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PRECIPITATION VARIABILITY, TRENDS AND REGIONS IN POLAND: TEMPORAL AND SPATIAL DISTRIBUTION IN THE YEARS 1951–2018

Robert Kalbarczyk, Eliza Kalbarczyk

ROBERT KALBARCZYK

Crowns of Scots pine trees in the clouds.

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Robert Kalbarczyk[1], Eliza Kalbarczyk[2]

Precipitation variability, trends and regions in Poland: Temporal and spatial distribution in the years 1951–2018

ABSTRACT: The goals of this work were to assess differences in precipitation totals (Pr) in Poland in both time and space and to distinguish regions based on precipitation variability in the years 1951–2018. To assess precipitation conditions, the study used statistical and spatial analyses implemented in ArcGIS Desktop and STATISTICA software. The largest number of significant, positive correlations describing the linear Pr trend were found for March. The lowest monthly Pr, which represents only approximately 6% of the multi-year precipitation totals, was recorded in October 1951; the highest monthly Pr, which represents as much as approximately 355% of the multi-year precipitation totals, was recorded in October 1974. The study distinguished three precipitation regions of Poland.

KEY WORDS: climate change, precipitation conditions, number of days with precipitation, precipitation regions, Poland.

Spremenljivost, trendi in območja padavin na Poljskem: časovna in prostorska porazdelitev med letoma 1951 in 2018

POVZETEK: V članku so proučene razlike v skupni količini padavin na Poljskem v času in prostoru, na podlagi česar so določena glavna padavinska območja med letoma 1951 in 2018. Padavinske razmere so ocenjene na podlagi statistične in prostorske analize, opravljene v programskih orodjih ArcGIS Desktop in STATISTICA. Največ statistično značilnih korelacij, ki nakazujejo linearni trend v skupni količini padavin, je bilo odkritih za mesec marec. Najmanjša mesečna skupna količina padavin (samo približno 6 % večletnega mesečnega povprečja) je bila zabeležena oktobra 1951, najvišja (približno 355 % večletnega mesečnega povprečja) pa oktobra 1974. Določena so tri padavinska območja na Poljskem.

KLJUČNE BESEDE: podnebne spremembe, padavinske razmere, število dni s padavinami, padavinska območja, Poljska

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1 Introduction

Despite many years of research on climate change, there are no clear indications as to the direction and intensification of precipitation variability. The scenarios and models presented in the literature all assume a global, albeit varied, increase in air temperature. On the other hand, research results on the direction and range of precipitation (Pr) variability in the future (including in Poland) remain burdened with much higher uncertainty (Kundzewicz and Kozyra 2011; IPCC 2014; Kalbarczyk et al. 2018).

Analyses of historical data that contains precipitation totals and the number of days with precipitation or extreme precipitation values indicate that in the 20th century and at the turn of the 21st century there were no clear regularities in their patterns (Halimatou, Kalifa and Kyei-Baffour 2017; Pathak et al. 2018; Caloiero, Caloiero and Frustaci 2018). Many reports frequently point to the lack of a significant trend of precipitation totals in Europe; however, regional occurrences of both positive and negative Pr trends have been reported (Kundzewicz, Radziejewski and Pińskwar 2006; Labudová, Faško and Ivaňáková 2015; Łupikasza 2017). Also, previous research on the multi-year variability of Pr conducted for various regions of Poland did not produce any unambiguous results so it is not certain how it will develop in the future (Majewski, Przewoźniczuk and Kleniewska 2010; Żarski et al. 2014; Ilnicki et al. 2015; Ziernicka-Wojtaszek and Kopcińska 2020). Precipitation variability occurring in Central Europe is mostly explained by its dependence on atmospheric circulation, which determines the prevalence of continental or oceanic weather trends and shapes the global and regional climates (Degirmendžić, Kożuchowski and Żmudzka 2004; Twardosz, Niedźwiedź and Łupikasza 2011; Młyński, Cebulska and Wałęga 2018). Out of the remaining factors shaping precipitation variability in Poland research studies included e.g. the importance of cloud cover and terrain (Bokwa and Skowera 2008; Żmudzka 2009). Knowledge of precipitation variability is vital for many sectors of the economy. The sum of precipitation and its temporal distribution affect the functioning and development of, for example, agriculture, fisheries, forestry, water transport, hydropower generation and tourism, thereby influencing the quality of life in a given country (Kalbarczyk, Kalbarczyk and Raszka 2011; Marcinkowski and Piniewski 2018; Radzka, Jankowski and Jankowska 2019). Recognizing the degree of Pr variability is essential for climate risk management (Marković et al. 2014; Šebenik, Brilly and Šraj 2017; Młyński, Cebulska and Wałęga 2018; Stefanova et al. 2019; Ziernicka-Wojtaszek and Kopcińska 2020). Floods resulting from sudden atmospheric precipitation are one of the biggest climatic threats to cities (Pedrozo-Acuña et al. 2017; Szewrański et al. 2018; Olsson et al. 2019), therefore determination of precipitation trends can be useful when planning adaptation measures to climate change for urban and rural areas (Hardoy et al. 2014; Reckien et al. 2015; Chu, Anguelovski and Roberts 2017). Knowledge of precipitation variability in a multi-year and spatial perspective requires continuous updating, so research studies are conducted anew for the changing climatic conditions in various regions of the world.

The aims of this paper were to determine the temporal and spatial variability of precipitation and to distinguish regions of Poland based on specific variability of precipitation totals.

2 Materials and methods

The paper used daily precipitation totals which were collected at 74 meteorological stations located across Poland (Figure 1). Precipitation totals (Pr, mm) were calculated for each year in the analyzed period between 1951 and 2018 for each individual month in each of these years. The initial data were made accessible by the Polish Institute of Meteorology and Water Management which is responsible for systematic measurements and observations with the use of their basic network of stations and special-purpose measurement networks.

Single missing daily precipitation totals were added on the basis of complete measurement series from the nearest stations. Longer series of missing daily totals (at least 10 days long) were determined by means of linear or non-linear regression equations whose calculated determination coefficients described at least a 64% fit of the empirical data to the regression function.

Precipitation patterns were described with the following indices: the mean ($\bar{x}$), standard deviation (SD), variation coefficient (V), and extreme values, i.e. the minimum (MIN) and the maximum (MAX) calculated on the basis of all the analyzed annual periods and months during the entire analyzed 1951–2018 period (further accepted also as the norm). Spearman's coefficient (r) was used to describe the linear precipitation trend. Precipitation conditions for chosen 2 years and the 24 months with the lowest and highest

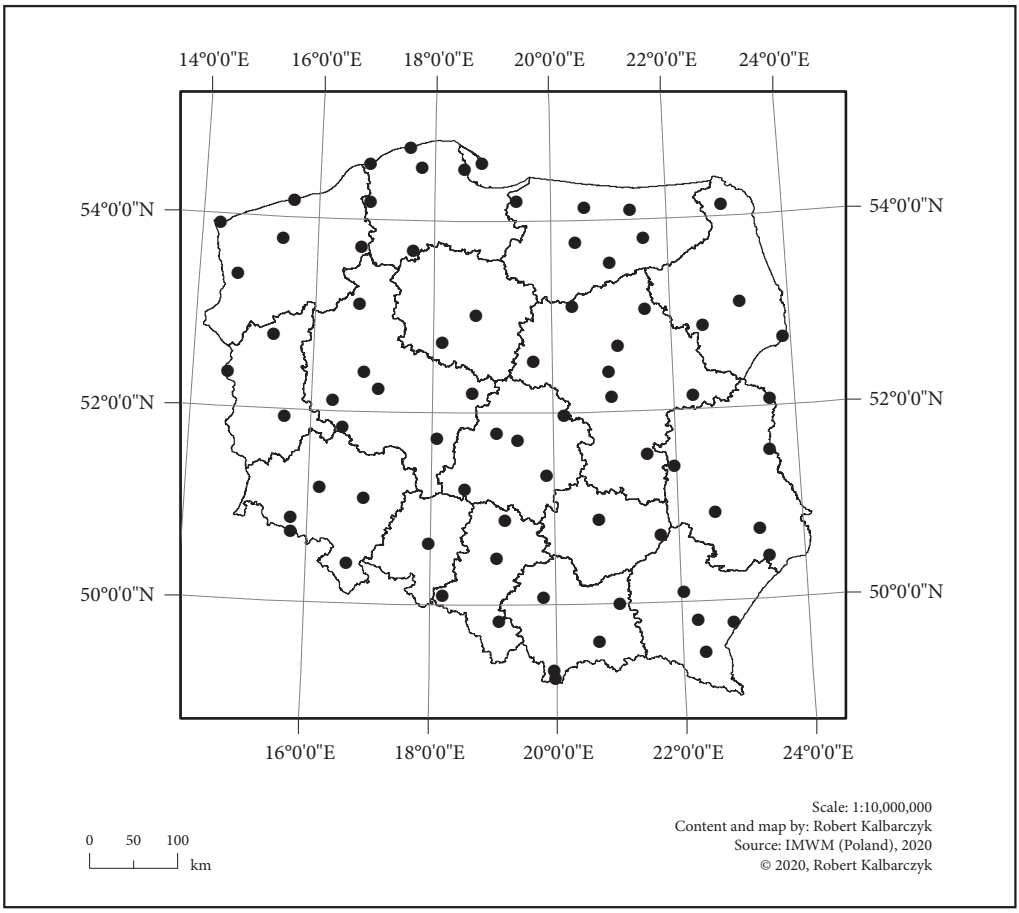


Figure 1: Locations of meteorological stations used in the research study.

precipitation totals were characterized by an index that expressed extreme values as a percentage of the sum of multi-year precipitation and the average number of days without precipitation (0.0) and with precipitation in the following ranges: 0.1–1, >1, >2, >5, >10, >20 and >50 mm (Olechnowicz-Bobrowska 1970; Bochenek 2020).

Maps presenting statistical characteristics of precipitation conditions in Poland in various time functions with a borders of the 16 administrative provinces were prepared using inverse distance weighting in *ArcGIS Desktop 10.6.1* software. Due to the fact that very high precipitation variability occurs in only one region of Poland, some maps were supplemented with a legend which does not use the same range of values in all intervals. Therefore, on the color scale the last two ranges of values were marked with grey and black. The legend showing the linear trend of precipitation totals gives critical values of Spearman's coefficient for $\alpha \leq 0.1$ and $\alpha \leq 0.01$, which amount to 0.201 and 0.311, respectively.

The regions in Poland with a similar variability of precipitation were determined on the basis of hierarchical clustering in 3 multi-year periods: 1951–1984 (the first half of the entire examined multi-year period), 1985–2018 (the second half of the entire examined multi-year period), and 1951–2018 (the whole examined multi-year period). The analysis took into consideration 24 variables: average multi-year precipitation totals and their average multi-year standard deviation values, both of which were calculated separately for each month for each meteorological station and each analyzed multi-year period. Before the analysis, the values of all variables (Z) were standardized according to the equation:

$$Z = \frac{(x_i - \bar{x})}{SD}$$

where x_i is the observed value of a variable from a given station in a given month and multi-year period, $\bar{x}$ is the arithmetic mean for all stations in a given month and multi-year period, and SD is the standard deviation from all stations in a given month and multi-year period.

The study used an agglomerative method of clustering to classify meteorological stations into groups so that the degree of correlation of a given station with stations from the same group would be possibly the strongest, and with stations from the remaining groups possibly the weakest. Distances between stations in multidimensional space were calculated by means of the city block distance (Manhattan distance), thanks to which the effect of outliers is reduced. Distances between new clusters were determined by Ward's method. The accepted measure of the linkage amounted to 110. The method aims to minimize the sum of the squared deviations of any two clusters which may be formed at any stage.

