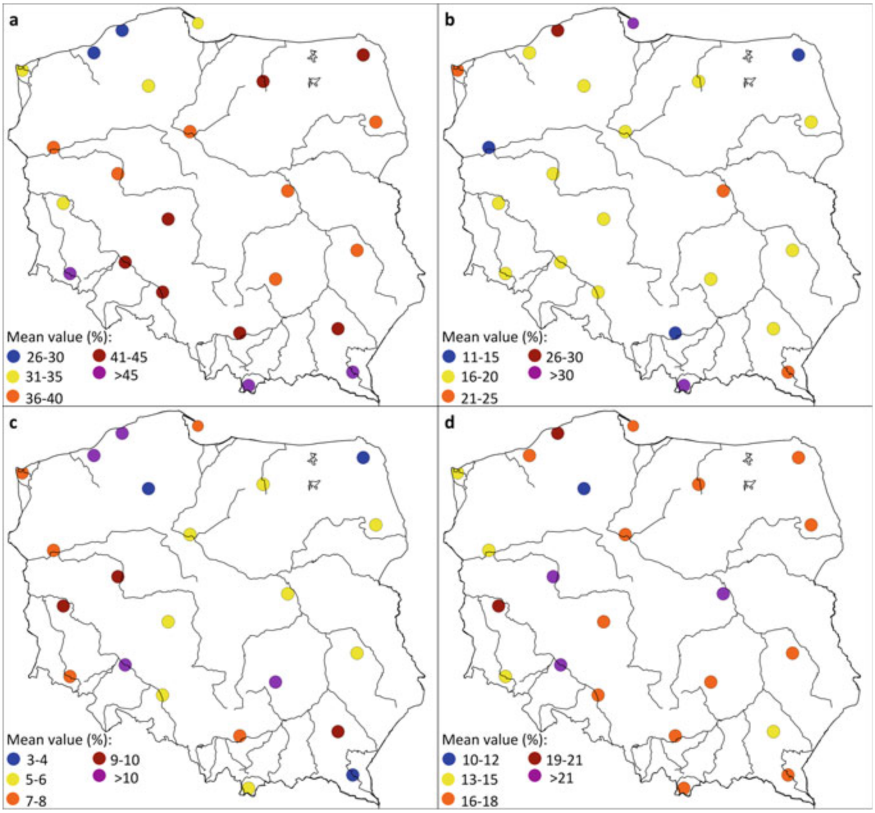

Fig. 10.15 Variability of annual average daily per cent of observations in Poland (1966–2018) for selected cloud genera: *Stratocumulus* (**a**), *Cumulus* (**b**), *Altostratus* (**c**) and *Cirrus* (**d**)

at the foot of the Tatra Mts., the frequency of *Cumulus* within the observations of low-level clouds is 30%.

When it comes to the structure of low-level cloudiness, both aforementioned stations share another distinctive feature—the lowest frequency of another low-level cloud, *Stratus*, across Poland: only 8% in Zakopane and 12% in Lesko. At the stations located at a lower altitude, this variable fluctuates between 13 and 17%, while in the Coastlands it reaches nearly 20%. The average for Poland is 15%.

Cumulonimbus, characterised by extensive vertical development, is the last analysed genus of low-level clouds. Spatial distribution of *Cumulonimbus* occurrence is highly diverse. In the Coastlands, it is observed in 6% of all cases in Hel and 11% in Ustka. In the Lakelands and Lowlands, the frequency varies from 5 to 7% (Poznań, Warszawa, Wrocław, Suwałki) to 13–14% (Olsztyn and Chojnice). In the Uplands, *Cumulonimbus* is observed once in every 9–10 cases, yet its frequency in Kraków is only 4%. At the stations located in Subcarpathians and the Carpathians, its frequency is highly diversified. In Rzeszów, it is 7%, in Zakopane—4%, while in Lesko it reaches 15%.

The analysis of long-term occurrence frequency of particular genera of low-level clouds in Poland during the period of 1966–2018 revealed a strong, statistically significant increase in the occurrence of *Stratocumulus*, *Cumulus* and *Cumulonimbus* (Fig. 10.16). As for the first listed genus, the increase is relatively stable and evenly spread over time. Both convective clouds were particularly often observed at the end of the previous century and during the first decade of the twenty-first century. Nowadays, the above-mentioned clouds are observed less frequently. The number of *Stratus* observations in terms of the whole research period also declined and the pace of this decline was rather uneven. After a period of a higher *Stratus* frequency lasting until 1980, there was a fast decline observed with minima in the 1980s and the 1990s. During the last few years, *Stratus* has been observed more frequently.

The average annual prevalence of mentioned genera of clouds in individual regions is very consistent for the *Cumulus* cloud. In the case of other low-cloud genera, some regional discrepancies can be observed. The reported dramatic increase in the frequency of the *Cumulonimbus* in the late 1990s was particularly evident in the coastal mountain foothill regions and in the mountains, whereas the other regions were characterised by a more stable course of cloud occurrence. In the case of the *Stratocumulus*, only a slight increase in its frequency was found at mountain stations. At stations located in the Coastlands, the minimum frequency of *Stratus* was shifted to the second half of the 1980s and the beginning of the 1990s, whereas at stations located in the Lakelands, there was relative stabilisation of the occurrence of this cloud.

The structure of medium-level cloudiness is dominated by *Altocumulus* clouds. They are observed in 21% of all cases, yet their frequency is substantially diversified. *Altocumulus* is most frequently observed in the sky over stations located in the Lowlands and in the south of Poland, with the exception of the Carpathians. Thus, the maximum frequency was recorded in Wrocław (36%), Zielona Góra and Warszawa (31%), and Kielce (28%). At the remaining stations of those regions, the frequency does not exceed 25%. In the mountain region, *Altocumulus* is usually

