PRECIPITATION OF THE MEDITERRANEAN ORIGIN IN POLAND – ITS SEASONAL AND LONG-TERM VARIABILITY

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Abstract: The article presents the results of the analysis of precipitation in Poland associated with cyclones moving from the Mediterranean Sea to East-Central Europe (Mediterranean Cyclonal Precipitation – MCP). The MCP accounts for about 10% of the total amount of precipitation in Poland. Average daily sum of MCP constitutes approximately 150% of daily amount of all precipitation in Poland. The MCP amount reaches its maxima at the end of April and in the mid-August. The highest MCP occurs in the Carpathians and the Sudetes as well as over stripes of land extending northward and covering the central-western and eastern parts of the country. In the years 1958–2008, the mean annual MCP was characterized by a significant decreasing trend - the MCP sum reduced by 29 mm, i.e. ca. 42% of its multiannual value.

Key words: Mediterranean precipitation, seasonality, long-term changes, Poland

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Introduction

Cyclonic systems moving over Europe migrate mostly from the West to the East along the tracks which were the subject of many climatological studies, starting from the works by W. Kőppen (1882) and van Bebber (1891). Among the trajectories of European cyclones, the track Vb distinguishes itself on van Bebber's map by running, unlike the others, longitudinally from the Adriatic through Central and Eastern Europe to the borders of Finland. Its odd trajectory and the area of cyclogenesis result in a significant role played by the cyclones following the track Vb in shaping climatic conditions, and especially the volume of precipitation in Central and Eastern Europe. These cyclones (MEC – Mediterranean European Cyclones) carry with them northward huge amounts of moisture, and on their western peripheries circulation develops which encounters the orographic barriers of the Western Carpathians, the Sudetes and the Alps, which is conducive to the formation of high precipitation in the region. A detailed description of the properties and the climatic role of Mediterranean cyclones can be found in the article by Bartoszek (2006).

Mediterranean cyclones, in their position east of Poland, form the eastern and north-eastern cyclonic circulation type E0 (according to the classification by Osuchowska-Klein 1978), bringing high precipitation both to the eastern part of the Polish sea coast (Świątek 2009), to north-western Poland (Kirschenstein 2013) and to the interior of the country, including Łódź (Wibig, Fortuniak 1998), as well as to the mountains and their foreland, for example Wrocław (Dubicka 1991) and Kraków (Twardosz 1997).

The MEC pressure systems cause flooding or blizzards in Poland and the neighbouring countries. As early as in 1906, Hann described the snowstorms that had passed over Vienna and the eastern part of Germany (i.e., probably also over the western part of Poland) in the spring of 1903 and of 1905, and linked them to Mediterranean cyclones. Some examples of activity of Mediterranean cyclones in recent years are the floods in the Czech Republic and Poland in 2010 and the heavy snowfalls in Central Europe and Ukraine in the autumn, winter and spring 2012–2013.

The subject of this study is atmospheric precipitation in Poland associated with the activity of the MEC systems. Daily precipitation sums were distinguished for this purpose which were assigned – according to the method described hereinafter – *Mediterranean origin*, i.e. origin formed under the influence of the MEC.

The objectives of this work are: (a) to assess the average amount of precipitation of the Mediterranean origin (the MCP – Mediterranean Cyclonic Precipitation) in the area of Poland, (b) to determine the share of the MCP in total atmospheric precipitation in Poland and (c) to determine the seasonal and long-term variability of the MCP in Poland. So far we have not had such assessments yet.

Several simple research assumptions have been examined in the study:

1. the amount and share of the MCP in total precipitation in Poland vary seasonally, in accordance with the changes in the occurrence of the MEC systems during the year, whose frequency increases in spring and autumn (Degirmendžić, Kożuchowski 2014); a similar correlation holds for multi-annual changes in the MCP sums and the trend of the incidence of the MEC;
2. the daily totals of Mediterranean precipitation are among the highest in Poland, and therefore the share of the MCP in precipitation totals increases with the amount of these totals;
3. both the amounts and the share of the MCP in total precipitation are the highest in the mountains and in areas of their foreland, i.e. in southern Poland.

Data and methods of their analysis

The study uses the database of cyclone systems created by Serreze (2009); it is a result of the application of automatic procedure of detecting and tracking cyclones moving over the Northern Hemisphere during the period between 01.01.1958 and 31.12.2008. The positions of cyclones were determined for each 24 hours at the following times: 00, 06, 12 and 18 UTC.

In order to isolate the Mediterranean European cyclones (MEC) passing from the Mediterranean Sea, the Black Sea or the Azov Sea to Central Europe, the following two criteria were used in this study:

1. at any stage of the development of a cyclonic system, its centre is located over the basins of the Mediterranean Sea, the Black Sea or the Azov Sea;
2. at a later stage of development, the centre of the cyclone moves over an area lying no farther than 350 km from the Polish borders.

In this way, 351 systems meeting the above conditions were selected in the period from 1958 through 2008, i.e., on average, 6.9 MEC systems were recorded annually, of which 2.4 cases of MEC occurred in spring, 1.4 in summer, 1.7 in autumn and 1.4 in winter. At this point, it is worth emphasizing a relatively low incidence of Mediterranean cyclones affecting the weather in Poland, as all types of cyclonic circulation cover Poland on 49 percent of days in the year (Piotrowski 2009).

The analysis of precipitation uses the series of daily precipitation totals derived from 66 meteorological stations in the period 1958–2008. The precipitation data were obtained from the Institute of Meteorology and Water Management (IMGW). Records of daily totals obtained from 46 meteorological stations (70% of all stations) are continuous and homogeneous in the period 1958–2008. Series from 7 stations include short gaps (<100 days), which means that 53 series of precipitation (80% of all stations) are nearly complete. Series with longer gaps (>610 days) refer to the stations evenly distributed on the territory of Poland throughout the period 1958–2008, therefore the MCP values averaged for the area of Poland should not be significantly biased toward plus or minus. The locations of the stations are shown in Fig. 1, which highlights the stations included in the group representing the mountains and their foreland area (13 stations).

In order to distinguish the precipitation of the Mediterranean origin (MCP) in Poland, the criterion was used according to which the daily precipitation which occurred at a station in Poland on a day when the centre of a Mediterranean cyclone was closest to the station as compared with the position of other cyclonic systems developing on that day in the Northern Hemisphere was recognized to be precipitation of the Mediterranean origin. The value of the great-circle connecting the station recording precipitation with the centre of every cyclone was calculated (i.e. for all cyclones occurring within the research period on days with precipitation regardless of the cyclone origin). Where the minimum value of the orthodrome was related to a MEC cyclone regardless of its position on the track, precipitation at the station was classified as "Mediterranean Cyclonic Precipitation" (MCP).

The centres of MEC generating precipitation of the Mediterranean origin in Poland are most frequently at a distance of 300-400 km from the recording station (Fig. 2). This distance approximately corresponds to the section between the Polish borders and the place on the trajectory of Mediterranean cyclones recognized according to an independent criterion (Degirmendžić et al. 2014) as their position corresponding to the high-

Fig. 1. Distribution of meteorological stations used in the study. Black dots represent stations in the mountain area and the foreland

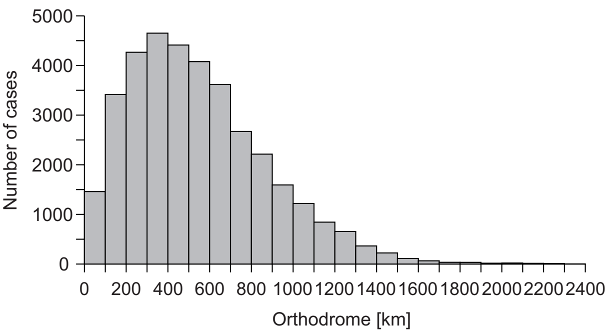

Fig. 2. Distribution of great circle values [km] determining the distance of the station where Mediterranean precipitation (MCP) occurred from the centre of the Mediterranean cyclone (MEC) (according to data from the period 1958–2008)

est precipitation in Poland (Fig. 3). This point is located near the Hungarian-Romanian border, at 21°E and 47°N.