Regression and cluster analysis were carried out in *STATISTICA 13.3* software.

3 Results

3.1 Precipitation distribution

In 1951–2018, the average precipitation total (Pr) for the whole of Poland was approximately 634 mm (Table 1). In some months, Pr fluctuated from approximately 31 mm in February to approximately 90 mm in July. Pr of up to 40 mm was also recorded in January and March, and Pr of over 70 mm was recorded in June and August. The annual standard deviation for multi-year precipitation totals amounted to ~82 mm, but in February it was only ~13 mm, and in July as much as 34 mm. A high standard deviation of Pr, i.e. >25 mm, was calculated for August and October. The highest variability of precipitation, expressed by variation coefficient V, was characteristic of precipitation in October (60.5%), and the lowest – precipitation in June (27.3%), with the variability of annual precipitation sums at a level of 13%. A significant positive increase in Pr for the whole country was found only for March (r=0.25, α≤0.05).

In Poland, the spatial distribution of average multi-year precipitation totals was very varied (Figure 2). The lowest Pr was observed in the central strip of Poland and amounted to <550 mm.

Precipitation increased latitudinally northwards and southwards, where the observed totals were the highest, namely >1300 mm. In some months, the spatial structure of Pr was slightly different than for the entire year (Figure 3).

Table 1: Characteristics of precipitation totals variability in Poland, 1951–2018.

	Characteristics		
Period / month	$\bar{x}$±SD	r	V
January–December	634.1±82.3	0.17^{ns}	13.0
January	36.3±15.0	0.15^{ns}	41.3
February	31.3±13.1	0.04^{ns}	41.9
March	35.4±13.5	0.25^{1}	38.1
April	41.0±14.4	-0.11^{ns}	35.1
May	62.5±20.3	0.03^{ns}	32.5
June	75.8±20.7	-0.07^{ns}	27.3
July	89.6±34.0	0.05^{ns}	37.9
August	72.0±25.1	-0.09^{ns}	34.8
September	56.3±23.7	0.11^{ns}	42.1
October	46.1±27.9	0.13^{ns}	60.5
November	44.9±16.4	0.01^{ns}	36.5
December	42.7±16.3	0.04^{ns}	38.2

Notes: $\bar{x}$ – arithmetic mean (mm), SD – standard deviation (mm), r – Spearman's correlation coefficient for a linear trend, V – coefficient of variation (%), ^{1} – significant at α≤0.05, ^{ns} – non-significant at α≥0.1

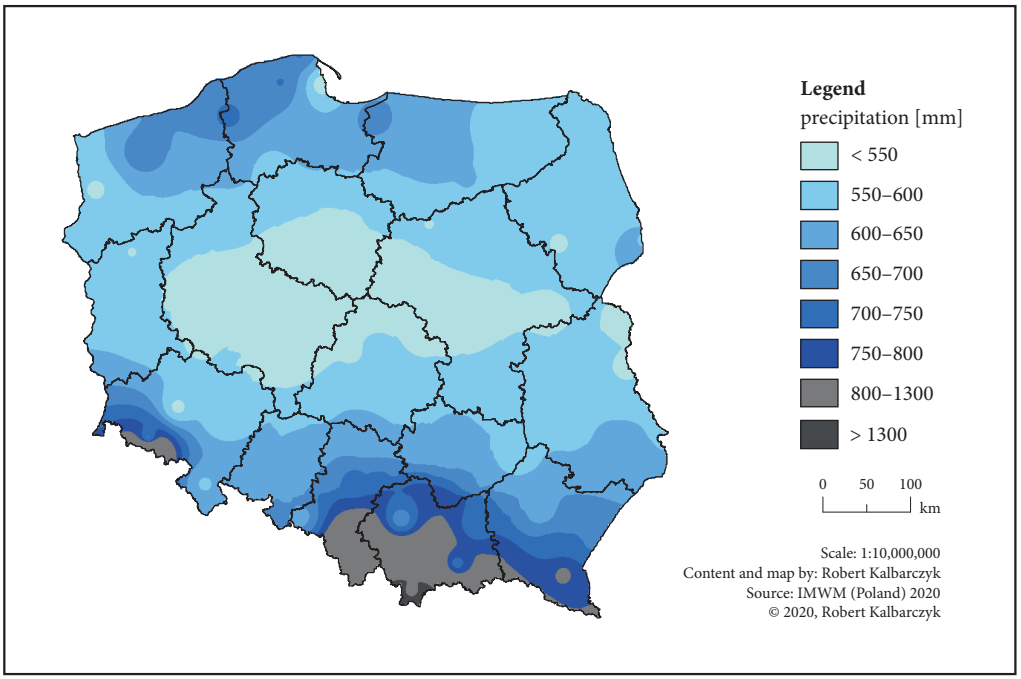


Figure 2: Spatial distribution of average multi-year annual precipitation totals in Poland, 1951–2018.

Figure 3: Spatial distribution of average multi-year precipitation [mm] totals by months in Poland, 1951–2018. ► p. 48–49

From January to March, the lowest value of precipitation (<30 mm) occurred mainly in central-east Poland; the highest, i.e. >80–90 mm, occurred in the southern part of the country. From April to June, the lowest Pr was observed in the Polish Plains (from <40 mm in April to <60 mm in May), and the highest was in the south (from >105 mm in April to >170 mm in June). In July, Pr oscillated from <80 mm to >180 mm, with the lowest values in the central-west and central-east parts; in August Pr oscillated from <60 to >150 mm, with the lowest values in central-west Poland; in September Pr oscillated from <50 to >110 mm, with the lowest values in the central-west part. In October in the central strip of Poland, which stretches horizontally, precipitation amounted to <40 mm; in the north and south it amounted to >85 mm. Finally, in November and December, a Pr of <40 mm occurred in central-east Poland, and a Pr of >90–95 mm occurred in the south.

3.2 Variability and precipitation trend

In 1951–2018, the annual standard deviation of Pr for whole of Poland fluctuated from <100 to >210 mm (Figure 4).

In the areas with the highest annual precipitation totals, the calculated standard deviation values (SD) were also the highest. In particular months, the standard deviation of Pr oscillated from <15 mm in January to >90 mm in July (Figure 5).

Figure 5: Spatial distribution of the standard deviation for monthly precipitation [mm] totals in Poland, 1951–2018. ► p. 50–51

The lowest SD was calculated for precipitation in 3 months: January, in some stations located in central Poland; February, in north-east and central Poland; March, in central Poland. The highest SD in all months was calculated for precipitation in the southern part of the country, i.e. in high-mountain areas, and also in October in the northern part of Poland. In the analyzed multi-year period, annual precipitation totals clearly decreased or increased only in some parts of Poland (Figure 6).

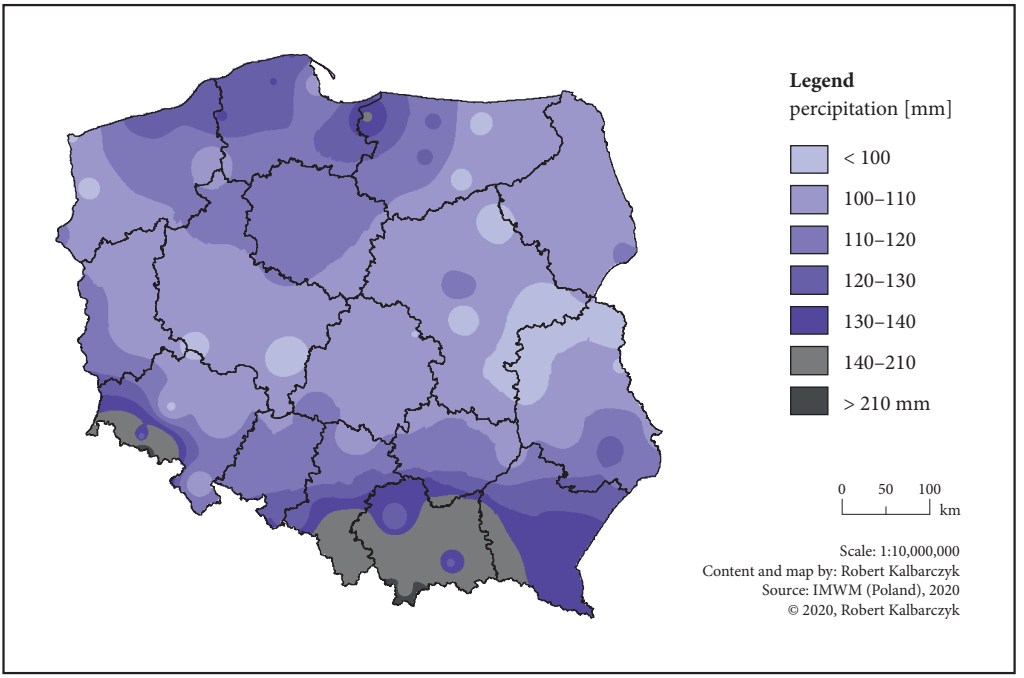


Figure 4: Spatial distribution of the standard deviation for annual precipitation totals in Poland, 1951–2018.