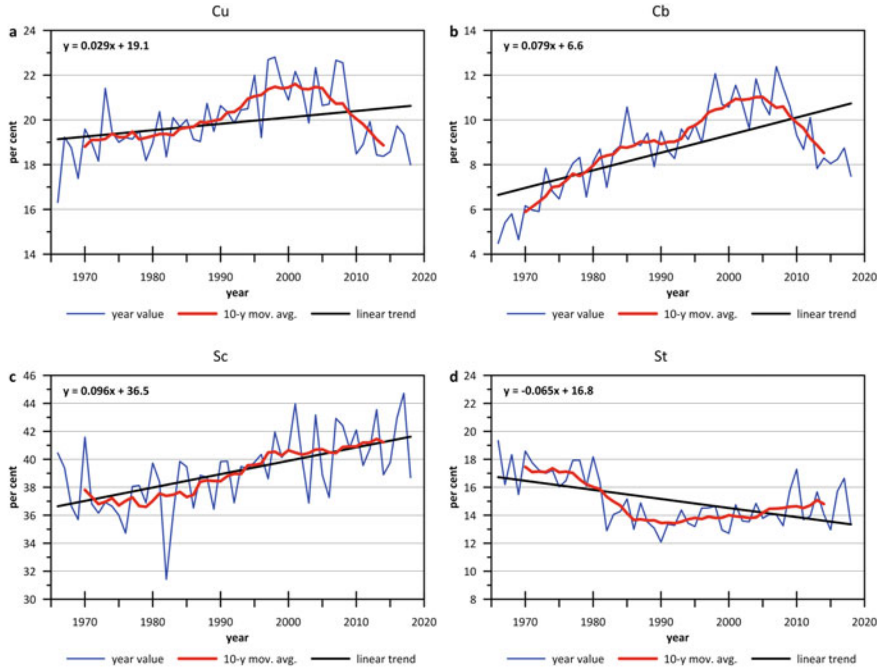

Fig. 10.16 Long-term variability of annual average daily per cent of observations in Poland (1966–2018) for low-cloud genera: *Cumulus* (Cu, **a**), *Cumulonimbus* (Cb, **b**), *Stratocumulus* (Sc, **c**) and *Stratus* (St, **d**). Mean annual value (*blue*), 10-year consecutive average (*red*) and line trend (*black*) were shown. The trend is statistically significant (0.05, in *bold*) in all cases

observed less often (Zakopane—nearly 17% and Lesko—13%, however, in Jelenia Góra in the foothills of the Karkonosze Mts., this value reaches 25%). In the Coastlands, *Altocumulus* represents from 11% (Hel) to 23% (Ustka) of all medium-level clouds observations. However, the lowest frequency is observed in the Lakelands: from almost 10% in Suwałki and 12% in Olsztyn to 20% in Toruń and 24% in Koszalin (located in the Lakeland region but very close to the coast).

The two remaining genera of medium-level clouds, *Altostratus* and *Nimbostratus*, are not frequently observed in Poland (their aggregated frequency of occurrence does not exceed the value for Ac).

On the whole, the number of the *Altostratus* observations seems to be declining from west to east (Fig. 10.15c). Nevertheless, its occurrence frequency is spatially diversified. In most cases, in the west of the country, the frequency of *Altostratus* is at least 7%, and in the east it is usually approx. 5–6%. *Altostratus* is often observable at the coastal stations (nearly 11% in Ustka, more than 6% in Świnoujście and Hel), but there are other three stations where the frequency of *Altostratus* exceeds 10%. They are: Koszalin, Wrocław (located in the Lowlands of western Poland) and Kielce in the Uplands. At a few stations located in the east, less than 7% of *Altostratus* frequency occurred, e.g. in Lesko and Suwałki it was less than 4%. The average value for the whole country is 7%.

The last analysed medium-level cloud with extensive horizontal and vertical development is *Nimbostratus*. Its frequency is even lower than the one calculated for *Altostratus*—approximately 4%. When it comes to spatial diversification, the *Nimbostratus* frequency varies from 2% in Zakopane and Jelenia Góra (both located in the foothills of the highest mountain ranges in Poland: the Tatra Mountains and Karkonosze Mountains) to almost 6% at some stations located in the north: Koszalin, Białystok and Suwałki. In the Coastlands, the frequency reaches 5% (Ustka and Świnoujście). The same value of this variable was recorded in the Lowlands, in Warszawa and Opole. In the remaining regions, observations of this cloud genus represent approx. 4–5% of all medium-level clouds observations and even less (3%) in the Uplands.

The structure of medium-level cloudiness in Poland during the period of 1966–2018 was affected by some statistically significant, long-term changes. The number of observed *Altostratus* and *Nimbostratus* systematically decreased overtime (Fig. 10.17a, b, respectively). They were observed much more often in the late 1970s and early 1980s, and then the number of observations dropped, though, since

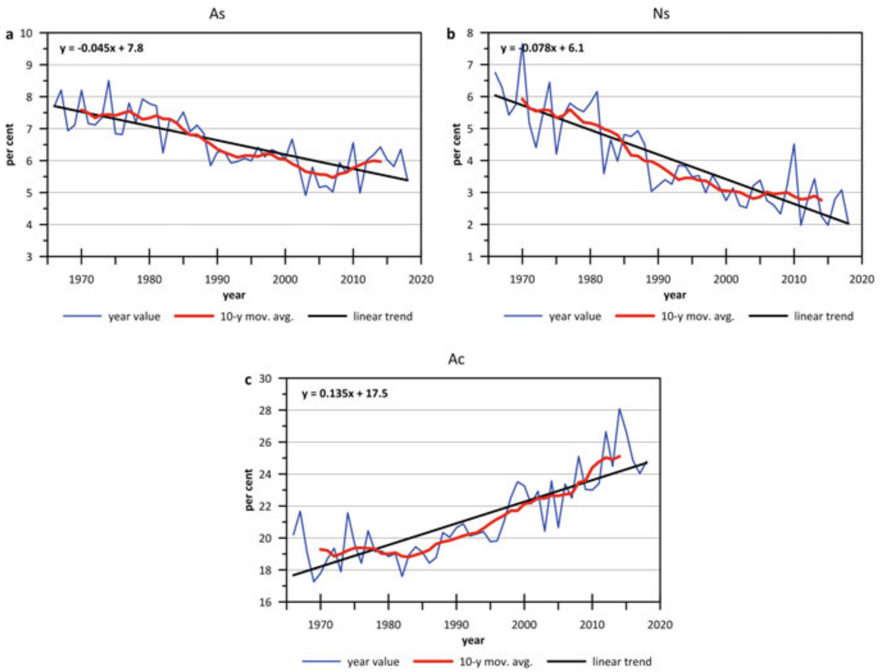

Fig. 10.17 Long-term variability of annual average daily per cent of observations in Poland (1966–2018) for middle cloud genera: *Altostratus* (As, **a**), *Nimbostratus* (Ns, **b**) and *Altocumulus* (Ac, **c**). Mean annual value (*blue*), 10-year consecutive average (*red*) and line trend (*black*) were shown. The trend is statistically significant (0.05, in *bold*) in all cases

the beginning of the twenty-first century, this negative trend has not been as strong as it used to be. *Altocumulus* was observed more frequently in the research period, but not systematically (Fig. 10.17c) and not during the first part of the analysed period. Its frequency began increasing rapidly in the last decade of the twentieth century.

Regional trends do not usually follow the average pattern determined for the whole country. In the case of *Altostratus*, a positive trend was observed in the Coastlands after a minimum had been recorded in the second half of the last decade of the former century. Moreover, the frequency of the same cloud decreased much faster at the stations located in the Subcarpathian region than at the others. In the mountains and in the Subcarpathians, *Altocumulus* formed differently than in the rest of the country. The *Altocumulus* frequency in the mountains was almost the same at the beginning and at the end of the analysed period. However, a clear minimum was recorded in the 1980s and 1990s. At the stations located in the Subcarpathian region, there was no strong positive trend observed. The regional frequency of *Nimbostratus* more or less reflects the national pattern.