However, the adopted method of classifying Mediterranean precipitation without taking into account the specific nature of the synoptic situation (for example, the position of fronts, the discontinuity line, positive vorticity advection in the upper atmospheric layers, etc.) does not indicate the type of the precipitation forming process. It only shows the possible involvement of the MEC being the closest to the area of Poland in generating the precipitation zone. It was noted, however, that even the Mediterranean

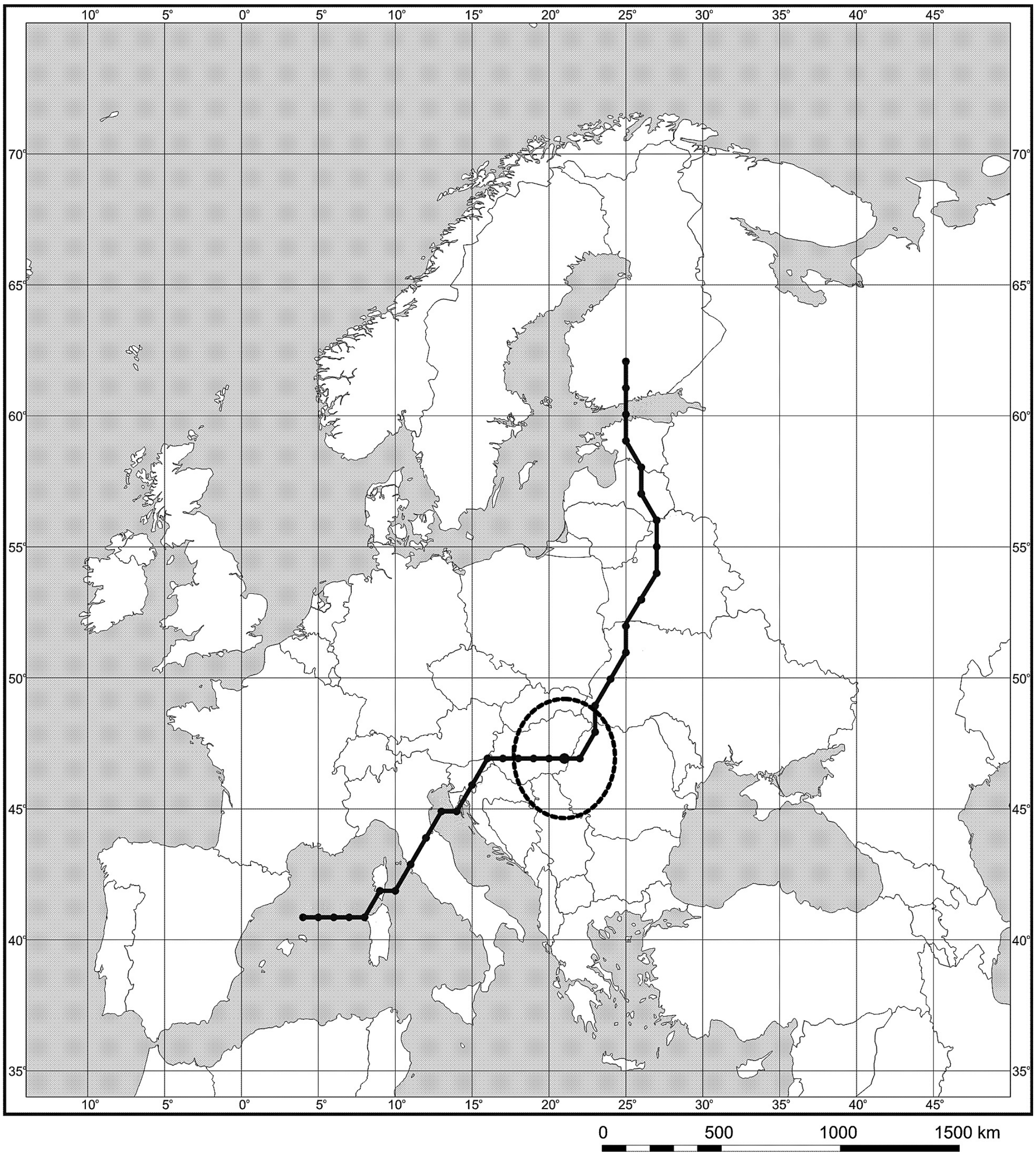

Fig. 3. Mean position of the track Vb of Mediterranean cyclones (MEC). Positions of cyclones involving the highest MCP in the area of Poland are delimited by a circle (after Degirmendžić et al., 2014)

cyclones which are considerably distant from Poland contribute to the occurrence of precipitation in the area of the country. The weather situation on 23.03.2014 may serve as an example. A cyclone situated over the Gulf of Genoa, i.e. the typical place of cyclogenesis of the MEC systems, was connected by the trough of reduced pressure to a cyclone from over the Baltic Sea. The precipitation occurring in the mountainous regions of Southern Poland was associated with disturbances of the westerly flow and a developing convergence line of air currents within the trough, while in the air flow over the Sudetes the northern component dominated.

In the analysis of the distinguished MCP, its annual, seasonal (months MAM, JJA, SON and DJF) and pentads of daily totals were calculated for individual stations, as well as averaged totals for the whole area of Poland (66 stations), averaged totals for the mountains and their foreland areas (13 stations) and the rest of the country (53 stations). The share of MCP in the distribution of total amounts of precipitation was determined in three ways: 1. ratios were calculated of pentad, seasonal and annual MCP precipitation and the corresponding total amounts of precipitation for these periods; ratios indicate what part of precipitation occurring in Poland is of the Mediterranean origin, 2. based on the total amounts of precipitation, deciles were determined for the distribution of precipitation at each station, and then the share of MCP was calculated in the precipitation ranges defined by the values of deciles, 3. the share of MCP in the adopted equal precipitation ranges (0–10.0, 10.1–20.0, 20.1–30.0 mm etc.) was calculated.

For the analysis of MCP the term of precipitation intensity was used. The precipitation intensity is defined as *the rate of precipitation, usually expressed in millimetres or inches per hour* (Glickman 2000: 593). There is also the second meaning of that term – according to Conrad and Pollak (1950: 205) *the ratio of the total amount of rain A to the number N of days with precipitation is called rain intensity I; I=A/N. Thus, I is the average amount of rain per rainy day*. In this study precipitation intensity is calculated according to the formula I=A/N and is given in millimetres per rainy day [mm day^{-1}]. The terms *raininess* or *precipitation abundance* are nearly closed to above mentioned *precipitation intensity*.

The indicator of precipitation intensity constitutes important information on the Mediterranean precipitation, especially as regards its spatial diversity in Poland and its seasonal changes. According to Tamulewicz (1993), this indicator also facilitates a comparison of the mean precipitation rate.

In the analysis of long-term variability of the Mediterranean precipitation, the linear trends of annual and seasonal totals for the period 1958–2008 were determined. The trend coefficients and determination coefficients were calculated, and the statistical significance of the trend was tested using the Mann-Kendall test and p-values associated with M-K statistics. The picture of MCP variability was completed by calculating cumulative deviations from the mean, based on annual MCP series averaged across Poland as well as in the mountain areas and their foreland.