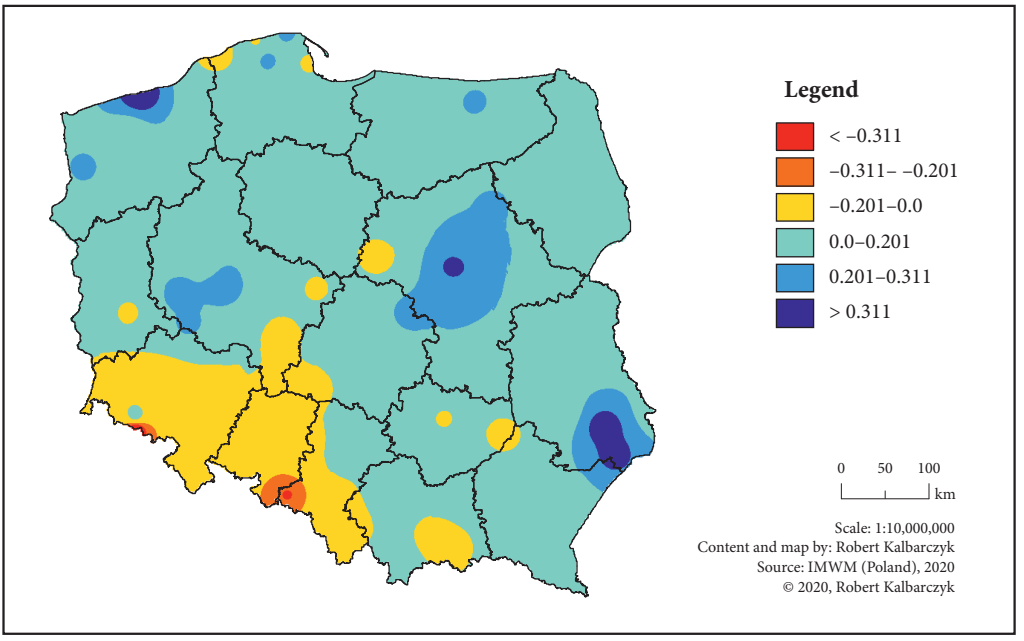
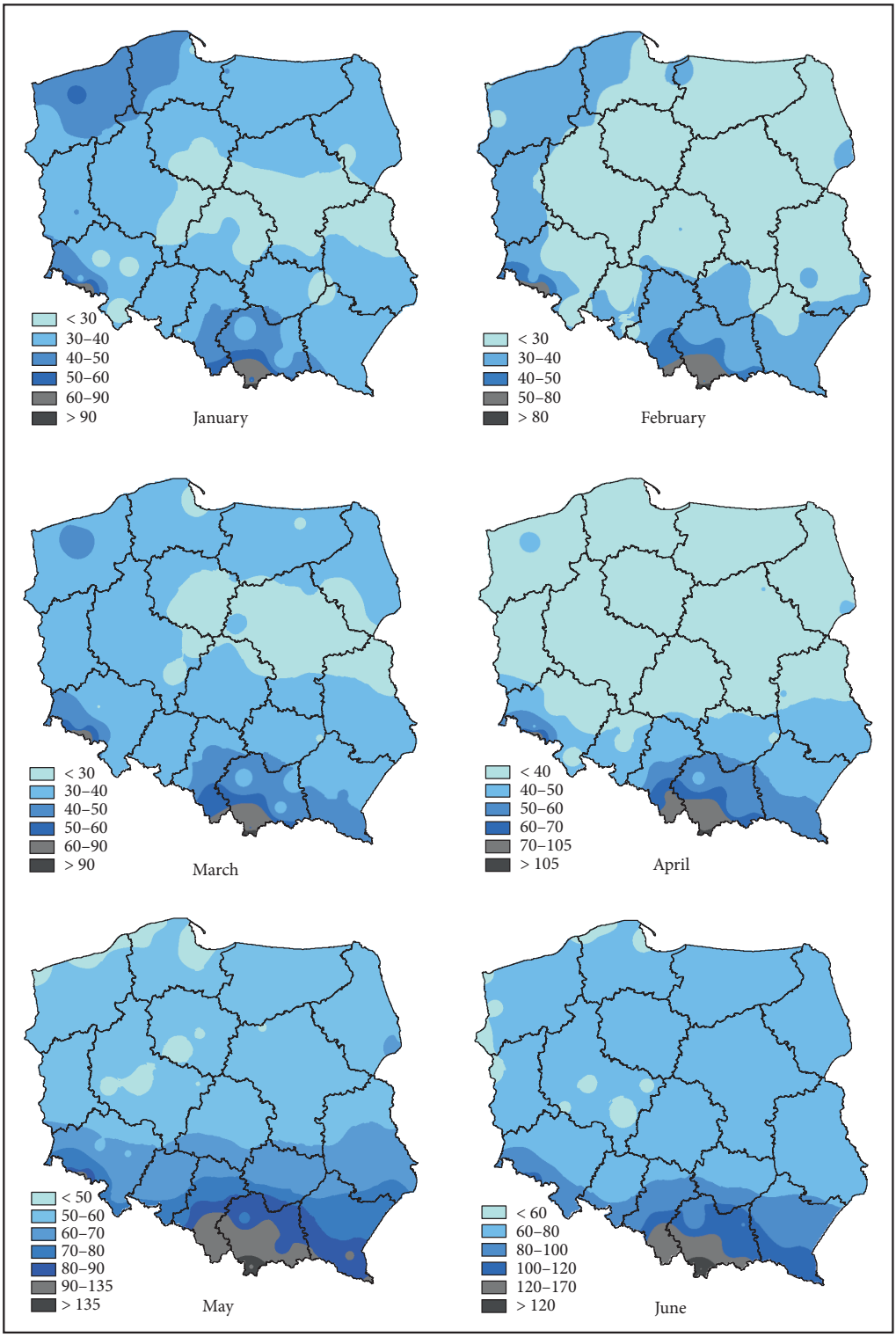


Figure 6: Spatial distribution of the Spearman correlation coefficient of the linear trend for annual precipitation totals in Poland, 1951–2018.

Figure 7: Spatial distribution of the Spearman correlation coefficient of the linear trend for monthly precipitation totals in Poland, 1951–2018. ➤ p. 52–53


< 30
30–40
40–50
50–60
60–90
> 90
January
< 30
30–40
40–50
50–80
> 80
February
< 30
30–40
40–50
50–60
60–90
> 90
March
< 40
40–50
50–60
60–70
70–105
> 105
April
< 50
50–60
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May
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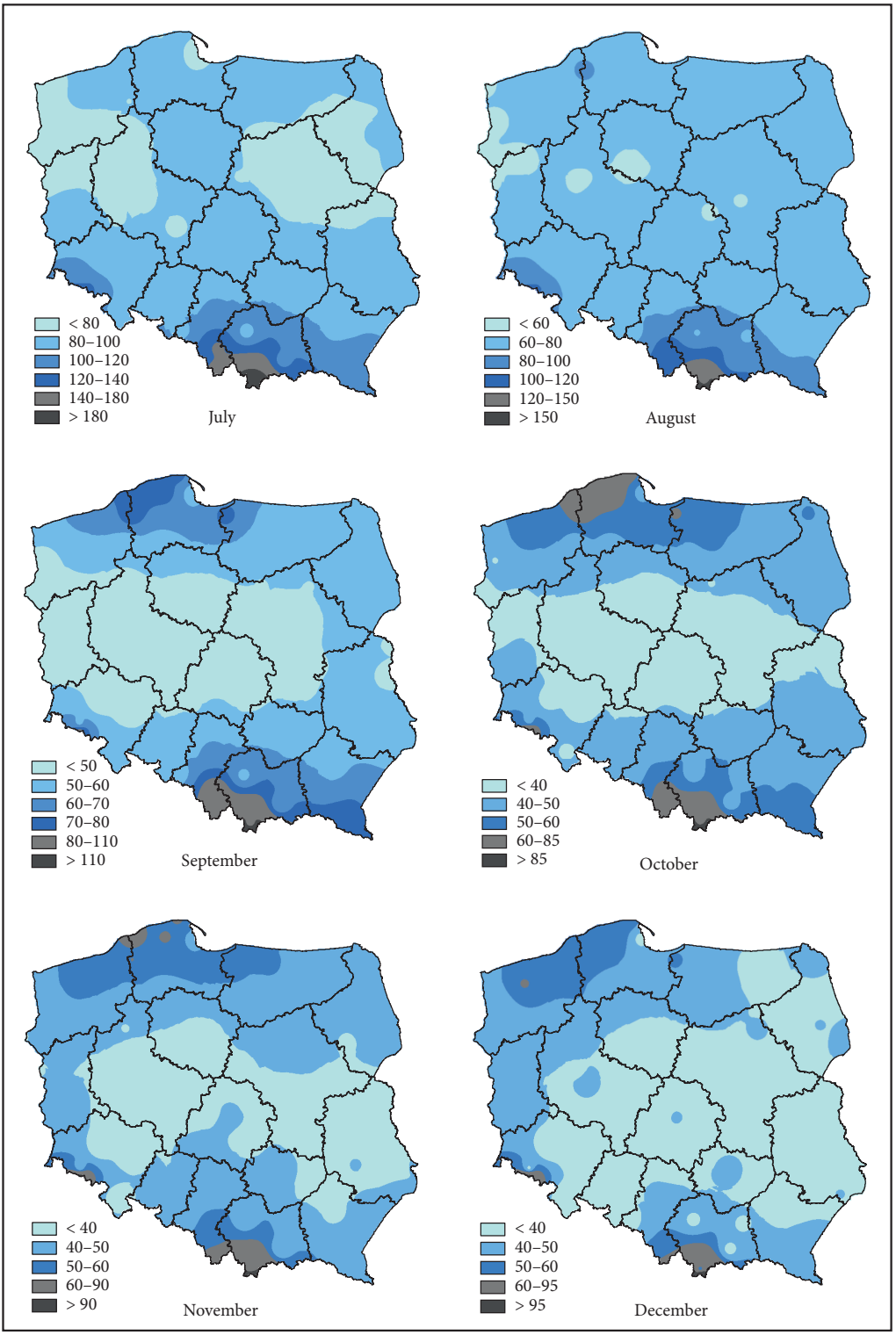
60–80
80–100
100–120
120–170
> 120
June


< 80
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140–180
> 180
July
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120–150
> 150
August
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80–110
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November
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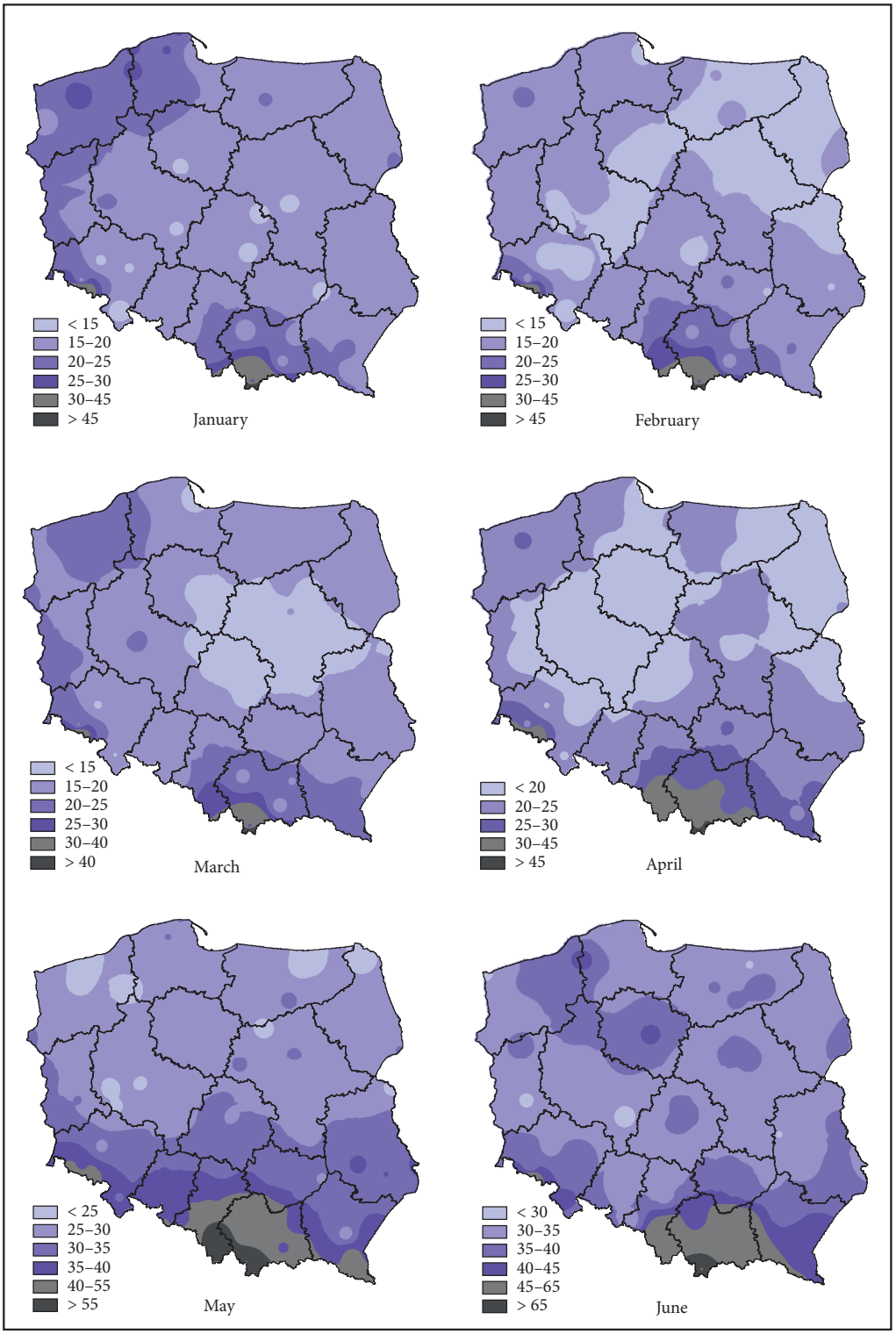
> 95
December