The most often observed high-level cloud in Poland is *Cirrus*, which represents 17% of all observations of high-level clouds in the country. Spatial diversification of the *Cirrus* frequency does not present any distinctive features (Fig. 10.15d). In central and eastern Poland, it is observed as often as the average for the whole country. In the west and north, the variable is much more diversified, even at neighbouring stations. The lowest frequency was recorded in Chojnice, the most elevated station in the Lakelands, where *Cirrus* observations represented only 10% of all cases. Other stations where this genus of cloud is observed relatively seldom (13–15% of all observed high-level clouds) are as follows: Świnoujście (in the Coastlands), Gorzów Wlkp. (in the Lakelands) and Jelenia Góra (foothills of Karkonosze Mts.), all of which are located in western Poland. In Ustka (in the Coastlands), the frequency reaches approx. 20%, and in Poznań and Wrocław (the Lowlands in the west of Poland), the *Cirrus* observations represent almost a quarter of all cases (22.5% in Wrocław).

Cirrostratus is the second most frequently observed high-level cloud with the average frequency of almost 7% across the country, although this value decreases from the west to the east of Poland. The frequency exceeds 10% at the stations located more westward: in Koszalin, Chojnice, Kalisz and Jelenia Góra (e.g. in Zielona Góra it reaches approx. 15%) whereas in the east there is only 2–4% (Warszawa—2%, Białystok and Suwałki—3%, Olsztyn—4%) However, in Kielce and Lublin, located in the Uplands, this variable reaches the value of 11–12%. *Cirrostratus* is often observed also in the mountains—11% of all observations of high-level clouds are recorded in Zakopane. In Rzeszów, in the Subcarpathians, it is a rarely observed genus of clouds (0.7% of all cases).

Cirrocumulus is most certainly the rarest high-level cloud observed in Poland. Its average frequency in Poland is less than 1% and it is the lowest on the coast; this value increases at stations located at higher altitudes.

The occurrence frequency of all three genera of high-level clouds has been systematically increasing in Poland (Fig. 10.18). The analysis showed that the minimum frequency of high-level clouds was recorded in the late 1980s and early 1990s (a bit

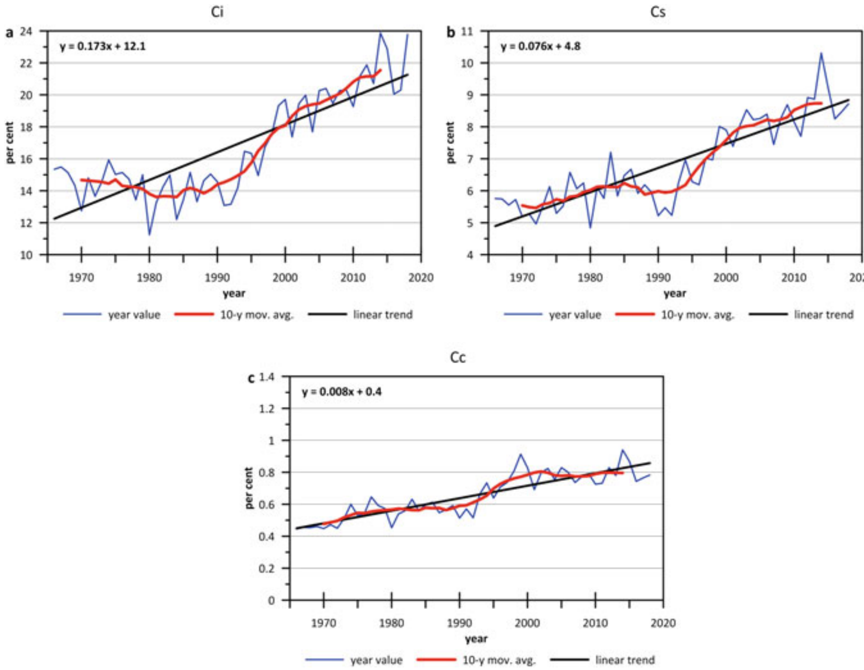

Fig. 10.18 Long-term variability of annual average daily per cent of observations in Poland (1966–2018) for high cloud genera: *Cirrus* (Ci, **a**), *Cirrostratus* (Cs, **b**) and *Cirrocumulus* (Cc, **c**). Mean annual value (*blue*), 10-year consecutive average (*red*) and line trend (*black*) were shown. The trend is statistically significant (0.05, in *bold*) in all cases

faster in the case of *Cirrus*). Then, after 1995, both *Cirrus* and *Cirrostratus* started to be observed more often. In the case of *Cirrocumulus*, the positive trend has slowed down since the beginning of the current century.

The average annual frequency of *Cirrus* is more or less the same in all analysed regions. In the case of *Cirrostratus*, its frequency different from the average is found on the coast. At the stations located by the sea, the *Cirrostratus* frequency was in line with the average only at the beginning of the analysed period, then the frequency dropped (while it increased in other regions) and increased again until the late 1990s. Afterwards, it continued to decrease during the last ten years of the analysed period. As for the *Cirrocumulus* frequency, a substantial growth was recorded at the stations located in the Lowlands in the 1990s. In the Lakelands, there was a stable increase recorded, whereas in the mountains the variable was highly diversified.

Discussion and Conclusions

The mean annual cloud cover in Poland in the years 1951–2018, calculated on the basis of data from 57 stations distributed relatively evenly throughout the country, was 68.2%. The maximum value equal to 73% was recorded in 1966, while the minimum value of nearly 61% occurred in 1982. There is a noticeable spatial variation in the value of the element at individual stations and regions. For example, the mean annual total cloudiness amount ranges from 64% in the Coastlands to 76% in the Karkonosze Mts.

The course of cloud cover throughout the year in Poland is also varied. The lowest level of cloudiness occurs in summer and the largest in winter. Between both seasons there is a difference in cloud cover of about 15–20%. Cloudiness in spring is lower than in autumn. In general, in spring and summer, cloudiness amount decreases eastwards. In autumn and winter, the total cloudiness amount increases towards the north of the country. However, the western part of Poland is more cloudy than the east of the country.

Based on the results of this study, it can be concluded that at the greater part of analysed stations the cloud cover did not change considerably and such observations on the long-term cloudiness variability at least up to the year 2000 are consistent with the results of other authors. In the analyses by Warren et al. (2007) and Eastman and Warren (2013) covering the period from 1971 to the first decade of the twenty-first century, Poland is an area of a continuing decline in cloudiness. Wibig (2008) indicated a significant decrease in cloudiness in the city of Łódź in central Poland in the second half of the twentieth century. Similar conclusions were reached by Żmudzka (2005), also in relation to the cloudiness over Poland in the period 1951–2000, and Filipiak and Miętus (2009), characterising total cloud cover in Poland in the years 1971–2000. However, in the most recent period, up to 2018, a decrease in mean annual cloudiness is still proceeding, but only in the northern part of the country. In the south, the increase of the cloudiness is observed and the process has been advanced in the later part of subperiods analysed in this study, 1985–2018. According to Matuszko (2003) and Lewik et al. (2010), cloudiness in Kraków increase from 1983 onwards.