Results

The share of Mediterranean precipitation in total amounts of precipitation

Table 1 shows the results of calculations of MCP sums against the total amounts of precipitation in Poland. The long-term means (1958–2008), the seasonal and annual precipitation totals averaged for the whole country (66 stations), for the areas of highlands and their forelands, as well as for the rest of the country – "the lowland Poland" were given. The table informs which part of precipitation occurring in Poland is the MCP and what the seasonal changes in the share of MCP in total precipitation amounts are like. The maps in Figure 4 shows the spatial distribution of the share of MCP in the annual and seasonal precipitation totals in the area of the country.

The mean total annual precipitation in the lowland Poland (605 mm) contains 55 mm (i.e. 9.1%) precipitation of the Mediterranean origin. In the mountains and their foreland areas, the mean MCP total is 112 mm (i.e. 11% of the annual total). For the whole country, this share amounts to 9.6%, which means that on the yearly average the Mediterranean precipitation of more than 66 mm falls on the area of Poland; this is more than the mean monthly precipitation total in Poland and more than what falls in May (58 mm on aver-

Table 1. Mean seasonal and annual Mediterranean precipitation (MCP) sums, total precipitation amounts and the share of MCP in precipitation totals in the area of Poland, in the highlands and their forelands, and in the remaining part of Poland (1958–2008)

Area	Precipitation Characteristics	Spring	Summer	Autumn	Winter	Year
Poland	MCP (mm)	21.3	21.4	15.8	7.6	66.2
	total (mm)	150.9	256.3	160.5	119.1	686.8
	share of MCP (%)	14.1	8.4	9.9	6.4	9.6
Highland and foreland areas	MCP (mm)	36.1	38.8	24.9	12.5	112.4
	total (mm)	233.3	400.9	220.5	164.8	1019.5
	share of MCP (%)	15.5	9.7	11.3	7.6	11.0
Rest of Poland	MCP (mm)	17.7	17.1	13.6	6.4	54.9
	total (mm)	130.7	220.8	145.7	107.9	605.2
	share of MCP (%)	13.6	7.8	9.3	5.9	9.1

age) or in September (52 mm) and as much as ¾ of the mean precipitation in July.

The share of MCP in the structure of distribution of daily precipitation totals increases with the amount of the totals (Fig. 5). The daily precipitation sum from the 9–10 decile range (one tenth of the observed precipitation totals with the highest amounts) contains in Poland on average 12.8 percent of the Mediterranean precipitation. Lower totals (<9 decile) contain between 5% and 8% of the MCP (Fig. 5). As much as 23.7% of precipitation from the range of daily totals of 80–90 mm is of the Mediterranean origin. Furthermore, it was found that starting from precipitation totals from the range of 50–60 mm, quite a number of stations can be found in Poland where the MCP is equal to 100% of the precipitation total.

The largest shares of the MCP in total annual precipitation is characteristic of south-western Poland (Kłodzko 14%, Legnica 13.5%, Jelenia Góra 13.3%, Racibórz 12.9%, Żywiec 12.7%, Mt Śnieżka and Wrocław 12.3%) and of the eastern area covering the Lublin region (Lublin 11%). The Sea Coast region has the smallest share of the MCP: in Łeba it is a mere 5.6%, in Ustka 5.7%, in Świnoujście 5.8% (Fig. 4a).

In the spring period, the incidence of the MEC systems is the highest (2.7%) and at the same time the share of the MCP in seasonal precipitation totals reaches its peak values: for the whole area of Poland it is 14.1%, while in the mountains – 15.5% (Table 1). The maxima of this share were found in Kłodzko (19.8%), in Racibórz (19.0%), on Śnieżka Mountain (18.2%), in Legnica (18.0%) and in Opole (17.9%). On the map of the share of the MCP in the spring precipitation totals (Fig. 4b), it can be seen how it decreases from the South to the North of the country; it mainly decreases in the direction from the Sudetes and their foreland to West Pomerania (in Koszalin it represents 8.8% of the total precipitation) and from the Carpathians to the Masuria and the Suwałki regions (in Mikołajki it is 10.7%).

In the summer season, the maximum shares of the MCP in seasonal precipitation totals are apparently associated with the Sudetes (Jelenia Góra 13.8%, Śnieżka and Legnica 13%) (Fig. 4c). The lowest shares of precipitation of this type occur in the northern part of the country: in Olsztyn 5.6%, in Goleniów 5.3%, and only 5% in Świnoujście. The MCP during the summer is slightly higher than in the spring, but its share in the precipitation totals in the summer season is smaller (Table 1); similarly, the summer incidence of Mediterranean cyclones is lower than their frequency in spring (1.5% and 2.7%, respectively). As far as the whole country is concerned, the share of summer Mediterranean precipitation in the total precipitation is 8.4%, while in the highlands and their foreland it is 9.7% (Table 1).

In the autumn season, the share of the MCP in seasonal totals grows again and in the larger part of Poland exceeds 10%, rising to 16.5% in Kłodzko and 15% in Żywiec (Fig. 4d). In autumn, like in spring, a high proportion of the MCP in precipitation totals occurs also in the eastern part of the country; in Lublin and Sandomierz it exceeds 13%, in Siedlce it is 12.9%, in Terespol 12.6%. In the Coast and the Pomerania regions this share is the smallest: in Ustka it is 4.9%, in Resko, Łeba and Kołobrzeg 5.2%, in Lębork 5.4%. The average share of the autumn MCP precipitation in Poland is 9.9%, while in the mountains and in their foreland areas – 11.3%, i.e. slightly lower than in