< 15
15–20
20–25
25–30
30–45
> 45
January
< 15
15–20
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> 45
February
< 15
15–20
20–25
25–30
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> 40
March
< 20
20–25
25–30
30–45
> 45
April
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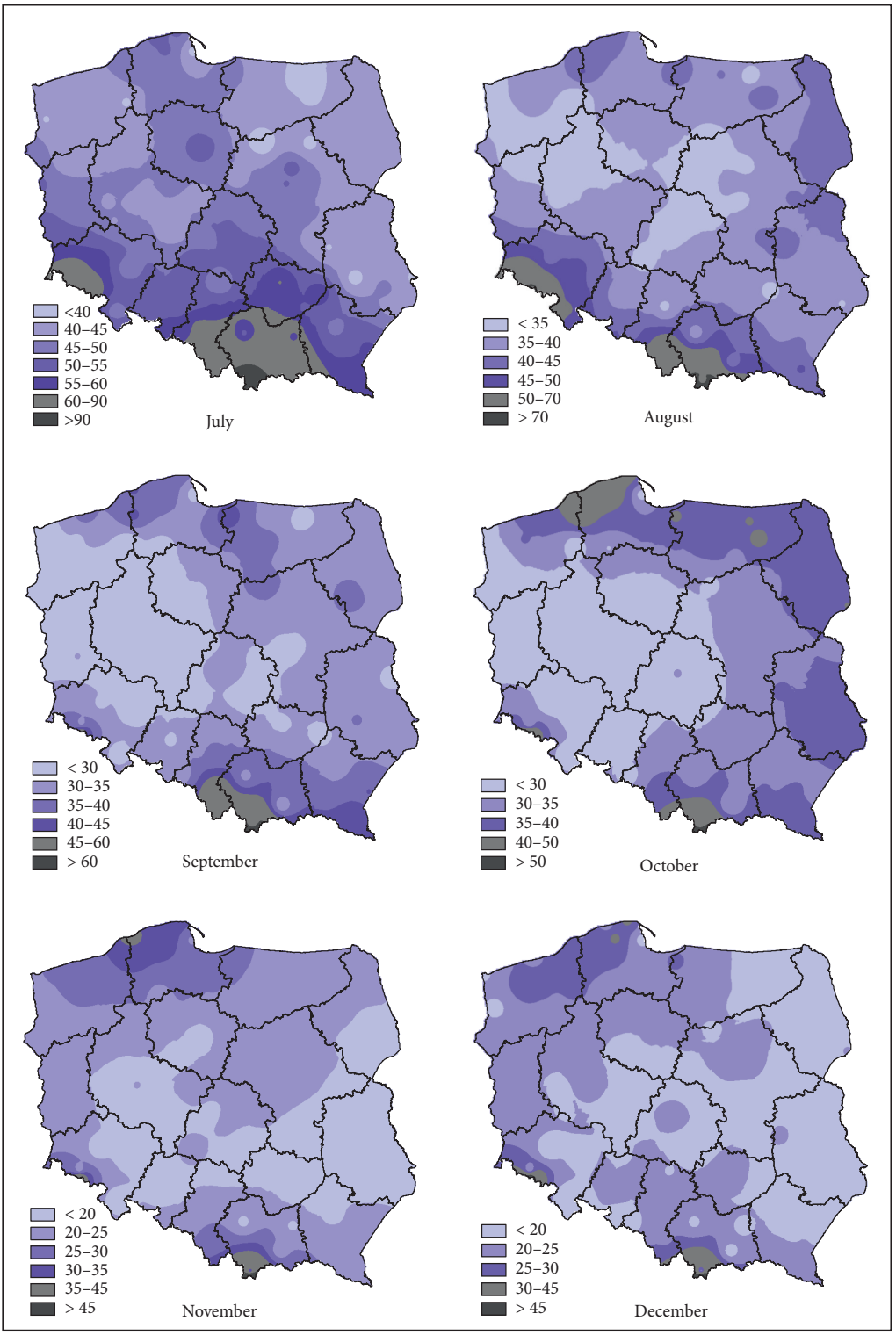
30–35
35–40
40–45
45–65
> 65
June


<40
40–45
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55–60
60–90
>90
July
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45–50
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> 70
August
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> 60
September
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30–35
35–40
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> 50
October
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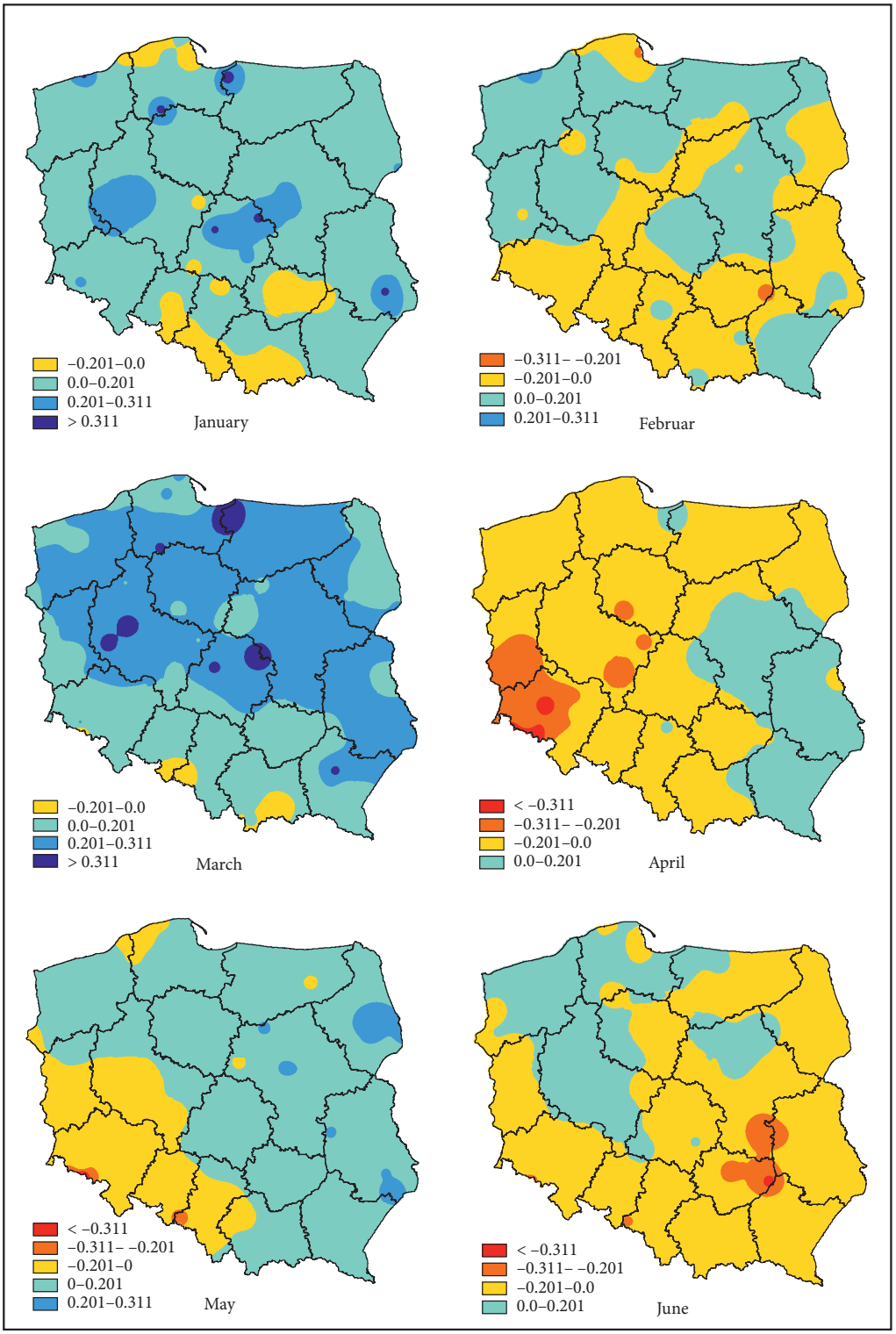
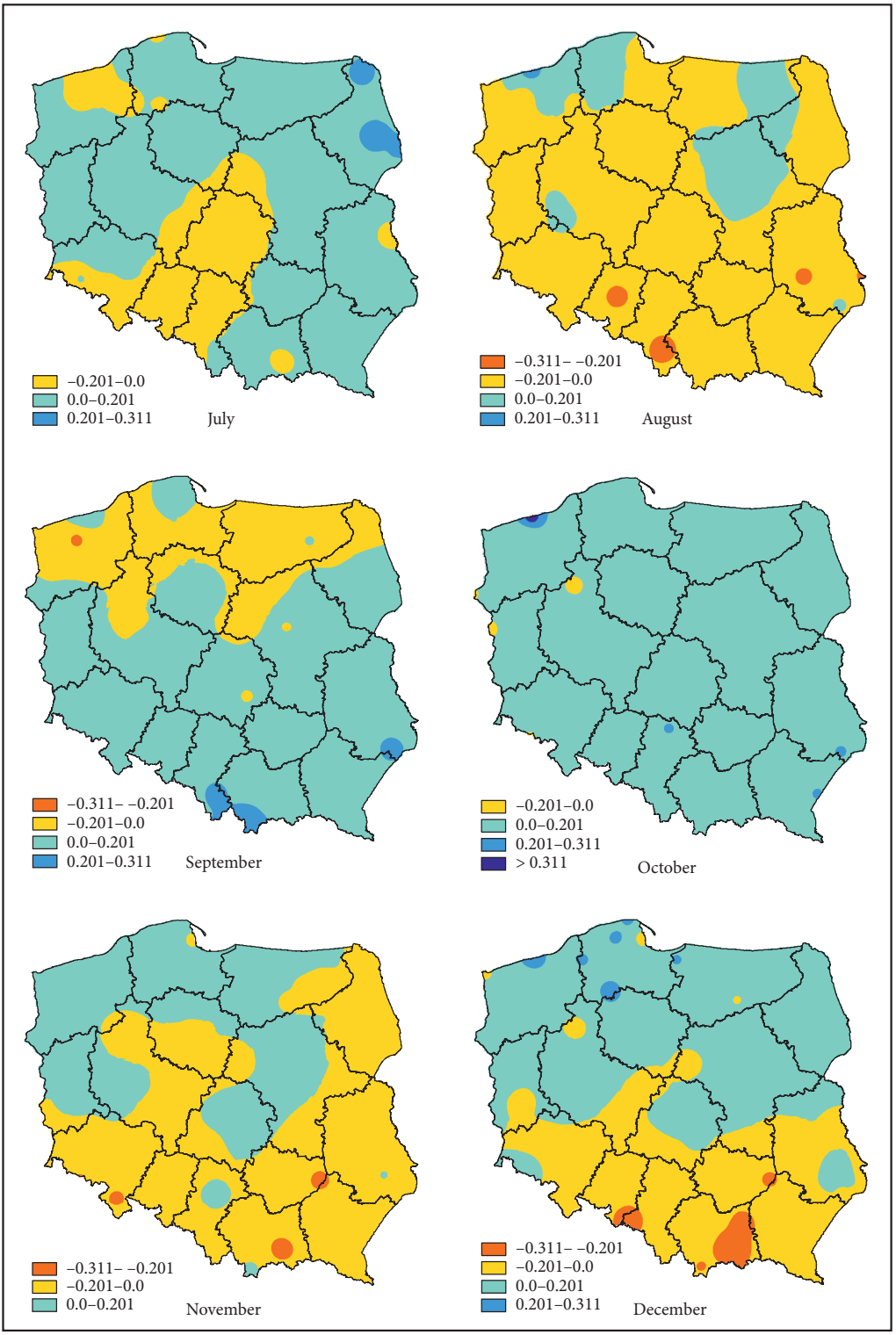
> 45
November
< 20
20–25
25–30
30–45
> 45
December


−0.201–0.0
0.0–0.201
0.201–0.311
> 0.311
January
−0.311– −0.201
−0.201–0.0
0.0–0.201
0.201–0.311
Februar
−0.201–0.0
0.0–0.201
0.201–0.311
> 0.311
March
< −0.311
−0.311– −0.201
−0.201–0.0
0.0–0.201
April
< −0.311
−0.311– −0.201
−0.201–0
0–0.201
0.201–0.311
May
< −0.311
−0.311– −0.201
−0.201–0.0
0.0–0.201
June


−0.201–0.0
0.0–0.201
0.201–0.311
July
−0.311– −0.201
−0.201–0.0
0.0–0.201
0.201–0.311
August
−0.311– −0.201
−0.201–0.0
0.0–0.201
0.201–0.311
September
−0.201–0.0
0.0–0.201
0.201–0.311
> 0.311
October
−0.311– −0.201
−0.201–0.0
0.0–0.201
November
−0.311– −0.201
−0.201–0.0
0.0–0.201
0.201–0.311
December

A significant (at least at a level of $\alpha \leq 0.1$) positive Spearman's coefficient of ≥0.201 that was calculated for Pr was found, for example, in Masovia region (central-east), Roztocze region (south-east) and the central part of the Slovincian Coast (north-east). A significant negative Spearman's coefficient was found in small areas of south-west Poland.