Statistically significant changes in the cloudiness amount in particular seasons in the period 1951–2018 are present only at a few stations in Poland, mostly located in the southern and southwestern parts Poland. More extreme changes are found by applying the analysis of the long-term variability of cloudiness in subperiods: 1951–1984 and 1985–2018. In case of winter, it can be observed the significant differentiation of both periods in terms of signs of trend coefficients of cloudiness in the country. While during the first subperiod cloudiness decreased, in the second, the trend completely reversed and a substantial, statistically significant increase in cloudiness was observed with the coefficient growing towards the south. More than 10 stations recorded a statistically significant change in cloudiness in spring in the period of 1951–1984, and the observed trends in the south were stronger than in the north. In the later subperiod, the observed trend is reversed. A few stations located in eastern Poland and in the highest parts of the Carpathians recorded statistically significant changes of cloudiness in summer in the years 1951–1984. In the period of 1985–2018, the decrease in cloudiness dominated in the country. The cloudiness in autumn slightly increased at the majority of stations in Poland in the years 1951–1984. After 1985, at a majority of stations, increases in cloudiness were observed.

Another important feature of the cloudiness conditions in Poland is related to the variability of the characteristic nephological days. In general, cloudy days are much more frequent in Poland than clear ones. They are most often observed in the Lakelands, where they constitute up to 160 days or more a year. There is a particularly strong contrast between the Lakelands and the Coastlands, where the discussed cases constitute on the average about 140 days or less. The number of clear days is decreasing considerably across the country, while in case of cloudy days, such negative changes concern only selected stations in the north, the Subcarpathians and lower ranges of the Carpathians. According to Żmudzka (2012), the number of both types of analysed characteristic nephological days declined in the period 1966–2000. Moreover, the pace of the decrease in the annual number of cloudy days was greater than in case of clear days, and this rate was particularly considerable in the case of winter. Matuszko (2007) commented on the course of the number of characteristic nephological days in Kraków in the twentieth century, which is closely related to the course of the cloud amount.

The above-mentioned situation is influenced by the fact that cloudiness is a meteorological element of complex origin and strongly related to other meteorological variables. However, many authors underline the key role of atmospheric circulation in shaping nephological conditions (Żmudzka 2003, 2004a, b, 2007; Matuszko 2003, 2009; Filipiak and Miętus 2009; Matuszko and Pluta 2012; Matuszko and Węglarczyk 2018). As with other elements (such as temperature or precipitation, Miętus and Filipiak 2001, 2002), its role increases in the cold season. As Filipiak (2012) reported, the results of the analyses of the influence of regional atmospheric circulation on the variability of the average monthly cloudiness demonstrated a strong relationship between the development of clouds and the properties of the inflowing air masses, as well as the characteristic weather features in baric systems. It was also clearly proved that characteristic properties of cloudiness in the months of the cool half of the year are largely determined by the character of the atmospheric circulation. However, in the warm half of the year, a more important role is played by the processes of thermal convection. Żmudzka (2004a, b, 2007, 2012) emphasised that the decrease in cloudiness is caused by anticyclonic systems with meridional air inflow—in the cold half of the year from the south, and in the warm mainly from the north—while the high frequency of cyclonic systems is conducive to the increase in cloudiness. Moreover, the trends of changes in the amount of cloudiness over Poland correspond with changes in macro-scale circulation conditions (so-called circulation epochs). Even up to 80% of changes resulting in variance in cloudiness results directly from atmospheric circulation. Her findings were partially proved by Szyga-Pluta (2015) in the study describing circulation influence on cloudiness in the city of Poznań. According to Henderson-Sellers (1986) the mentioned long-term decrease in cloudiness in Central Europe up to the beginning of 1980s was directly dependent on the circulational conditions and particularly in the higher than usual frequency of radiative weather associated with baric highs. The evidence on the strong relationship between cloudiness in Kraków and North Atlantic Oscillation was presented by Lewik et al. (2010).

The key role of regional atmospheric circulation in shaping the described element means that the mean annual cloud amount in Poland does not differ significantly from the values recorded in neighbouring European countries and in the entire Baltic Sea basin (Henderson-Sellers 1986; Miętus 1998; Tuomenvirta et al. 2000; BACC 2008). This regional climatic factor may also explain why relatively high amount of clouds in Poland can be observed. It is perhaps related to the effect of the Atlantic Ocean, the source of humid masses of maritime polar air, prevailing throughout almost the whole year in Poland. When this type of air mass flows into the country, there is a characteristic increase in cloudiness.

Despite this fact, it should be highlighted that regional atmospheric circulation is not the only factor shaping the variability of the cloudiness in Poland. An important role in this case is also played by processes on a local scale. The diverse relief of the Lakelands of western Poland, situated on the route of the inflow of mentioned humid maritime polar air masses into Poland, may be a good example of how the local conditions may modify the level of cloudiness. It constitutes a factor favourable for the development of cloudiness. Mountains are another example which illustrates the influence of local factors affecting the formation of clouds. Orography greatly influences the dynamic and thermal conditions in this area, causing the intensification of turbulent fluxes and the development of local dynamic convective movements (Trepińska 2002). According to Szyga-Pluta (2017), who described the variability of cloud cover in the Sudety Mts the increase of cloudiness is, in general, observed with an altitude as it can be seen at Śnieżka Mt. However, there are some specific conditions related to the occurrence of anticyclonic circulation in autumn and winter, when the thermal inversion may develop in the valleys, leading to the reverse of the cloudiness field over the mountains and its foothills. Thus, cloud cover may develop at a lower altitude, below high parts of the mountains, which remain very clear. This situation, observed mostly in the cold half of the year, with the maximum in January and least frequently from May to July, explains why mountain stations are the most clouded places in Poland in summer and spring and not in winter. Moreover, the number of clear days in winter recorded at Śnieżka Mt., and especially at Kasprowy Wierch Mt., are the greatest in Poland.

It is worth noting that observations of cloudiness are conducted at stations usually located in cities. Thus, the variability of the analysed element is also influenced by factors related to the development of the city—its territorial and industrial development, anthropogenic heat emission, change in land use, or increased presence of aerosols above the urban area. Morawska-Horawska (1985) and Matuszko (2003) in the analyses of the variability of cloudiness over Kraków, drew attention to the impact of the urban environment in shaping the variability of nephological conditions. One of the aspects of the city's impact may be, in their opinion, the fact that economic activity is conducive to, inter alia, drying the atmosphere over urban areas and the associated decrease in air humidity, which in turn hinders the development of cloud cover.