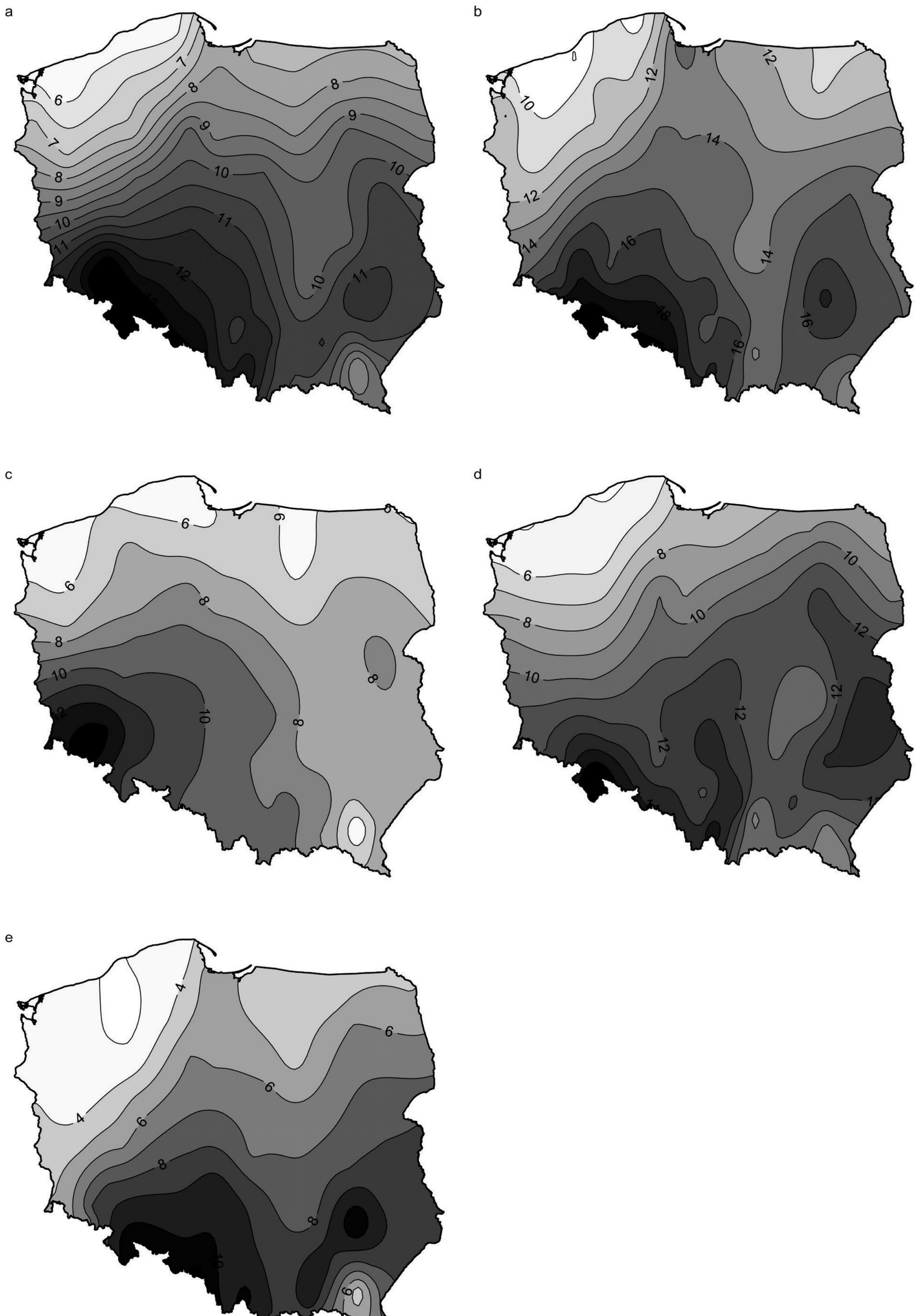

Fig. 4. Average share of MCP [%] in total annual and seasonal precipitation in the area of Poland during 1958–2008
a – year, b – spring, c – summer, d – autumn, e – winter

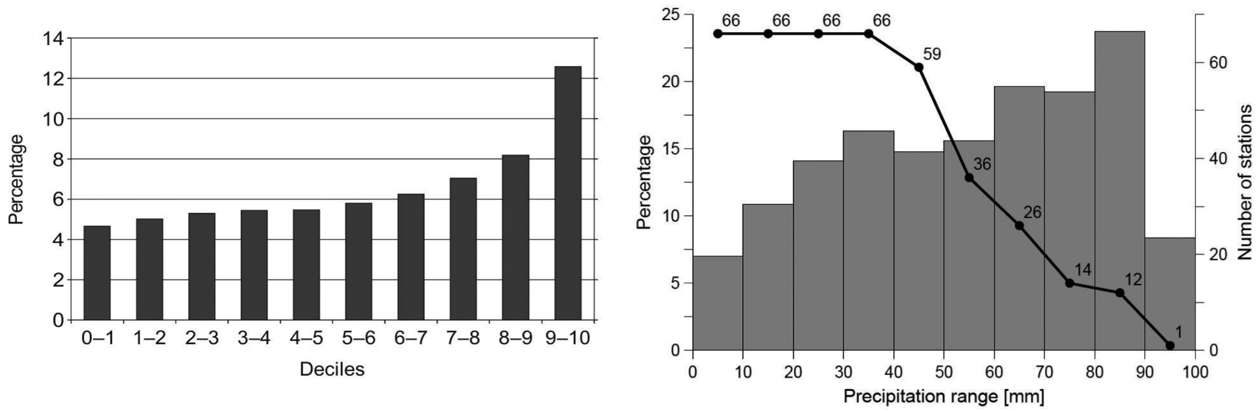

Fig. 5. Percentage of daily MCP sums in total precipitation in the area of Poland: according to deciles of daily totals distribution (left graph) and to ranges of daily totals of 0–10, 10–20, 20–30 mm etc. (right-closed intervals; right graph). In the right graph, the number of meteorological stations which recorded MCP is indicated (black line with numbers)

spring, which corresponds to a smaller number of the MEC systems than in spring at this time of the year (1.7%).

In winter, the frequency of the MEC systems is the smallest (1.4%), and, similarly, the share of the MCP in the winter precipitation totals is the lowest: in the area of Poland it varies from 11% in Sandomierz, 10.6% in Kłodzko and 10.5% in Żywiec to only 3.1% in Ustka and 3.3% in Szczecin and Świnoujście (Fig. 4e). The whole country's mean value of the share of the MCP in winter precipitation totals is 6.4%, while in the mountains it amounts to 7.6% (Table 1).

The seasonal values of the MCP share in seasonal precipitation totals apparently correlate with the frequency of the MEC systems: they are the greatest in spring and autumn. However, the absolute amounts of the MCP in summer are similar or even slightly higher than in spring. Taking into account seasonal frequency of the MEC systems generating Mediterranean precipitation in Poland, it can be demonstrated that the intensity of the MCP is the highest in summer.

Intensity of the MCP

In the area of Poland, the mean annual precipitation intensity amounts to 3 to 4 mm day^{-1}, and it is only in the South of the country that it exceeds 4 mm day^{-1}, reaching nearly 8 mm day^{-1} high in the mountains (Tamulewicz 1993).

Table 2 shows the seasonal and annual amounts of daily precipitation (on days with precipitation) averaged for the entire Polish territory, for the region of mountains and foothills, and for the lowland Poland. The mean annual intensity of precipitation of the Mediterranean origin is clearly higher than the mean intensity determined based on total precipitation amounts and the total number of rainy days. This "surplus" appears in all seasons of the year, both in the mountains and in the lowland parts of the country. The mean annual intensity of all precipitation in Poland in the period 1958–2008 was 4.1 mm day^{-1}, in the area of mountains and foothills 5.3 mm day^{-1}, in the lowland parts of the country 3.7 mm day^{-1}, while the mean intensity of Mediterranean precipitation amounted to 5.8 mm day^{-1}, 8.0 mm day^{-1} and 5.1 mm day^{-1} (Table 2). The dominance of the mean intensity of Mediterranean precipitation over the mean intensity of precipitation coming from other sources is expressed by the quotients of both the quantities, presented in Table 3. On this basis, it can be estimated that the mean intensity of the MCP amounts approximately to 150% of the mean intensity of precipitation associated with the activity of other precipitation-forming processes. In spring, in the mountainous area the mean intensity of Mediterranean precipitation increases to 168% of the value characteristic of other, *non-Mediterranean* precipitation.

The mean intensity of the MCP precipitation has a clear annual cycle with the summer maximum, similar to the changes of total precipitation amounts and their mean intensities during the year. It can also be noted that the amplitude of the annual cycle in the mean intensity of Mediterranean precipitation is slightly greater than the amplitude of changes in precipitation totals: the ratio of the mean intensities of summer and win-

Table 2. Total number of rainy days, number of days with the MCP and mean precipitation intensity (mm day^{-1}). Period 1958–2008

Area	Precipitation Characteristics	Spring	Summer	Autumn	Winter	Year
Poland	Number of precipitation days	39.7	40.5	40.8	47.1	168.1
	Mean precipitation intensity	3.8	6.3	4.2	2.5	4.1
	Number of days with MCP	3.98	2.35	2.77	2.24	11.35
	Mean intensity of MCP	5.4	9.1	5.7	3.4	5.8
Mountains & Foothills	Number of precipitation days	49.5	48.8	44.9	50.1	193.3
	Mean precipitation intensity	4.7	8.2	4.9	3.3	5.3
	Number of days with MCP	4.93	3.14	3.4	2.56	14.05
	Mean intensity of MCP	7.3	12.4	7.3	4.9	8.0
Lowlands	Number of precipitation days	38.8	39.7	36.6	47.4	162.5
	Mean precipitation intensity	3.4	5.5	3.9	2.3	3.7
	Number of days with MCP	3.75	2.15	2.62	2.16	10.68
	Mean intensity of MCP	4.7	8.0	5.2	3.0	5.1

ter MCP in Poland is 2.67, while the ratio of the mean intensities of total precipitation amounts in these seasons is 2.52. In spring, the mean intensity of the MCP as well as of total precipitation is slightly smaller than in autumn, and only in the mountains the mean intensities of the MCP are equal in both seasons (Table 2).