In March, a significant positive increase in Pr was found in northern and central Poland (Figure 7). An increase in Pr was found for 8 months, mainly in northern and eastern Poland: January, February, May, July, August, September, October and December. A significant decrease in Pr in 1951–2018 was proved in a small area of the country, mainly in western and southern Poland, also in 8 months: February, April, May, June, August, September, November and December.

3.3 The lowest and highest precipitation

The lowest and highest annual precipitation totals in the entire analyzed multi-year period were respectively recorded in 1982 and 2010, amounting to approximately 454 and 852 mm (Figure 8).

In subsequent months of the year (Figure 9), the highest Pr values in some months occurred in different years than the lowest totals. The lowest annual precipitation total in Poland, which was recorded in 1982, constituted ~72% of the multi-year precipitation average (Table 2).

In that dry year, precipitation was not recorded on ~233 days. For ~53 days, Pr values were within a range of 0.1–1 mm, and for ~79 days they were >1 mm. In 1982, the average number of days with precipitation of >5, >10, >20 and >50 mm amounted to 27.9, 10.0, 2.4 and 0.1 days, respectively. In some months,

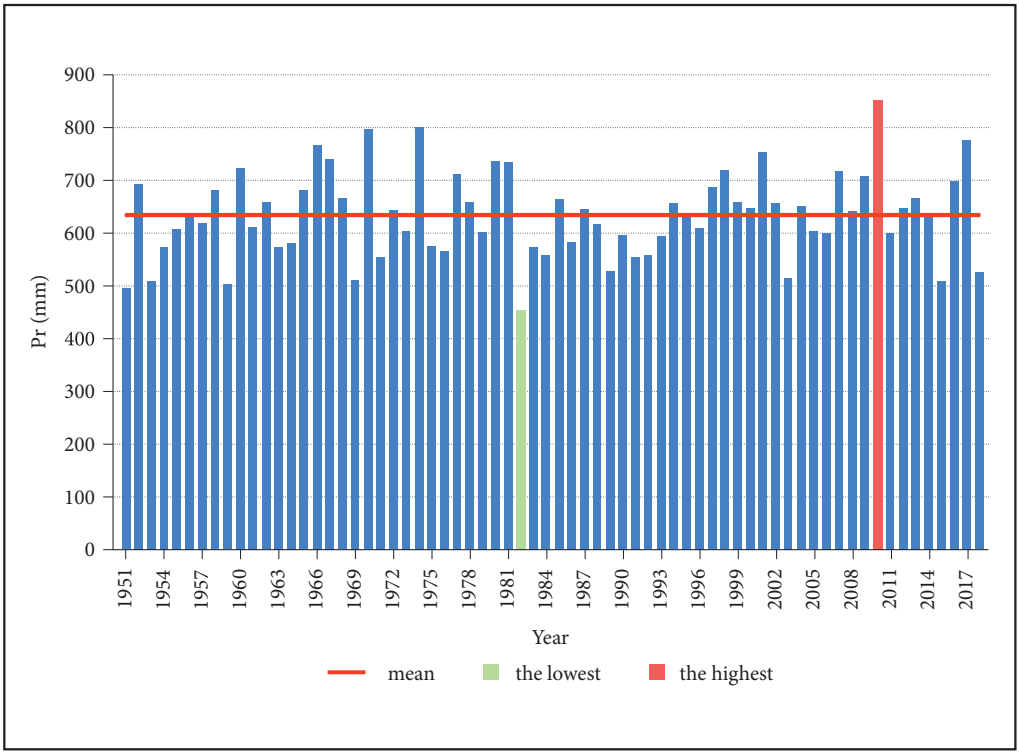
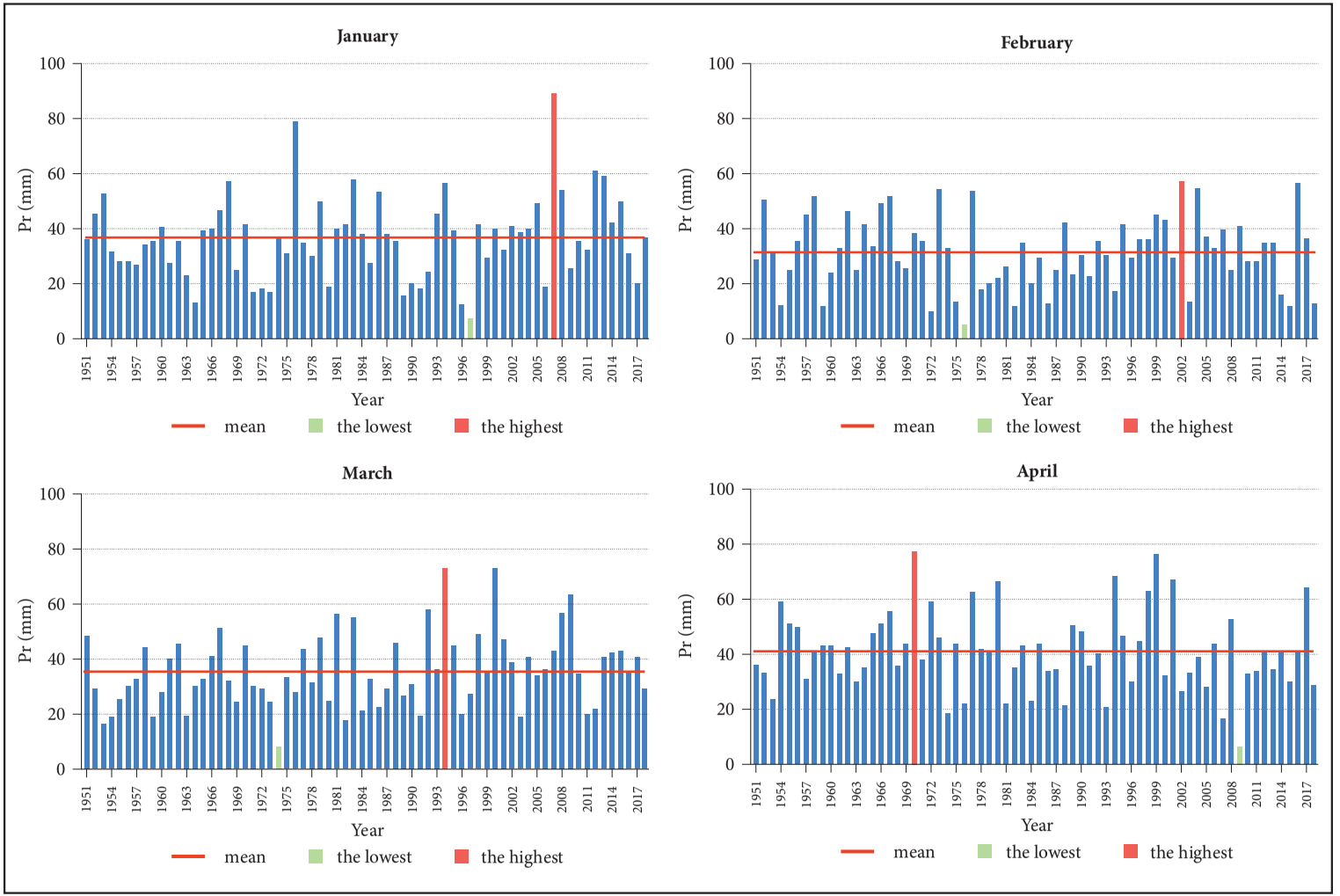
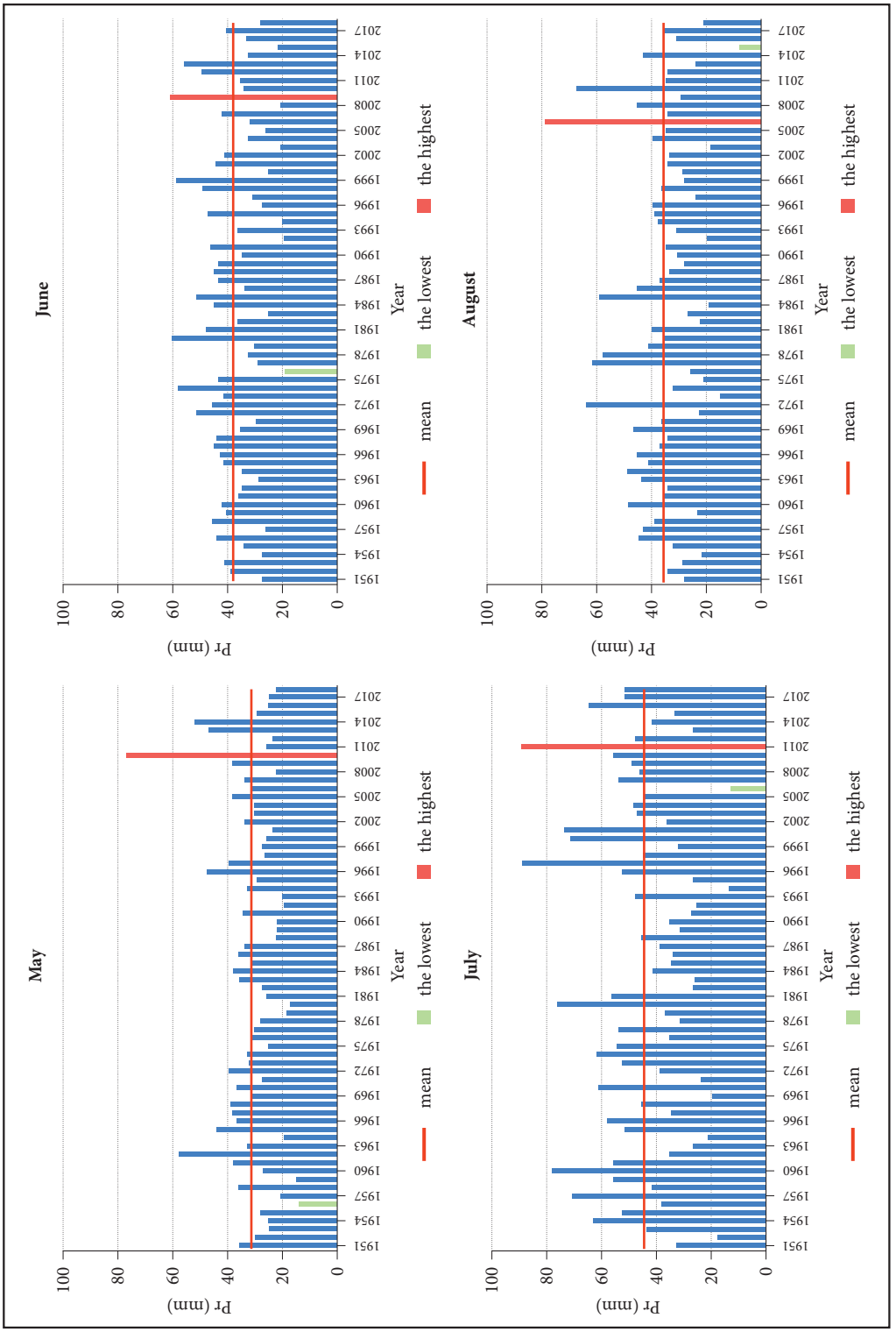


Figure 8: Temporal distribution of annual (January–December) precipitation totals in Poland, 1951–2018.