Filipiak (2003) and Limanówka et al. (2012) studied the character and rate of changes of selected hygric elements at 10 selected stations in northwestern Poland in the years 1951–2000 and more than 50 stations in Poland in 1966–2008. Both analyses revealed that long-term relative air humidity decreases dominate both annually and seasonally in the analysed periods. Overall, the air dried out the most in spring. A less dynamic decrease in the value of the element is also observed in summer. In autumn and winter, situations of long-term growth in the value of the element are markedly more frequent than in the above discussed two seasons. In winter, in 10 series of more than the 50 analysed, the changes are statistically significant. In the case of water vapour pressure, the value increases during 1966–2008, particularly in winter. In spring and summer, the changes are not so dramatic, but above the majority of the country, an increase in the value of the element can be observed. In autumn the changes are the weakest, but positive trends also predominate in long-term water vapour pressure changes. Therefore, long-term changes of hygric elements favour the increase in precipitable water in the atmosphere, but the decreasing relative humidity may limit the development of clouds.

Another interesting aspect of cloudiness analysis concerns cloud type. Its spatial variability and temporal changes have been analysed by numerous Polish authors over the last few decades. Warakomski (1962) found that the most frequently recorded cloud genera in Poland are *Stratocumulus* and *Altocumulus*. Both clouds show the largest regional differences in the frequency of occurrence. They are most frequent in southwestern Poland, whereas convective clouds *Cumulus* and *Cumulonimbus* occur most often over the northeastern part of Poland. Nowak (1971) compared the incidence of *Cumulus* and *Cumulonimbus* clouds in Gdańsk and Kraków in 1961–1965, finding convective clouds more frequent in Gdańsk due to the effect of breezes, and in Kraków the relation of occurrence of both clouds to the thermal convection. Szyga-Pluta (2002) concluded that *Stratocumulus*, *Altocumulus* and *Cirrus* clouds were the most common in northwestern Poland in 1971–1990, while the other high-level clouds were the rarest. A long-term increase in the number of cases of *Cirrus*, *Altocumulus* and *Cumulus* clouds, and a decrease in the number of *Cirrocumulus*, *Cirrostratus* and *Cumulonimbus* clouds was also detected. According to Miętus et al. (2003), in Hel in the second half of the twentieth century, there is a rise in convective clouds, accompanied by a decrease in the incidence of *Stratocumulus*, *Stratus*, *Altostratus* and *Nimbostratus* clouds. Similar changes, expressed by a decrease in the frequency of stratiform clouds *Stratus* and *Nimbostratus*, associated with a slightly smaller decline of *Stratocumulus* and a rapid increase in cloudiness by *Cumulonimbus* and *Cumulus* clouds, also occur in Łódź (Wibig 2008). Moreover, it is associated with the more frequent occurrence of *Altocumulus* and high-level clouds and the fall in *Altostratus*. The study by Filipiak and Miętus (2009), related to the years 1971–2000, confirmed that *Stratocumulus*, *Altocumulus* and *Cirrus* are the most frequent clouds among, respectively the low-level, middle-level and high-level clouds in Poland, but its percentage ranges considerably in various regions. Coastlands are more favourable than the interior of the country for the occurrence of convective clouds and *Stratus* clouds. *Stratocumulus* clouds are the most frequent in areas with a diverse relief. Essentially, the frequency of *Altostratus* and *Nimbostratus* clouds is similar all over the country. On the whole, *Cirrostratus* clouds are the most frequent in western Poland, while *Cirrocumulus* clouds are the rarest.

The observations made in this paper on the spatial cloud type variability and its long-term changes are consistent with the findings of other authors presented above, and constitute a logical extension of information on the variability of cloud genera from the first decade of the twenty-first century. Some important discrepancies do exist, however.

Stratocumulus is still the most frequently observed of all low-level clouds in Poland, especially at stations located in the regions with diverse orography and at high altitudes (in the Lakelands, Uplands and in the mountains). The highest frequency of *Cumulus* is recorded in the Coastlands, while in case of *Cumulonimbus*, it is highly diversified, from 4% in Zakopane at the foothills of the Tatra Mts. to 14% in Chojnice in the Lakelands. *Stratus* occurs most frequently in the Coastlands. The first three genera of low-level clouds were observed more and more frequently in Poland during the period of 1966–2018. In the case of *Stratocumulus*, such a conclusion is distinct from the findings related to the twentieth century by the mentioned authors, e.g. Szyga-Pluta (2002), Miętus et al. (2003) and Wibig (2008). However, it is Matuszko and Węglarczyk (2018), who, in their recent paper on the long-term variability of amount and genera of clouds in Kraków in the years 1906–2015, presented evidence of the noteworthy increase of *Stratocumulus* since the 1960s. The finding on the decrease in frequency of both convective clouds since the beginning of the current century, after the earlier few decades of significant increase in their occurrence, is also consistent with the conclusions presented by Matuszko and Węglarczyk (2018). The number of *Stratus* observations also declined in the research period in Poland, which was indicated by mentioned authors (Szyga-Pluta 2002; Miętus et al. 2003; Wibig 2008; Matuszko and Węglarczyk 2018).

Altocumulus clouds dominate in the structure of medium-level cloudiness. As Warakomski (1962) observed, it is mostly observed at the stations in the southwestern part of Poland. Again, dependence on the diverse relief can be observed, like in case of *Stratocumulus*. *Altostratus* and *Nimbostratus*, are not frequently observed in Poland. The frequency of occurrence of *Altostratus* slightly decreases from west to east. The more rare *Nimbostratus* is observed in 5–6% of cases maximum. The number of observed *Altostratus* and *Nimbostratus* systematically decreased, while in case of *Altocumulus*, an increase in its occurrence can be observed. These conclusions are consistent with the results related to the earlier periods in mentioned papers. Matuszko and Węglarczyk (2018) also reported on the considerable increase in both middle-level stratiform clouds, but it worth noting that, in contrast to this study, the occurrence of *Altocumulus* in Kraków has been declining since the beginning of the twenty-first century.

Among high-level clouds, *Cirrus* is most frequently observed in Poland with a frequency of occurrence between 10 and 22% at particular stations, but with quite chaotic spatial distribution. *Cirrostratus* is observed with an average frequency of almost 7% in the country, however this value decreases from the west to the east of

Poland. The average frequency of *Cirrocumulus* in Poland is less than 1%, with the lowest value in the Coastlands, increasing with altitude. The occurrence frequency of all three genera of high-level clouds has been systematically increasing in Poland. The positive trend is most pronounced in case of *Cirrus*. Wibig (2008) reported on the proliferation of all genera of high-level clouds in Łódź in the second half of the twentieth century. Alternatively, Matuszko and Węglarczyk (2018) found a decreasing tendency for *Cirrostratus* in Kraków.