The maps in Figure 6 show the images of the spatial diversity of mean MCP intensity in the Polish territory in a year and seasons. The general feature of this diversity is the mean MCP intensity gradient pointing from the South (more precisely: from SSW) to the North of the area. This gradient reaches the highest values in the area of foothills, where the contrasts of this precipitation indicator are the greatest.

The mean annual intensity of the MCP (Fig. 6a) decreases from 11–12 mm day^{-1} in the Tatra Mountains and 10 mm day^{-1} on Mt Śnieżka to about 6 mm day^{-1} in the Carpathian Foothills and the Silesian Lowland. In the Polish lowland areas, the mean intensity of the MCP is about 5–6 mm per day with precipitation, in the Coast region and Pomerania it decreases to ca. 4 mm day^{-1}; however, everywhere it is greater than the total precipitation intensity and is usually close to 150% of its value.

In spring (Fig. 6b), the greatest mean MCP intensity occurs in the mountains (Hala Gąsienicowa 11 mm day^{-1}, Kasprowy Wierch and Śnieżka 9 mm day^{-1}). A relatively high mean intensity (about 5 mm day^{-1}) is characteristic of the MCP precipitation appearing in the southern belt of Poland, including the southern part of Wielkopolska (Greater Poland), the Silesian Lowland and the Lublin Upland. The mean MCP intensity on the coast and in Lubusz Land (Gorzów Wielkopolski) falls to 4 mm day^{-1}.

The summer picture of diversity of the mean MCP intensity shows a large contrast between south-western Poland and the eastern and northern parts of the country. The 8 mm day^{-1} isoline embraces the whole area lying to the South and West of Poznań, Toruń, Sulejów and Tarnów. The highest values are in the Tatra Mountains and the Karkonosze (Giant Mountains) (Hala Gąsienicowa 19 mm day^{-1}, Kasprowy Wierch 17 mm day^{-1}, Śnieżka 15 mm day^{-1}), a relatively high mean intensity is characteristic of the areas of foothills and those situated quite far in the mountain foreland (Bielsko Biała and Legnica 12 mm day^{-1}, Wrocław and Częstochowa 11 mm day^{-1}, Kalisz 9 mm day^{-1}). Even in Toruń and Poznań the mean MCP intensity exceeds 8 mm day^{-1}, similar high values occur in the central part of the Pomeranian Lake District (in Chojnice, Szczecinek and in Koszalin). A less delineated area with a fairly high mean MCP intensity (>7 mm day^{-1}) lies in the north-eastern part of the country. The lowest values (6 mm day^{-1}) were recorded in Świnoujście and Mława (Fig. 6c).

Table 3. Mean intensity ratios of MCP and other precipitation. Period 1958–2008

Area	Spring	Summer	Autumn	Winter	Year
Poland	1.49	1.50	1.35	1.36	1.47
Mountains & Foothills	1.68	1.56	1.56	1.52	1.58
Lowlands	1.48	1.48	1.35	1.31	1.42

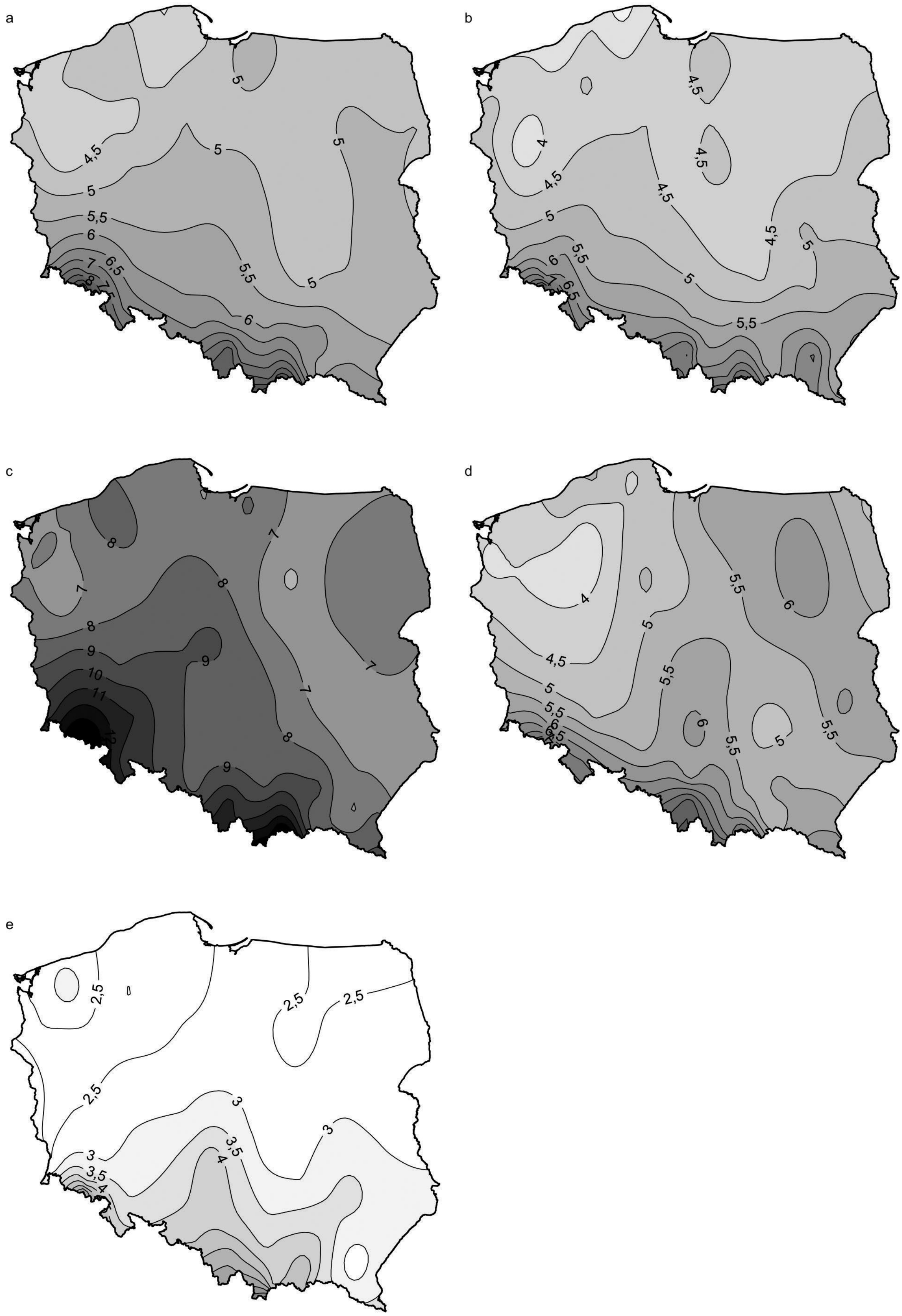

Fig. 6. Mean MCP intensity in Poland [mm day-1] in 1958–2008
a – year, b – spring, c – summer, d – autumn, e – winter

In autumn, the Mediterranean precipitation is most abundant in the mountains (Hala Gąsienicowa 10 mm day^{-1}, Kasprowy Wierch 9 mm day^{-1}, Śnieżka 8 mm day^{-1}) and in the belt stretching from the Beskid Żywiecki (Żywiec 8 mm day^{-1}, Bielsko-Biała 9 mm day^{-1}) through Upper Silesia and the Częstochowa Upland to Łódź (Katowice, Częstochowa and Łódź 6 mm day^{-1}). The second belt of elevated mean MCP intensity runs through eastern Poland – from the Lublin Upland through Podlasie to Masuria. The mean MCP intensity in this belt exceeds 6 mm day^{-1} in some places (e.g. in Lublin and Ostrołęka).