Figure 9: Temporal distribution of monthly precipitation totals in Poland, 1951–2018. ► p. 55–57


January
February
March
April
Pr (mm)
Year
mean
the lowest
the highest


June
May
August
July
Pr (mm)
Year
mean
the lowest
the highest
0
20
40
60
80
100
1951
1954
1957
1960
1963
1966
1969
1972
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1978
1981
1984
1987
1990
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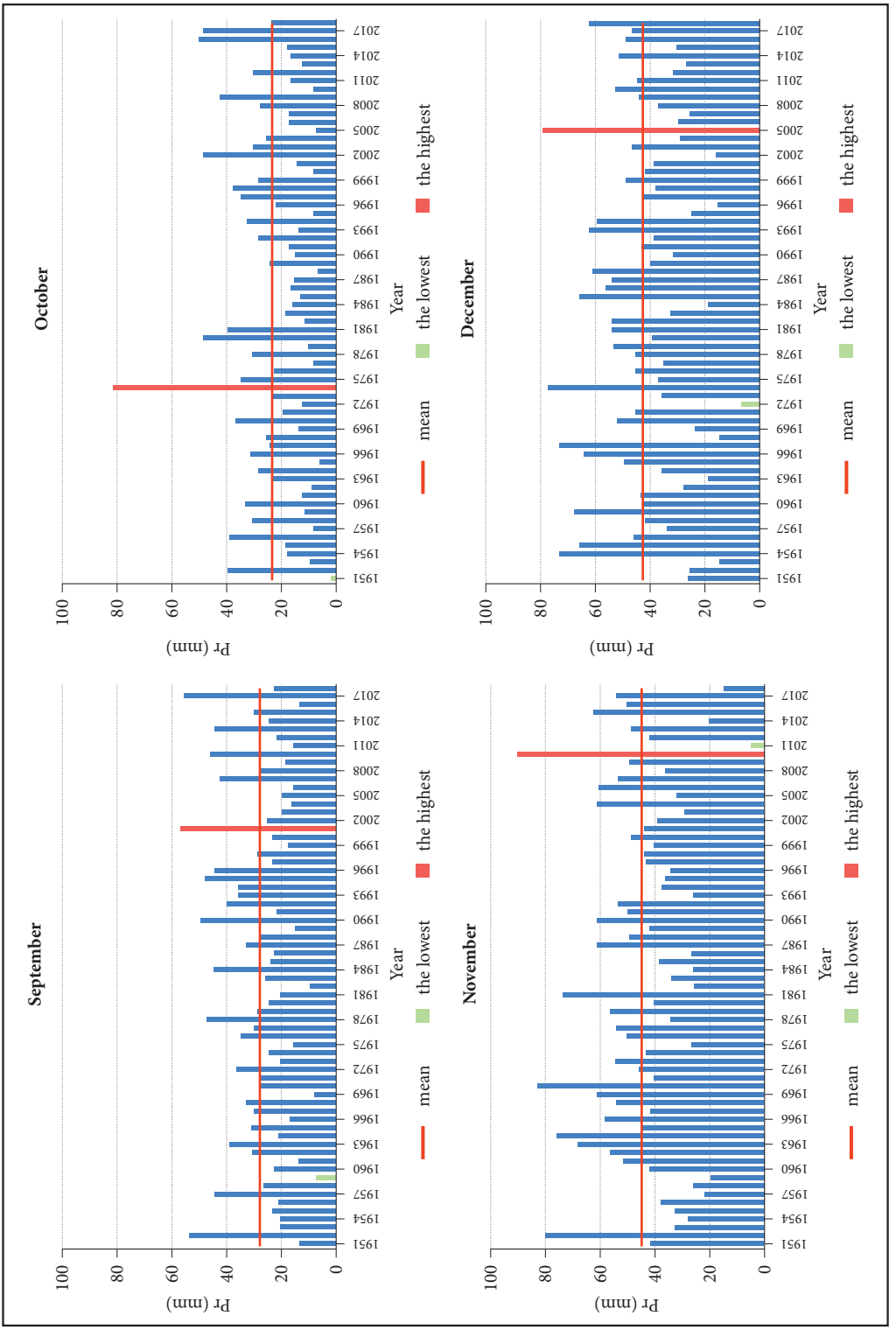
2014
2017


October
December
September
November
Pr (mm)
Year
mean
the lowest
the highest
0
20
40
60
80
100
1951
1954
1957
1960
1963
1966
1969
1972
1975
1978
1981
1984
1987
1990
1993
1996
1999
2002
2005
2008
2011
2014
2017

Pr constituted only about 6% of the norm in October (in 1951) to about 51% of the norm in June (1976). In the months of the lowest Pr, the average number of days without precipitation fluctuated from 22 days in June (1976) to 29 days in October (1951). The average number of days with precipitation within a range of 0.1–1 mm oscillated from 1.2 days in October (1951) to 6.6 days in January (1997). On the other hand, the average number of days with precipitation of >1 mm fluctuated from 0.8 days in October (1951) to 5.6 days in June (1976); the average number of days with precipitation of >2 mm varied from 0.3 to 4.7 days in October (1951) and June (1976), respectively. Higher Pr values, i.e. >5 mm, in dry months were observed much more rarely as the average number of days with such precipitation oscillated between 0.1 and 2.8 days.

The spatial distribution of the lowest annual and monthly precipitation totals in Poland is presented in Figures 10 and 11. In 1982, the totals fluctuated from <400 mm in central-west and central-east Poland to >1200 mm in the south (Figure 10). The lowest Pr values, which were recorded in 1982, were on average 150 mm lower than in the multi-year period of 1951–2018 (Figure 2). In particular dry months, Pr values oscillated from <5 mm to >105 mm (Figure 11).

Depending on the month, precipitation of <5 mm was recorded mainly in the cold half of the year in various parts of Poland, namely in the strip stretching from the north-west to the central-east (January 1997), in the east (February 1976), in the south-east (March 1974), in the central strip stretching from the north to the south (April 2009), in most of the country (October 1951), in the south and the central strip situated along the west-east axis (November (2011) and mainly in central-east Poland (December 1972).

On the other hand, Pr of >105 mm occurred in May (1956) and June (1976) in the south of Poland. In other dry months, the highest Pr was recorded in different parts of Poland, e.g. >15 mm in February (1976) in central-west Poland, >25 mm in April (2009) in the south-east, >60 mm in September (1959) in the north, and >70 mm in November (2011) in the north-west.

The highest annual Pr in Poland was registered in 2010 and constituted ~135% of the norm (Table 3).

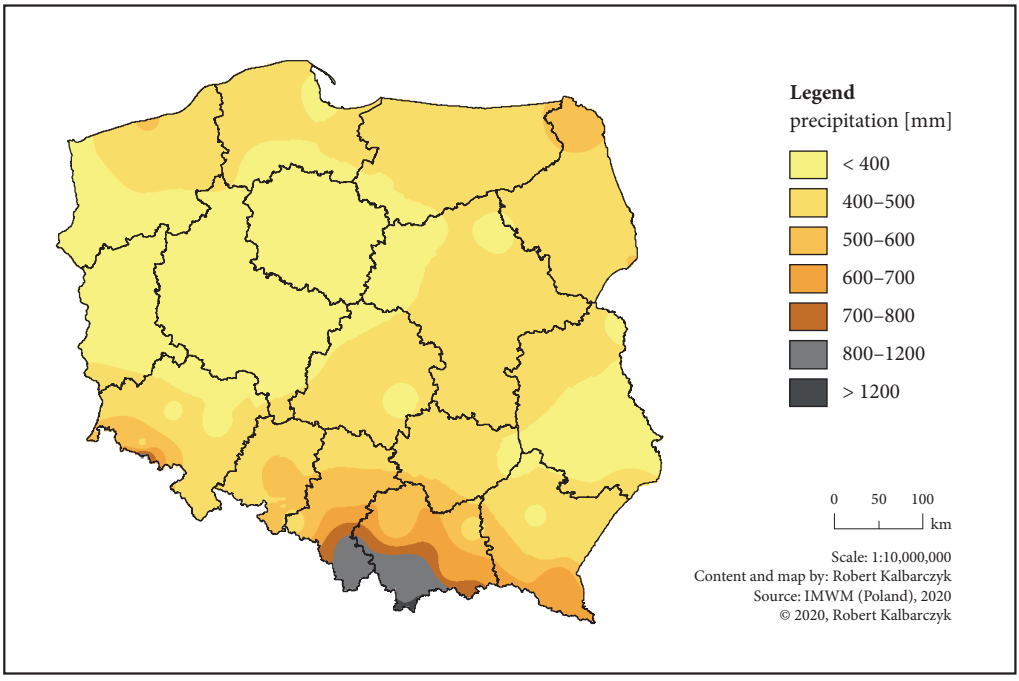


Figure 10: Spatial distribution of the lowest annual precipitation totals in Poland in all the analyzed years, 1951–2018.