It is the matter of discussion why such diversified trends in the occurrence of various genera of clouds are present in the analysed series. In the case of *Cirrus*, one of the most probable explanations is related to the intensification of the air traffic resulting in the increase in contrails transforming into *Cirrus* clouds (Henderson-Sellers 1986). The occurrence of other cloud genera is associated with the specific circulation conditions. According to Warakomski (1962) and Matuszko and Węglarczyk (2018), the great frequency of occurrence of *Stratocumulus* and *Altocumulus* clouds results from their linkage to maritime polar mass inflow, prevailing throughout nearly the whole year in Poland, especially in the cold half of the year. Though very high values of North Atlantic Oscillation index occurred in the 1990s (Hurrell et al. 2003) resulting in the rise in advection of humid maritime polar masses, a positive anomaly in the long-term variability of *Stratocumulus* and *Altocumulus* occurrence corresponding to it can be observed. However, in the course of *Altocumulus* occurrence, a positive anomaly can be observed in the 2010s when very high values of NAO index occurred again (Deser et al. 2017). Current global climate change manifested in the rise of surface temperature may create conditions favourable to the more frequent occurrence of convective clouds. On the contrary, a decrease in relative humidity may limit such development. It may prove that the coupling between the occurrence of the particular cloud genera and circulation patterns is non-linear. Additionally, the opinion by Matuszko and Węglarczyk (2018) on the correctness of visual observations which constitute the research material is sensible. For a group of observers, it is still challenging to differentiate between some genera of clouds, which may result in misleading results of any analyses of the occurrence of cloud type.

There is also an important question about the future long-term development of cloud cover. The currently observed climate change, manifested in many ways, e.g. in the ongoing warming of the troposphere, have significant implications for the energy and mass fluxes between the atmosphere and the ground. Systematic changes of the total cloud amount are associated with long-term declines or increases in the values of a number of other climatic elements. For the area of Europe, and especially the part located within the Baltic Sea basin, there is a positive correlation between changes in air temperature and atmospheric precipitation (BACC 2008; BACC II 2015), at least for winter, spring and autumn. This phenomenon is consistent with the Clausius-Clapeyron equation, whereby the mean air temperature increase of 1 °C entails about 7% increase in the potential quantity of water in the atmosphere, including, in particular, water vapour content, the most crucial long-wave radiation absorbent. The consistency of the nature of temperature and precipitation changes is primarily of advection origin. In summer, the presence of water in the atmosphere is to a lesser degree determined by the advection factor in favour of local processes, which also significantly influence cloudiness (Numaguti 1999). A decrease in daily temperature amplitude, observed in the majority of areas on the planet, is connected with an increase in total cloudiness degree (Karl et al. 1993; Zhou et al. 2016). Changes in cloudiness are in turn the result of a number of meteorological processes related to the quantity of water vapour, its condensability and thermal balance of the atmosphere, and the associated development or inhibition of atmospheric instability (Dai et al. 1999; Willett et al. 2010; Tobin et al. 2012). Hence, the question arises to what extent the expected changes in cloudiness amount will be concurrent with changes in other climatic elements.

Given the results the statistical empirical projections of climate elements of Poland for the selected period of the twenty-first century obtained by Filipiak (2012) and Miętus et al. (2012), it can be concluded that the most noticeable changes in cloudiness, on the scale of the twenty-first century, reaching nearly 10% compared to the years 1971–2000, will take place in summer. In light of the research of the above-mentioned authors, it can be assumed that the progressive decrease in cloudiness will also find its implications in the variability of other climatic elements. Although in summer, the importance of local-scale processes, such as the effect of the ground, or local convection, grows significantly in comparison to other seasons (Namaguti 1999), an increase in air temperature during this century, forecast by a majority of climatologists, should be kept in mind (Boucher et al. 2013). The warming of the lower troposphere is accompanied by changes in the value of evaporation resulting, on the one hand, from the acceleration of the very evaporation rate, or on the other, from ground desiccation. Sensible and latent heat fluxes intensify. Although the water vapour pressure increases, relative humidity decreases quite rapidly, which means less favourable conditions for the development of cloudiness. The decrease in cloudiness during the day may lead to an increase in direct solar radiation. Considering also strong negative correlation between cloudiness degree and maximum temperature, an increase in the value of the thermal index should also be expected.

The expected increase in cloudiness in winter will also be conducive to systematic warming projected by various simulations performed with selected RCMs (BACC 2008; Filipiak 2012; Miętus et al. 2012; BACC II 2015). The same simulations also indicate an increase in precipitation totals in the coldest months of the year. The probable reason for the changes is a combination of the process of the air warming with the intensification of moisture flux from lower latitudes and the Atlantic Ocean into the northern and central regions of the continent, where Poland is located. The cloudiness increase will be consistent with the projected minimum air temperature increase, and the presence of clouds due to the increased downward thermal radiation will mitigate the nighttime cooling of the ground.

The reduction in cloudiness in spring is in contradiction with the increase in temperature in the light of the suggested schemes. However, it is likely that a further decline in stratiform cloudiness, with a simultaneous increase in convective cloudiness, will continue (Wibig 2008; Miętus et al. 2003; Matuszko and Węglarczyk 2018), formed as a result of increasing insolation in spring when the sky is clear.

The autumn changes in all the climatic elements, from temperature, to hygric indicators, to cloudiness are, in turn, small enough that a certain stability of the situation, characteristic of the described reference period, can be assumed.

References

BACC Author Team (2008) Assessment of climate change for the Baltic Sea basin. Regional climate studies, Springer Verlag, Berlin, Heidelberg

BACC II Author Team (2015) Second assessment of climate change for the Baltic Sea basin. Regional climate studies, Springer, Cham, Heidelberg New York, Dordrecht and London

Boers R, Brandsma T, Siebesma AP (2017) Impact of aerosols and clouds on decadal trends in all-sky solar radiation over the Netherlands (1966–2015). Atmos Chem Phys 17:8081–8100. https://doi.org/10.5194/acp-17-8081-2017

Boucher OD, Randall P, Artaxo C, Bretherton G, Feingold P, Forster V-M, Kerminen Y, Kondo H, Liao U, Lohmann P, Rasch SK, Satheesh S, Sherwood B, Stevens B, Zhang XY (2013) Clouds and aerosols. In: Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds) Climate change 2013: the physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, UK and New York, NY

Charlson RJ, Schwartz SE, Hales JM, Cess RD, Coakley JA Jr, Hansen JE, Hofmann DJ (1992) Climate forcing by anthropogenic aerosols. Science 225:423–430

Cox C, Walden V, Rowe P, Shupe MD (2015) Humidity trends imply increased sensitivity to clouds in a warming Arctic. Nat Commun 6:10117. https://doi.org/10.1038/ncomms10117

Dai A, Trenberth KE, Karl TR (1999) Effects of clouds, soil moisture, precipitation and water vapour on diurnal temperature range. J Clim 12:2451–2473. https://doi.org/10.1175/1520-0442(1999)012%3c2451:EOCSMP%3e2.0.CO;2