In winter, the mean MCP intensity is the smallest; in the northern half of Poland it does not reach 3 mm day^{-1}. It is higher in the mountains, especially in the Tatra Mountains (Kasprowy Wierch 9 mm day^{-1}) and in the Karkonosze (Mt Śnieżka 7 mm day^{-1}). The belts of relatively high mean winter MCP intensity extend from the South to the North through Central Poland and the eastern part of the country (Fig. 6e).

The isarithms of mean Mediterranean precipitation intensity, besides reflecting the occurrence of most abundant precipitation in the mountains, reveal a tendency to be arranged in more or less meridionally elongated belts of mean MCP intensity. In the arrangement of seasonal as well as annual values, the presence of two belts of high values of mean MCP intensity can be observed: the western belt extends to Wielkopolska from the foot of the Sudetes and the Western Beskid Mountains, the second (eastern) belt, more variable during the year, locates itself in eastern or north-eastern Poland.

The zones of maximum precipitation in Poland have a meridional course; an example was already given by Mycielska and Michalczewski (1972), who showed the distribution of torrential precipitation totals in July 1970, associated with South-European cyclonic circulation, and causing floods in the Vistula basin. The existence of two tracks of torrential precipitation, extending northward from the Sudetes and the Carpathians, was also described by Kożuchowski and Wibig (1988). The overlap of these longitudinally oriented routes of torrential precipitation and the latitudinally arranged zones of mean precipitation totals, largely related to the land relief (sea coast and lake districts, lowlands, uplands, mountains), results in Poland in a "grate" character of the fields of precipitation (Kożuchowski 2010). The image of the field of highest monthly Mediterranean precipitation in Poland (August 1972, mean MCP precipitation in Poland 69.4 mm) confirms this statement: there is a clearly visible meridional strip of highest precipitation which stretches along the eastern border of the country (Fig. 7). Such strips change their position: sometimes they may follow the longitudinal axis stretched from the Beskid Żywiecki Mountains through Central Poland to the Vistula Lagoon, sometimes situated along the eastern border, and some other times extended from the Sudetenland to the Pomeranian Lake District.

Seasonality of the MCP

An analysis of mean seasonal amounts of precipitation of the Mediterranean origin, of their share in precipitation totals and of the mean MCP intensity points to the existence of various rhythms of changes in these precipitation indicators during the year. The amounts (seasonal MCP totals) are the highest in summer and spring, the share of MCP in general precipitation totals has its maxima in spring and autumn, and the mean MCP intensity reaches its highest values in summer. However, the seasonal values form only a generalized picture of the annual rhythm of precipitation changes. In order to obtain more detailed data on the seasonal variability of MCP, the mean pentad of daily totals were used and

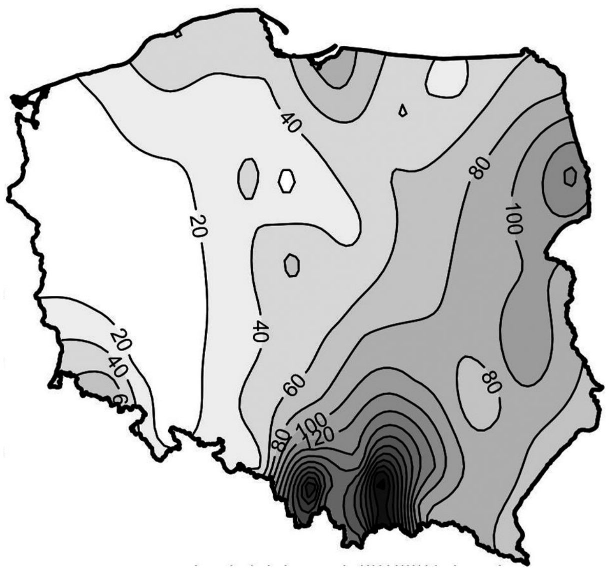

Fig. 7. Monthly MCP totals [mm] in Poland in August 1972

their averaged values from all over the area of Poland were considered.

The pentad means of Mediterranean precipitation in the period 1958–2008 are characterized by considerable changeability during the year, which is caused, on the one hand, by low frequency of MCP precipitation events, resulting in the image of their annual course being quite chaotic, and on the other hand by the fact that the already mentioned rhythms of frequency, amount and intensity of MCP cause the pentad sums to vary depending on the interference of these rhythms.

Figure 8 shows the annual course of pentad mean MCP against the mean precipitation totals in Poland. The highest 5-day total appears in the 20th pentad, i.e. during the period of April 6–10. Its average amount (nearly 3 mm) is equal to one third of the mean total rainfall which occurred on those days. The next highest mean pentad MCP totals are found in the 44th, 48th, 31st and 58th pentads, i.e. respectively on 4-8.08, 24–28.08, 31.05-4.06 and 13–17.10. The share of these totals amounts to ca. 20% of total precipitation in Poland.

The annual course of pentad totals can therefore be divided into two main phases of Mediterranean precipitation in Poland: the first begins in the 15th pentad of the year (12–16.03) when the MCP starts increasing after its winter decrease, the second phase begins at the beginning of August and continues until the end of the year. In this phase, the amount of the MCP gradually decreases, however, its share in precipitation totals still remains at quite a high level, at times significantly exceeding its mean annual value of 9.6%. Taking into account the amounts of the MCP smoothed by a moving average, the maximum of the first phase can be located at the end of April (21–25.04), while the second phase maximum is in mid-August (14–18.08).

The peculiarity of the annual course of the MCP amounts is that there occurs their depression from late June to late July. It can be observed particularly with respect to the high total amounts of precipitation of the period. The second such depression includes the winter months of January and February (Fig. 8). Both the minima are likely associated with increased zonal circulation, which is not conducive to Mediterranean cyclones moving northward. Furthermore, the winter minimum can also be explained by a seasonal drop in the moisture content in the atmosphere and the stability of thermal stratification, i.e. the conditions not favourable to the formation of heavy precipitation.

The annual rhythm of Mediterranean precipitation is fundamentally different from the course of total amounts of precipitation in Poland. The described depression of the July MCP occurs at