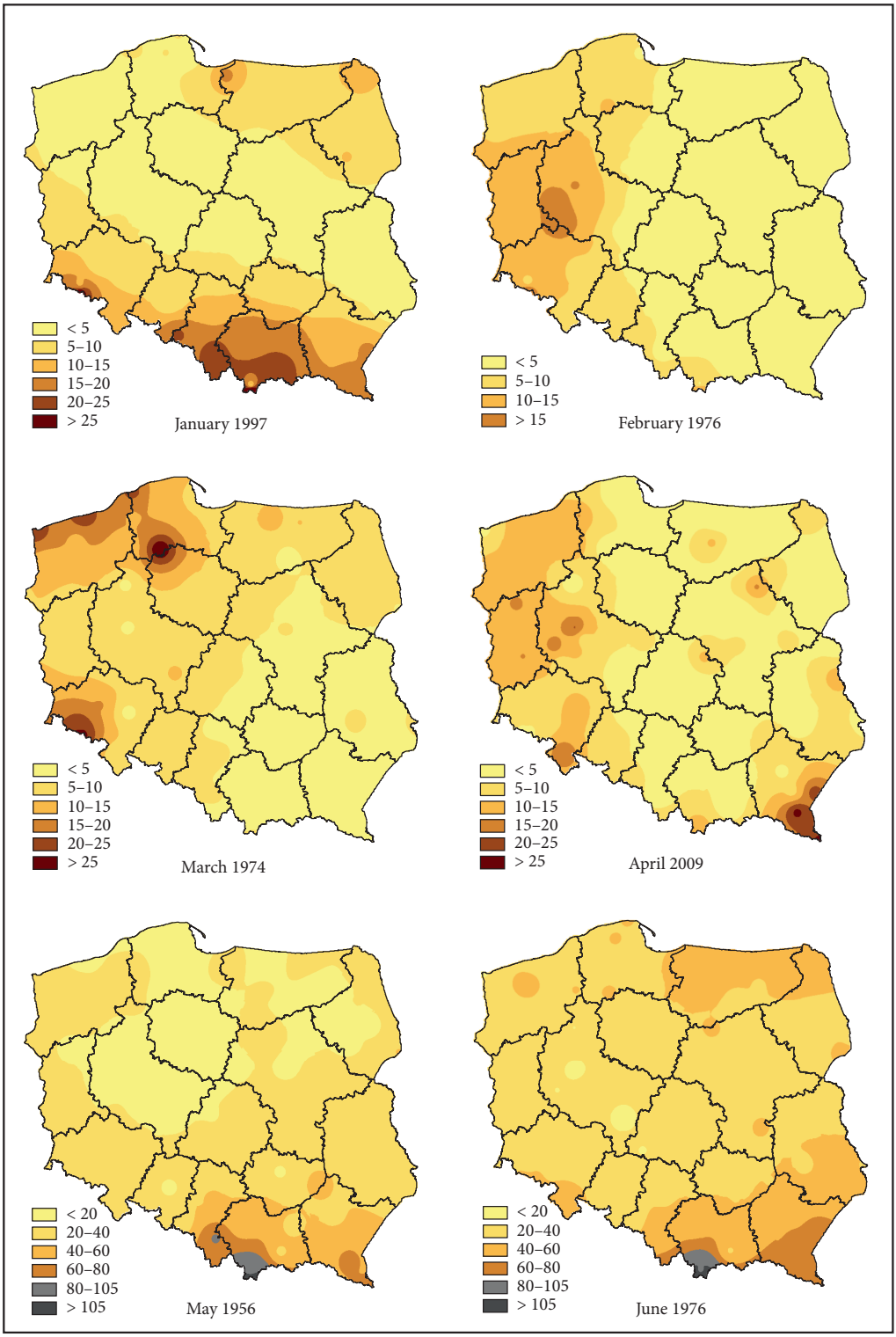
Figure 11: Spatial distribution of the lowest monthly precipitation [mm] totals in Poland in all the analyzed months, 1951–2018. ► p. 60–61

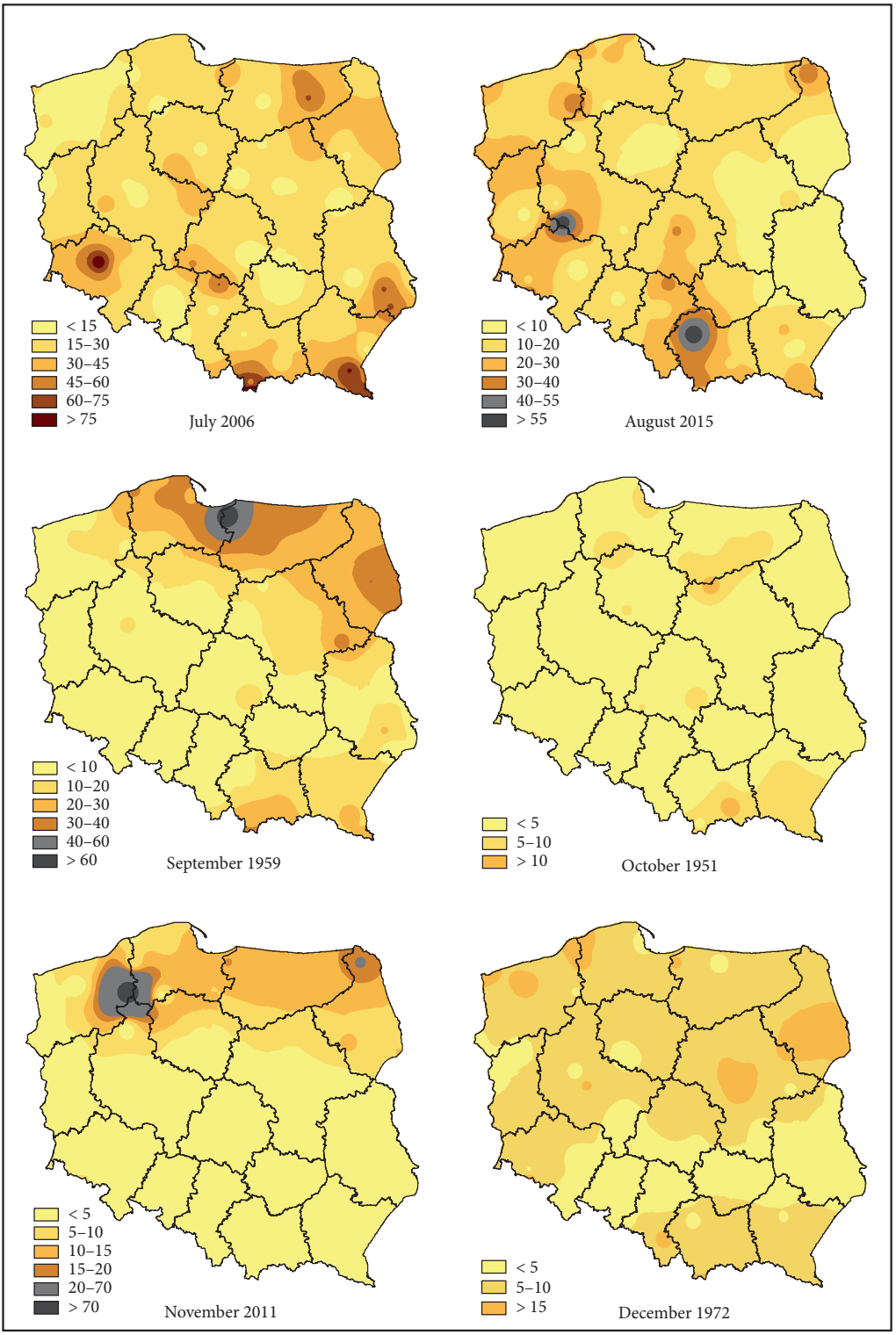
Table 2: Characteristics of the structure of the lowest precipitation totals in Poland, 1951–2018.

Period / month	Year with the lowest precipitation totals	% of multi-year precipitation total	Average number of days without precipitation and with precipitation							
			0.0 (mm)	0.1–1	>1	>2	>5	>10	>20	>50
January–December	1982	71.6	232.5	53.4	79.1	57.8	27.9	10.0	2.4	0.1
January	1997	20.5	22.7	6.6	1.7	1.0	0.3	0.1	0.0	0.0
February	1976	15.2	24.5	3.0	1.5	0.8	0.1	0.0	0.0	0.0
March	1974	21.4	26.7	2.4	1.9	1.3	0.4	0.0	0.0	0.0
April	2009	15.9	27.3	1.4	1.3	0.9	0.3	0.2	0.0	0.0
May	1956	44.7	22.3	3.4	5.3	3.8	1.4	0.6	0.1	0.0
June	1976	50.5	22.0	2.4	5.6	4.7	2.8	1.2	0.1	0.0
July	2006	28.6	25.4	2.3	3.3	2.7	1.5	0.8	0.2	0.0
August	2015	22.5	25.3	2.6	3.1	2.2	0.9	0.3	0.1	0.0
September	1959	25.6	22.6	3.6	3.8	2.3	0.6	0.1	0.0	0.0
October	1951	6.4	29.0	1.2	0.8	0.3	0.1	0.0	0.0	0.0
November	2011	11.1	25.7	3.4	0.9	0.5	0.1	0.0	0.0	0.0
December	1972	15.8	24.0	5.0	2.0	1.0	0.1	0.0	0.0	0.0

Table 3: Characteristics of the structure of the highest precipitation totals in Poland, 1951–2018.

Period / month	Year with the highest precipitation totals	% of multi-year precipitation total	Average number of days without precipitation and with precipitation							
			0.0 (mm)	0.1–1	>1	>2	>5	>10	>20	>50
January–December	2010	134.4	180.7	66.6	117.7	91.5	50.3	22.1	7.2	0.9
January	2007	245.3	6.0	8.2	16.8	12.1	5.6	2.0	0.3	0.0
February	2002	184.1	10.6	5.5	11.9	8.5	4.0	1.0	0.1	0.0
March	1994	207.2	8.6	6.9	15.5	11.6	4.7	1.2	0.0	0.0
April	1970	190.1	10.7	6.7	12.6	9.6	5.6	2.3	0.3	0.0
May	2010	246.0	8.8	4.9	17.3	14.7	9.3	4.4	1.6	0.2
June	2009	160.7	9.2	5.8	15.0	12.2	7.8	4.1	1.0	0.1
July	2011	200.3	10.8	4.8	15.4	13.5	9.9	6.2	2.5	0.2
August	2006	220.1	9.8	5.2	16.0	13.7	8.9	5.2	2.1	0.2
September	2001	203.4	10.0	5.3	14.7	12.2	7.3	3.7	1.0	0.0
October	1974	354.9	7.5	6.2	17.3	14.8	10.1	5.7	1.8	0.1
November	2010	201.4	9.5	6.5	14.0	11.3	6.4	2.6	0.3	0.0
December	2005	186.3	8.4	7.8	14.8	11.3	5.2	1.9	0.2	0.0


< 5
5–10
10–15
15–20
20–25
> 25
January 1997
< 5
5–10
10–15
> 15
February 1976
< 5
5–10
10–15
15–20
20–25
> 25
March 1974
< 5
5–10
10–15
15–20
20–25
> 25
April 2009
< 20
20–40
40–60
60–80
80–105
> 105
May 1956
< 20
20–40
40–60
60–80
80–105
> 105
June 1976


< 15
15–30
30–45
45–60
60–75
> 75
July 2006
< 10
10–20
20–30
30–40
40–55
> 55
August 2015
< 10
10–20
20–30
30–40
40–60
> 60
September 1959
< 5
5–10
> 10
October 1951
< 5
5–10
10–15
15–20
20–70
> 70
November 2011
< 5
5–10
> 15
December 1972

In wet 2010 year, no precipitation was registered on ~181 days. In 2010, the average number of days on which precipitation was registered in Poland was the following: >1 mm (~118 days), >2 mm (~92 days), >5 mm (~50 days), >10 mm (~22 days), >20 mm (~7 days), and >50 mm (~1 day). The highest monthly Pr ranged from about 164% of the multi-year precipitation in June (2009) to as much as approximately 355% in October (1974). In both these months, there was no rain only for 8–9 days. Precipitation of >1 mm per day was observed on about 15 and 17 days in June and October, respectively: >5 mm – about 8 and 10 days, >10 mm – about 4 and 6 days, and >20 mm – about 1 and 2 days.

In 2010, which has the highest Pr in the multi-year period, precipitation fluctuated from <750 mm in the central strip and the north to >1700 mm in the south of Poland (Figure 12).

The highest Pr in consecutive months of the year was observed in various parts of Poland, most frequently in the south (Figure 13). High precipitation values also occurred in the north (e.g. in January 2007 and October 1974), in the north-west (e.g. in February 2002 and April 1970), in the north-east (e.g. in August 2006 and October 1974) and in the east (e.g. in August 2006 and October 1974). The biggest differences in Pr occurred in May, when the totals oscillated from <100 to >375 mm, and July when the totals oscillated from <100 to >320 mm; the highest totals were recorded in the southern and eastern parts of the country.

3.4 Precipitation regions

In Poland, the area of each of the three regions (separated based on precipitation totals and precipitation variability) changed depending on the analyzed multi-year period (Figure 14).