Deser C, Hurrell JW, Phillips AS (2017) The role of the North Atlantic Oscillation in European climate projections. Clim Dyn 49:3141–3157. https://doi.org/10.1007/s00382-016-3502-z

Eastman R, Warren SG (2013) A 39-Yr survey of cloud changes from land stations worldwide 1971–2009: long-term trends, relation to aerosols, and expansion of the Tropical Belt. J Clim 26(4):1286–1303. https://doi.org/10.1175/jcli-d-12-00280.1

Eastman R, Warren SG, Hahn CJ (2011) Variations in Cloud Cover and Cloud Types over the Ocean from Surface Observations, 1954–2008. J Clim 24(22): 5914-5934. https://doi.org/10.1175/2011jcli3972.1

Filipiak J (2003) Zmienność zachmurzenia na wybrzeżu Morza Bałtyckiego i Pojezierzu Pomorskim w drugiej połowie XX wieku. Sprawozdanie z Tematu Badawczego KBN-5. IMGW Oddział Morski w Gdyni (manuscript)

Filipiak J, Miętus M (2009) Spatial and temporal variability of cloudiness in Poland, 1971-2000. Int J Climatol 29:1294–1311. https://doi.org/10.1002/joc.1777

Filipiak J (2012) Scenariusze zmian klimatu Polski. Warunki nefologiczne. Raport końcowy z wykonania prac w zakresie podzadania 1.2. Sprawozdanie z Projektu KLIMAT Wpływ zmian klimatu na środowisko, gospodarkę i społeczeństwo. IMGW-PIB, Warszawa (manuscript)

Henderson-Sellers A (1986) Cloud changes in a warmer Europe. Clim Change 8:25–52

Hollmann R, Merchant CJ, Saunders R, Downy C, Buchwitz M, Cazenave A, Chuvieco E, Defourny P, de Leeuw G, Forsberg R, Holzer-Popp T, Paul F, Sandven S, Sathyendranath S, van Roozendael M, Wagner W (2013) The ESA climate change initiative: satellite data records for essential climate variables. Bull Am Meteorol Soc 94:1541–1552. https://doi.org/10.1175/bams-d-11-00254.1

Hurrell JW, Kushnir Y, Ottersen G, Visbeck M (2003) An overview of the North Atlantic Oscillation. In: Hurrell JW, Kushnir Y, Ottersen G, Visbeck M (eds), The North Atlantic Oscillation: climatic significance and environmental impact. Geophys Monograph 134:1–35. https://doi.org/10.1029/134GM01

IMGW-PIB (2013) Metody określania rzetelności obserwacji meteorologicznych oraz eliminacji lub redukcji zmian tej rzetelności. Temat Badawczy DS-M Doskonalenie jakości procesu pozyskiwania i weryfikacji danych meteorologicznych z naziemnego systemu stacji synoptycznych (manuscript)

Jun S-Y, Ho CH, Jeong J-H, Choi Y-S, Kim B-M (2016) Recent changes in winter Arctic clouds and their relationships with sea ice and atmospheric conditions. Tellus A 68. https://doi.org/10.3402/tellusa.v68.29130

Karl TR, Knight RW, Gallo KP, Peterson TC, Jones PD, Kukla G, Plummer N, Razuvayev V, Lindseay J, Charlson RJ (1993) A new perspective on recent global warming: asymmetric trends of daily maximum and minimum temperature. Bull Am Meteorol Soc 74:1007–1023. https://doi.org/10.1175/1520-0477(1993)074%3c1007:ANPORG%3e2.0.CO;2

Lewik P, Matuszko D, Morawska-Horawska M (2010) Multi-annual variability of cloudiness and sunshine duration in Krakow between 1826 and 2005. In: Przybylak R, Majorowicz J, Brazdil R, Kejna M (eds) The Polish climate in the European context: an historical overview. Advances in global change research, vol XVIII. Springer. Dordrecht, The Netherlands, Heidelberg, Germany, London and New York, NY, pp 341–353

Limanówka D, Biernacik D, Czernecki B, Farat R, Filipiak J, Kasprowicz T, Pyrc R, Urban G, Wójcik R (2012) Zmiany i zmienność klimatu od połowy XX w. In: Wibig J, Jakusik E (eds) Warunki klimatyczne i oceanograficzne w Polsce i na Bałtyku Południowym. IMGW-PIB, Warszawa, pp 7–32

Matuszko D (2003) Cloudiness changes in Cracow in the 20th century. Int J Climatol 23(8):975–984. https://doi.org/10.1002/joc.887

Matuszko D (2007) Zachmurzenie. In: Matuszko D (ed) Klimat Krakowa w XX wieku. IGiGP UJ, Kraków

Matuszko D (2009) Wpływ zachmurzenia na usłonecznienie i całkowite promieniowanie słoneczne (na przykładzie krakowskiej serii pomiarów). Wydawnictwo Uniwersytetu Jagiellońskiego, Kraków

Matuszko D, Pluta G (2012) Rola cyrkulacji atmosfery w kształtowaniu zachmurzenia (na przykładzie Krakowa). In: Bielec-Bąkowska Z, Łupikasza E, Widawski A (eds) Rola cyrkulacji atmosfery w kształtowaniu klimatu. Uniwersytet Śląski, Sosnowiec, pp 147–156

Matuszko D, Węglarczyk S (2018) Long-term variability of the cloud amount and cloud genera and their relationship with circulation (Kraków, Poland). Int J Climatol 38:1205–1220. https://doi.org/10.1002/joc.5445

Miętus M (ed) (1998) The climate of the Baltic Sea basin. World Meteorological Organization, Marine Meteorology and Related Oceanographic Activities, Rep. No. 41, WMO/TD-No. 933

Miętus M, Filipiak J (2001) Struktura czasowo-przestrzennej zmienności warunków termicznych w rejonie Zatoki Gdańskiej, Materiały Badawcze IMGW, Seria Meteorologia, 32, 53 pp

Miętus M, Filipiak J (2002) Struktura czasowo-przestrzennej zmienności warunków opadowych w rejonie Zatoki Gdańskiej, Materiały Badawcze IMGW, Seria Meteorologia, 34, 79 pp

Miętus M, Filipiak J, Owczarek M (2003) Czasowa i przestrzenna zmienność opadów atmosferycznych w rejonie wybrzeża Zatoki Gdańskiej oraz jej spodziewane zmiany w skali XXI wieku. In: Cyberski J (ed) The Flood in Gdansk. GTN, Gdansk, pp 35–55

Miętus M, Biernacik D, Czernecki B, Filipiak J, Marosz M, Owczarek M, Pilarski M, Wójcik R (2012) Statystyczno-empiryczne projekcje wybranych elementów klimatu Polski na lata 2011–2030. In: Wibig J, Jakusik E (eds) Warunki klimatyczne i oceanograficzne w Polsce i na Bałtyku Południowym. IMGW-PIB, Warszawa, pp 34–91