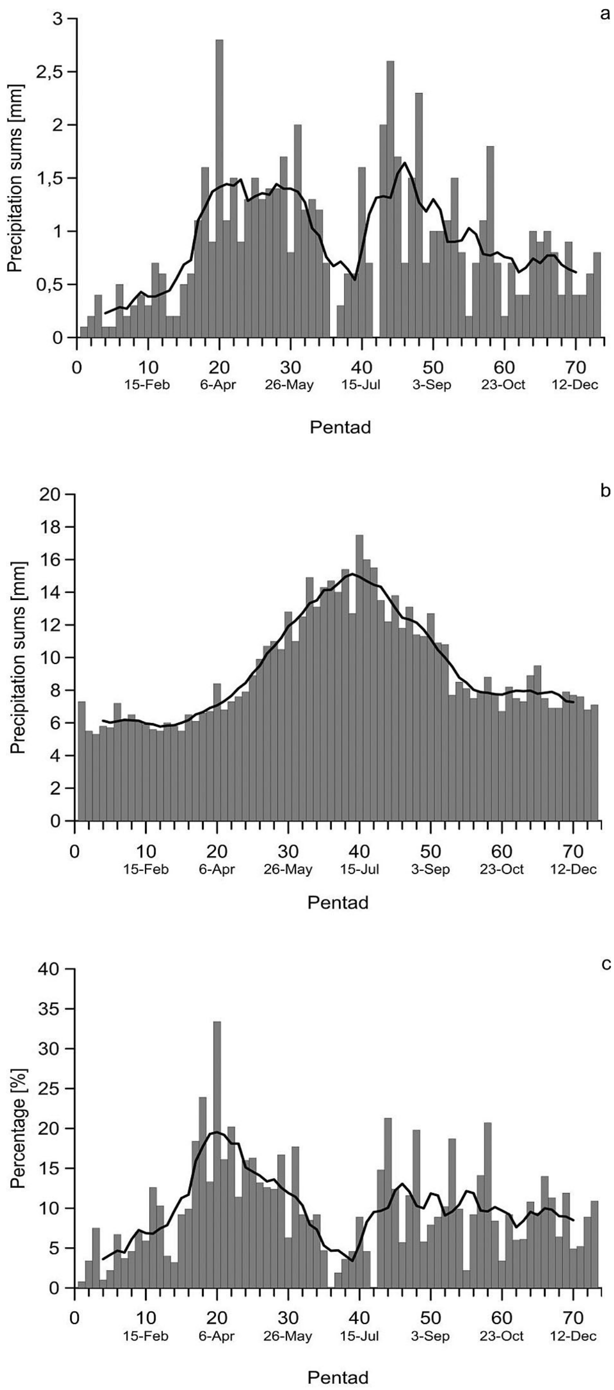

Fig. 8. Mean pentad of MCP daily totals [mm] (a), total precipitation in Poland [mm] (b) and proportion of MCP in total precipitation [%] (c)

the time of the highest rainfall in Poland. The abundant MCP precipitation in the spring period comes when the seasonal total precipitation is small; therefore the MCP considerably contributes to shaping the pluvial conditions in spring. If not for Mediterranean precipitation, spring in Poland would probably be much drier.

Long-term changes in MCP amounts

In the years 1958–2008, precipitation of the Mediterranean origin in Poland exhibited considerable variability; its averaged annual totals for the whole country ranged from 20 to over 150 mm. This variability was dominated by a declining trend. The linear trends of the 51-year series of the MCP precipitation show a regular decrease in its amount, both during the year and in the seasons of the year, except for summer. In mountainous areas, rainfall is characterized by a decreasing trend also in the summer season (Table 4, Fig. 9).

In the analyzed period 1958–2008, the annual MCP totals in Poland decreased by 29 mm, which accounts for 43% of their multi-annual average amount. In the mountains, this drop was equal to 63 mm (56%). These are statistically significant ($p<0.05$) decreasing trends. The downward trend in the winter MCP in the area of Poland is also significant. In mountainous areas only summer trend is insignificant (Table 4).

The accumulated deviations of the annual MCP totals from their long-term mean confirm the decreasing trend of the MCP. Two precipitation epochs can be distinguished in the studied multi-year period. The "surplus" MCP dominated until 1981, then its "shortages" prevailed (Fig. 10). The negative trends in the MCP precipitation correspond to the declining trend of the frequency of Mediterranean cyclones; based on the linear trend of frequency of the MEC systems, it can be stated that during the period 1958–2008 the number of Mediterranean cyclones decreased from 8.7 to 5 MEC/(50 yrs) (3,7 MEC per 50 years, Table. 4). The biggest decline in the frequency of MEC cyclones was observed in spring (down by 1.3 MEC), while in summer their number decreased by only 0.4 MEC (the MCP in the season remained virtually unchanged). In winter, the number of Mediterranean cyclones decreased quite significantly (–1.1). During this season, a significant downward trend of the MCP was recorded (Table 4).

The phenomenon of decreasing amount of Mediterranean precipitation which, as shown, is characterized by the highest intensity and the largest share in the total precipitation in the area of southern Poland, can be associated with the decreasing precipitation trend observed in the southern half of Poland. The changing precipitation amount in the second half of the twentieth century and at the beginning of the current century were reported, among others, by Zawora and Ziernicka (2003), Ziernicka-Wojtaszek (2006) and Marosz et al. (2011). Simultaneously with a small increase in the mean annual precipitation totals across Poland, in some regions of the central and southern part of the country significant downward trends were observed. The spatial distribution of changes in precipitation totals in the area of Poland in the years 1961–2008 (Fig. 11) allows to formulate the thesis that the decreasing precipitation of the Mediterranean origin contributes in shaping the field of these changes. The reduced precipitation is concentrated in the South-West of the country and occurs in longitudinally oriented strips extending up to the central and eastern districts of Poland.

Table 4. Trends in the number of Mediterranean cyclones (MEC) and in the mean MCP in Poland and in the mountains and foothills. Period 1958–2008. A – slope of linear trend, R^2 – coefficient of determination, p – level of significance associated with Mann-Kendall statistics

Season	MEC			MCP - Poland			MCP – mountains & foothills		
	A (MEC/50 yrs)	R^2 (%)	p	A (mm/50 yrs)	R^2 (%)	p	A (mm/50 yrs)	R^2 (%)	p
Spring	–1.3	8.6	0.06	–9.0	4.1	0.12	–20.4*	6.0	0.05
Summer	–0.4	1.6	0.22	+1.4	0.0	0.54	–11.4	0.8	0.22
Autumn	–0.8	3.8	0.22	–13.0	6.3	0.06	–16.9*	6.5	0.05
Winter	–1.1	6.3	0.18	–7.8*	6.2	0.02	–14.5*	8.9	0.03
Year	–3.7*	17.7	0.00	–27.9*	8.0	0.04	–62.1*	13.5	0.01

* trends significant at a 0.05 level

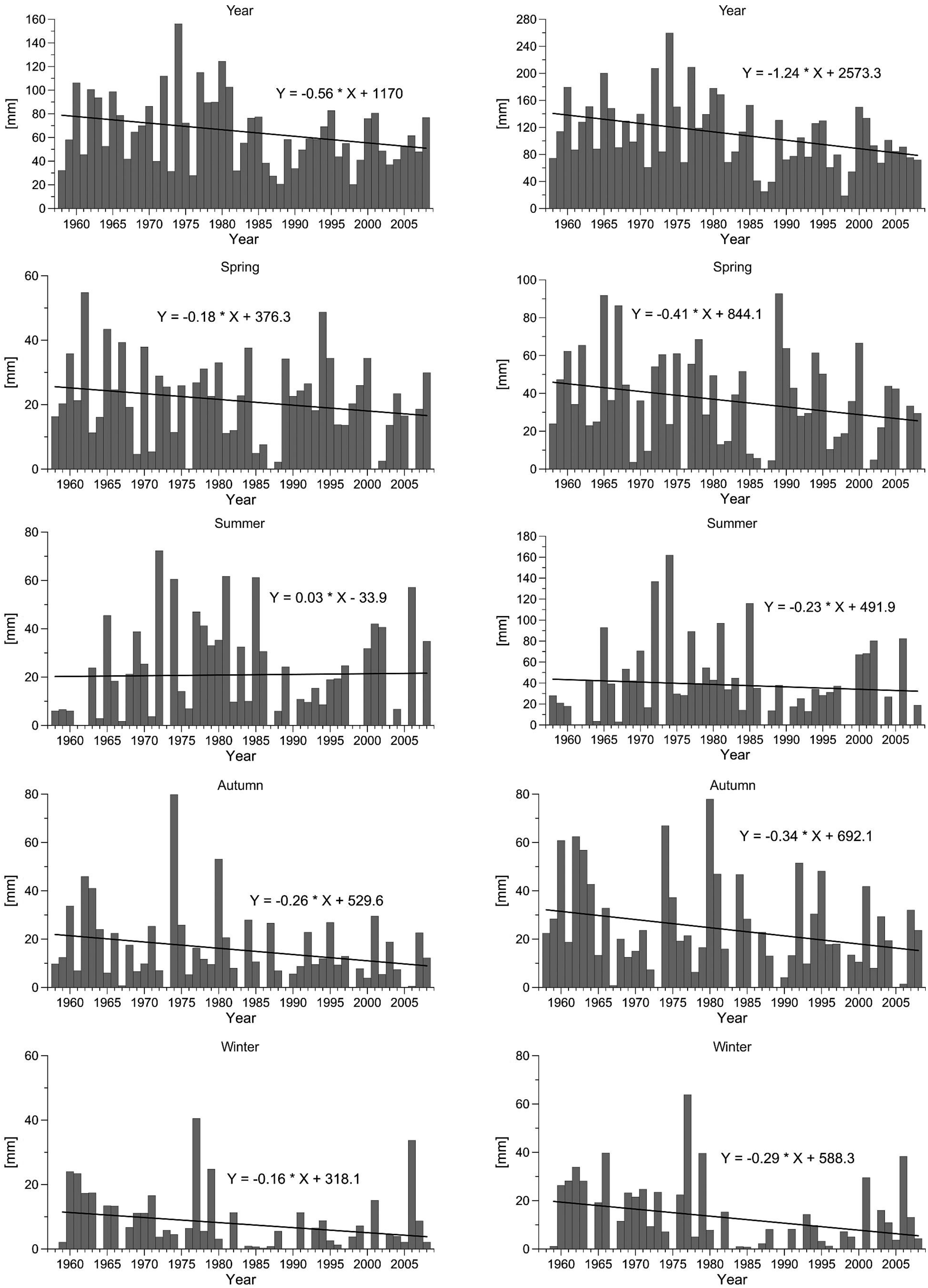

Fig. 9. Mean annual and seasonal MCP totals [mm] in the years 1958–2008 and their linear trends. Left panel – mean MCP in the area of Poland, right panel – mean values in the area of mountains and their foreland

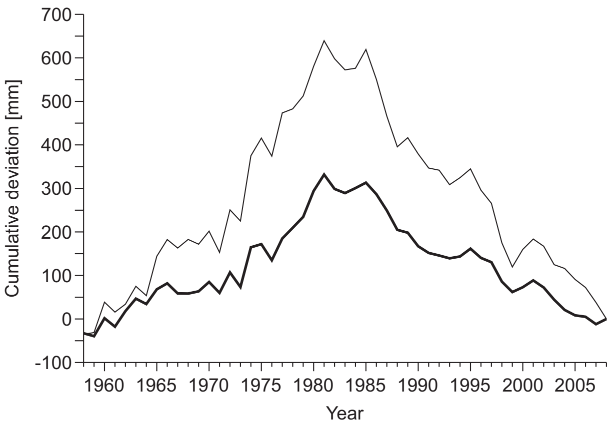

Fig. 10. Cumulated deviations of annual MCP totals [mm] from the long-term mean for the period 1958–2008. Bold line – mean deviations in the area of Poland, thin line – mean deviations in the mountain and foreland areas

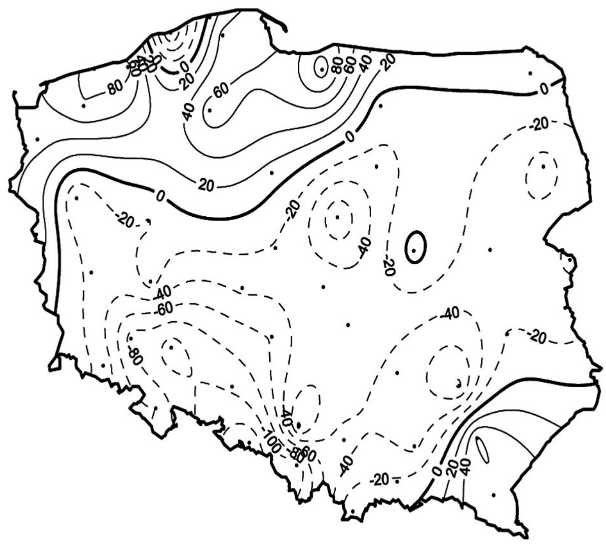

Fig. 11. Changes in annual precipitation totals in Poland (mm/48 yrs) in the years 1961–2008 (after Marosz et al. 2011)

Summary

The precipitation associated with the activities of Mediterranean cyclones moving towards and over East-Central Europe accounts on average for ca. 10% of the total amount of precipitation occurring in Poland. In extreme cases, the monthly Mediterranean precipitation totals are close to or slightly higher than the mean total amounts of precipitation in Poland (August 1972 – 91% of the long-term mean, October 1974 – 131%). Some of the absolute maxima of daily precipitation totals in Poland (Stach 2009) also have Mediterranean origins. These include, inter alia: the daily precipitation of 147 mm in Bielsko-Biała on 21.08.1972, the fall of 150 mm of 30.07.1977 on Mt Śnieżka, 206 mm on 17.06.1979 in Wałbrzych, the rainfall of 119 mm in Jelenia Góra on 20.07.2001. These data confirm the assumption that the precipitation associated with Mediterranean cyclones belongs in the most intense precipitation in Poland.

The share of MCP in total precipitation increases with the amount of such totals. Daily precipitation of >80 mm consists on average of almost ¼ MCP. The mean intensity of Mediterranean precipitation (amount of MCP/rainy day) represents approximately 150% of the mean intensity of all precipitation in Poland.

The amount of the MCP and its share in precipitation totals vary seasonally, with the maxima in late April and in the second half of August. In April (6–10.04), the Mediterranean precipitation accounts for nearly one third of the total precipitation in Poland. A characteristic feature of the annual course of the MCP is the depression occurring in the period between the end of June and the end of July which separates two phases of intense MCP rainfall: the first in spring and the second which lasts from late summer to autumn.

The seasonal changes in the MCP precipitation are correlated with the annual course of the number of MEC cyclones. The aforementioned depression coincides with the low frequency of the MEC in July (4.2% of the annual number of the MEC), the spring maximum – with high frequencies of cyclones in April and May (15% and 11% of the annual number of the MEC).

In the years 1958–2008, the amount of the MCP decreased; the linear trend indicates that during the 51 years the mean MCP totals decreased by 29 mm, i.e. ca. 42% of their long-term average. The decreasing trend in the MCP proved to be significant. At the same time, the number of Mediterranean cyclones over East-Central Europe decreased. In the period 1958–2008, the annual incidence of MEC decreased by 53% of its long-term value (6.9 MEC/year on average). Thus, it can be assumed that the intensity of the MCP slightly increased; however, the evaluation of this change would require a more detailed analysis.

The above findings make it possible to verify positively the first two hypotheses formulated in the introductory part of the article. However, the third hypothesis, assuming a decisive influence of orography on the amount of Mediterranean precipitation in Poland, requires an extension which must demonstrate that the relatively high

MCP occurs also outside the mountain areas and foothills, in longitudinally extending strips covering the areas of central or even north-eastern Poland. It can be assumed that these strips are formed directly by the circulation associated with Mediterranean cyclones, i.e. the position of the systems of fronts and convergence zones which are conducive to precipitation. It would be more difficult to assume that the orographic barrier of the Carpathians and the Sudetes has such a wide range of influence on precipitation.

Precipitation of the Mediterranean origin is a sort of peculiarity of the Polish climate; it does not appear often, but significantly influences the income portion of the water balance. It is worth noticing that its occurrence in spring mitigates to a certain extent the development of moisture deficits in this season. On the other hand, the precipitation formed in connection with the activity of Mediterranean cyclones, especially in summer, is exceptionally abundant and is responsible for the highest daily precipitation totals recorded in Poland. It can therefore be regarded as a class of extreme climatic events.

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