Morawska-Horawska M (1985) Cloudiness and sunshine in Cracow, 1861–1980, and its contemporary tendencies. J Climatol 5:633–642. https://doi.org/10.1002/joc.3370050605

Norris JR, Slingo A (2009) Trends in observed cloudiness and Earth's radiation budget: what do we not know and what do we need to know? In: Clouds in the perturbed climate system. Heintzenberg J, Charlson RJ (eds.). MIT Press, Cambridge, MA, pp 17–36

Norris JR, Allen R, Evan A, Zelinka MD, O'Dell CW, Klein SA (2016) Evidence for climate change in the satellite cloud record. Nature 536:72–75. https://doi.org/10.1038/nature18273

Nowak M (1971) Częstość występowania chmur Cumulus i Cumulonimbus w Gdańsku i Krakowie, 1961-1965. Zesz. Nauk. Wydz. BiNoZ UG 1

Numaguti A (1999) Origin and recycling processes of precipitating water over the Eurasian continent: Experiments using an atmospheric general circulation model. J Geophys Res 104: 1957–1972 https://doi.org/10.1029/1998JD200026

Schneider T, Kaul CM, Pressel KG (2019) Possible climate transitions from breakup of stratocumulus decks under greenhouse warming. Nat Geosci 12:163–167. https://doi.org/10.1038/s41561-019-0310-1

Siebesma AP, Brenguier J-L, Bretherton CS, Grabowski WW, Heintzenberg J, Kärcher B, Lehmann K, Petch JC, Spichtinger P, Stevens B, Stratmann F (2009) Cloud-controlling factors. In: Heintzenberg J, Charlson RJ (eds) Clouds in the perturbed climate system: their relationship to energy balance, atmospheric dynamics, and precipitation. MIT Press, Cambridge, pp 269–290

Solon J, Borzyszkowski J, Bidłasik M, Richling A, Badora K, Balon J, Brzezińska-Wójcik T, Chabudziński Ł, Dobrowolski R, Grzegorczyk I, Jodłowski M, Kistowski M, Kot R, Krąż P, Lechnio J, Macias A, Majchrowska A, Malinowska E, Migoń P, Myga-Piątek U, Nita J, Papińska E, Rodzik J, Strzyż M, Terpiłowski S, Ziaja W (2018) Physico–geographical mesoregions of Poland: verification and adjustment of boundaries on the basis of contemporary spatial data. Geographia Polonica 91:143–170. https://doi.org/10.7163/gpol.0115

Stjern CW, Kristjànsson JE, Hansen AW (2009) Global dimming and global brightening—an analysis of surface radiation and cloud cover data in northern Europe. Int J Climatol 29:643–653. https://doi.org/10.1002/joc.1735

Szyga-Pluta K (2002) Częstość występowania rodzajów chmur w Polsce Północno-Zachodniej. UAM, Poznań

Szyga-Pluta K (2015) Circulation influence on cloudiness in Poznań. Quaestiones Geographicae 34:141–149. https://doi.org/10.1515/quageo-2015-0021

Szyga-Pluta K (2017) Variation of cloudiness in the mountain region on the example of the Sudetes. Badania Fizjograficzne Seria A Geografia Fizyczna A 68: 205–221. https://doi.org/10.14746/bfg.2017.8.15

Tobin I, Bony S, Roca R (2012) Observational evidence for relationships between the degree of aggregation of deep convection, water vapor, surface fluxes, and radiation. J Clim 25(20):6885–6904. https://doi.org/10.1175/jcli-d-11-00258.1

Trepińska J (2002) Górskie klimaty. Wyd. IGiGP UJ, Kraków

Tuomenvirta H, Alexandersson H, Drebs A, Frich P, Nordli PØ (2000) Trends in Nordic and Arctic temperature extremes and ranges. J Clim 13:977–990. https://doi.org/10.1175/1520-0442(2000)013%3c0977:TINAAT%3e2.0.CO;2

Ustrnul Z, Niedźwiedź T (1994) Wstępna analiza zachmurzenia Polski. Sprawozdanie z Tematu Badawczego M-2. IMGW Oddział w Krakowie (manuscript)

Vavrus SJ, Bhatt US, Alexeev VA (2011) Factors influencing simulated changes in future Arctic cloudiness. J Clim 24(18):4817–4830. https://doi.org/10.1175/2011JCLI4029.1

Warakomski W (1962) O częstości występowania poszczególnych rodzajów chmur w Polsce. Prz Geof 3:185–192

Warren SG, Eastman RM, Hahn CJ (2007) A survey of changes in cloud cover and cloud types over land from surface observations, 1971–1996. J Clim 20:717–738. https://doi.org/10.1175/JCLI4031.1

Webb MJ, Andrews T, Bodas-Salcedo A, Bony S, Bretherton CS, Chadwick R, Chepfer H, Douville H, Good P, Kay JE, Klein SA, Marchand R, Medeiros B, Siebesma AP, Skinner CB, Stevens B, Tselioudis G, Tsushima Y, Watanabe M (2017) The Cloud Feedback Model Intercomparison Project (CFMIP) contribution to CMIP6. Geosci Model Dev 10:359–384. https://doi.org/10.5194/gmd-10-359-2017

Wibig J (2008) Cloudiness variations in Łódź in the second half of the 20th century. Int J Climatol 28:479–491. https://doi.org/10.1002/joc.1544

Willett KM, Jones PD, Thorne PW (2010) A comparison of large scale changes in surface humidity over land in observations and CMIP3 general circulation models. Environ Res Lett 5:1–13. https://doi.org/10.1088/1748-9326/5/2/025210
WMO (2018) Manual on codes—international codes. Volume I.1 Annex to the WMO Technical Regulations: part A - Alphanumeric Codes. WMO TD No. 306
Zhou C, Zelinka MD, Klein SA (2016) Impact of decadal cloud variations on the Earth's energy budget. Nat Geosci 9:871–874. https://doi.org/10.1038/ngeo2828
Żmudzka E (2003) Wielkość zachmurzenia w Polsce w drugiej połowie XX wieku. Prz Geofizyczny 3–4:159–185
Żmudzka E (2004a) Epoki cyrkulacyjne a zmienność zachmurzenia w Polsce. Prz Geofizyczny 1–2:25–41
Żmudzka E (2004b) Uwarunkowania cyrkulacyjne zmienności zachmurzenia w Polsce. Czas Geogr 75:1–2
Żmudzka E (2007) Zmienność zachmurzenia nad Polską i jej uwarunkowania cyrkulacyjne (1951–2000). Wydawnictwo UW, Warszawa
Żmudzka E (2012) Nefologiczne dni charakterystyczne – różne kryteria wydzielania i ich wpływ na wyniki badań. Prz Geofizyczny 1: 21-33.