In the first half of the examined multi-year period, i.e. in 1951–1984, the region with the lowest Pr (Cluster I) mostly covered the central-east part of Poland; the second Pr region (Cluster II) covered a bigger part of the country, namely the north, west and partly the south of Poland; the third Pr region

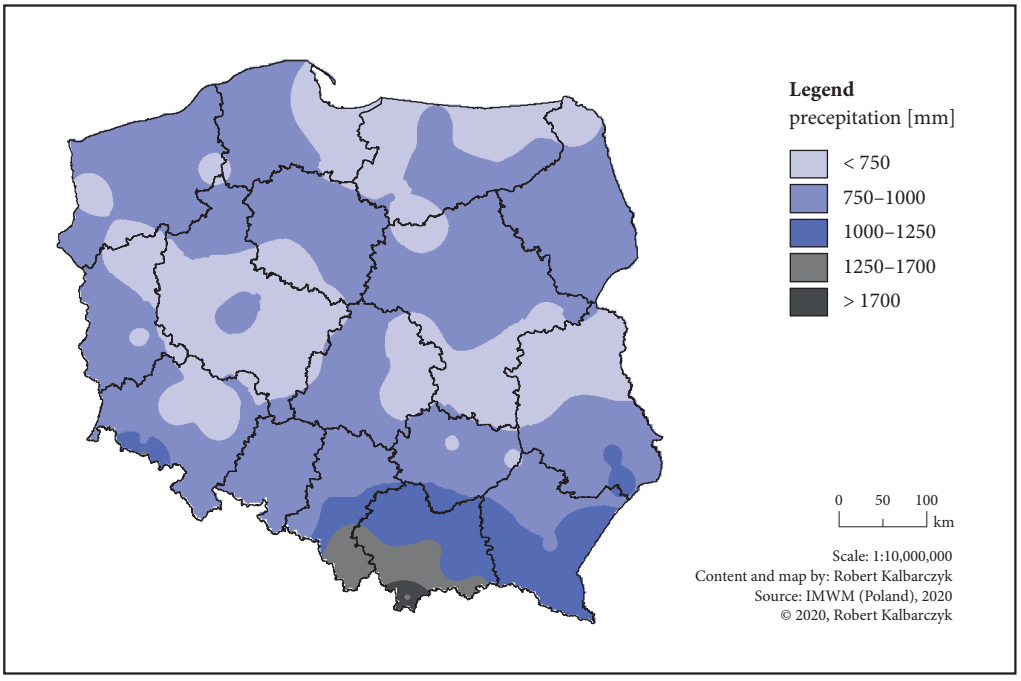


Figure 12: Spatial distribution of the highest annual precipitation totals in Poland in all the analyzed years, 1951–2018.

Figure 13: Spatial distribution of the highest monthly precipitation [mm] totals in Poland in all the analyzed months, 1951–2018. ➤ p. 64–65

(Cluster III) encompassed a small area in the south and the south-west of Poland. In the second half of the considered multi-year period, i.e. in 1985–2018, regions with a characteristic precipitation variability covered slightly different areas of Poland. In 1985–2018, the first Pr region was approximately 50% larger than in 1951–1984 and covered the entire central strip of Poland up to the north-western and north-eastern parts of the country. The second Pr region shrank at the cost of the first region and covered areas only in the north and the south of the country; the third region, on the other hand, slightly shrank at the cost of the second region. As expected, in the whole analyzed multi-year period (1951–2018) the distribution of the distinguished precipitation regions was similar to the distributions in the first and second halves of the entire multi-year period. In 1951–2018, the first and second Pr regions covered almost the same area in terms of size. The first Pr region covered central Poland, while the second one covered the northern and southern parts. The third Pr region was situated in the south and the south-west of Poland and its area was slightly smaller than in 1951–1984.

In all the three analyzed multi-year periods, the stations of the lowest precipitation totals were classified as the first Pr region, while the stations of the highest totals were classified as the third Pr region (Table 4).

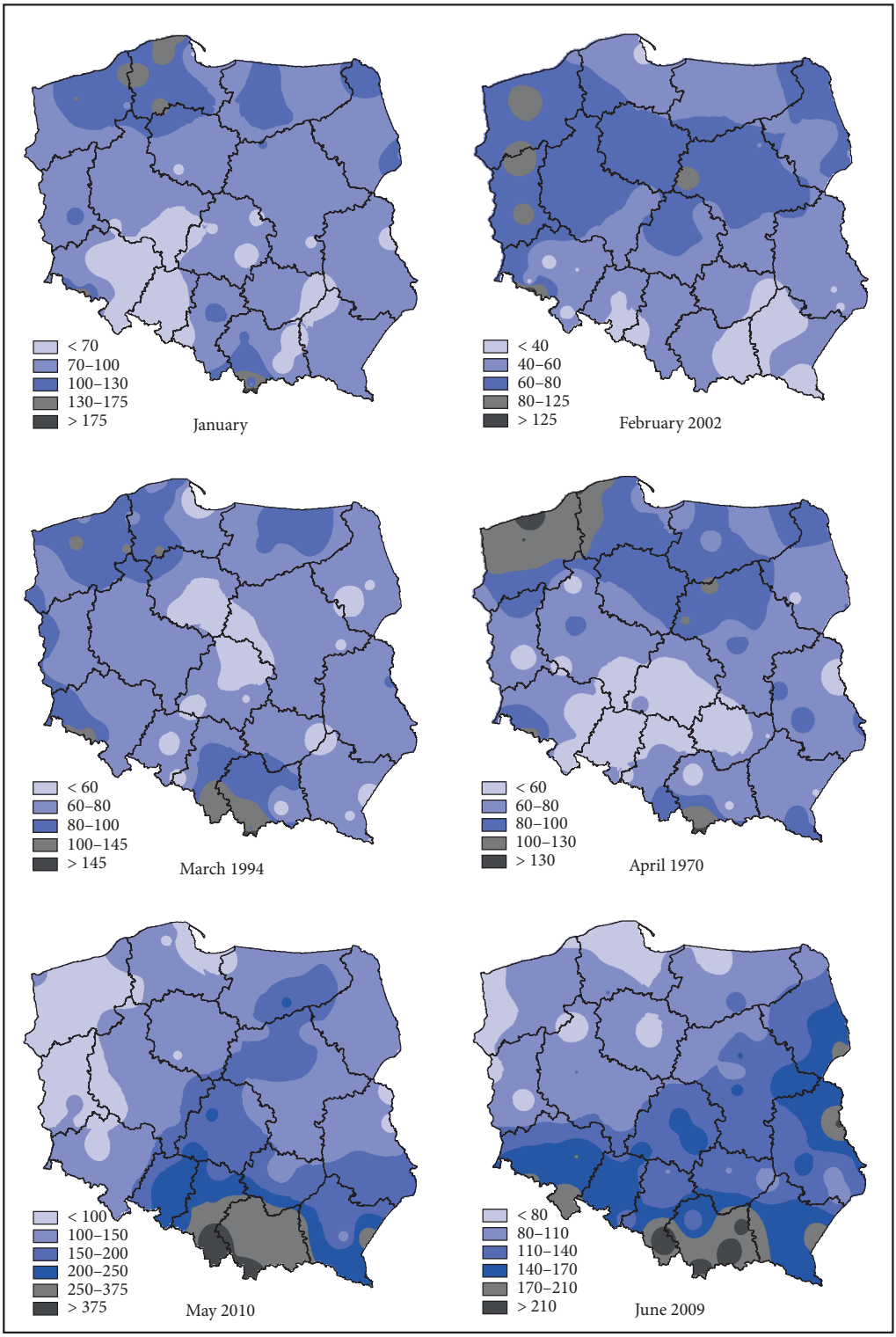
In 1951–1984, average precipitation totals were ~550 mm in the first region, ~650 mm in the second and ~1310 mm in the third; in 1985–2018 these values were ~577, ~713 and ~1237 mm, respectively. In all the separated regions, lower Pr values in 1951–1984, in comparison with 1985–2018, occurred only in three months: March, May and September. Comparing the two examined sub-periods, a higher average standard deviation of Pr was calculated in 1985–2018 in Region I and Region III and in 1951–1984 in Region II. In particular months, Pr variability determined on the basis of the standard deviation was lower in as many as 10 months in 1951–1984 in Region II, 8 months in Region I, 6 months in Region III, and in 5 months, i.e. March, April, May, July and September, in all regions.

In the multi-year period of 1951–2018, average annual Pr oscillated from 567 mm in Region I to about 1272 mm in Region III (Table 4). In Region I, i.e. in central Poland, average monthly Pr values fluctuated from about 28 to 82 mm; in Region II they fluctuated from about 33 to 95 mm, and in Region III they fluctuated from about 73 to 172 mm; the lowest totals occurred in February and the highest were in July. The highest variability of Pr in 1951–2018, as in the years 1951–1984 and 1985–2018, was noted in Region III.

Table 4: Characteristics ($\bar{x}$±SD) of precipitation totals in Poland by regions (I, II, III) in 1951–1984, 1985–2018, 1951–2018.

Period / month	1951–1984 Region			1985–2018 Region			1951–2018 Region		
	I	II	III	I	II	III	I	II	III
January–December	549.7± 28.6	649.1± 58.7	1306.3± 335.9	577.1± 44.6	713.4±38.2	1236.7±352.6	567.0±36.4	693.3±41.4	1271.5±338.2
January	29.6±15.3	38.4±19.4	79.1±40.3	33.5±18.3	40.6±21.6	73.6±40.3	32.0±17.1	40.5±21.4	76.3±40.5
February	26.0±15.3	31.0±18.5	75.6±45.7	28.6±14.7	34.8±16.7	69.4±34.7	27.6±15.2	33.3±18.2	72.5±40.7
March	27.3±14.6	33.3±18.3	78.3±36.9	35.1±17.4	40.5±20.3	79.3±38.2	31.5±16.5	37.6±20.2	78.8±37.6
April	36.4±18.6	41.8±22.8	101.8±42.9	35.8±20.5	43.9±23.7	84.3±44.6	36.4±19.8	43.1±23.9	93.0±46.6
May	55.3±26.9	60.5±29.4	129.1±53.7	57.3±29.5	69.8±35.9	130.7±66.1	56.7±28.8	64.4±31.9	129.9±63.6
June	67.7±32.7	76.6±36.0	176.1±69.0	67.7±34.7	80.6±39.7	147.9±61.9	67.9±33.8	80.2±38.4	162.0±67.1
July	80.5±43.7	90.0±48.1	176.2±89.9	82.6±47.3	96.2±55.2	168.3±93.5	81.7±45.6	95.0±52.2	172.3±93.2
August	64.4±36.6	75.3±39.8	143.5±72.8	64.8±37.1	80.2±40.9	125.7±70.1	65.0±37.0	79.1±41.0	134.6±71.8
September	45.6±27.6	58.1±31.5	93.6±48.2	52.4±31.8	72.7±41.8	113.0±64.1	49.5±29.9	66.5±37.2	103.3±57.6
October	40.7±34.2	50.6±37.6	81.0±53.5	40.1±27.3	56.8±36.3	81.5±45.2	40.5±30.7	55.3±37.7	81.3±49.4
November	39.9±20.7	49.0±25.4	87.7±43.3	39.7±19.8	49.6±25.7	80.7±37.2	40.1±20.3	50.6±26.1	84.2±40.5
December	36.2±19.7	44.5±23.4	84.6±37.8	39.5±18.6	47.7±22.4	82.1±42.7	38.1±19.3	47.6±23.4	83.4±40.5

Figure 14: Regions (I, II, III) of Poland of similar precipitation totals and precipitation variability in 1951–1984, 1985–2018 and 1951–2018. ➤ p. 66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70–100
100–130
130–175
> 175
January
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40–60
60–80
80–125
> 125
February 2002
< 60
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80–100
100–145
> 145
March 1994
< 60
60–80
80–100
100–130
> 130
April 1970
< 100
100–150
150–200
200–250
250–375
> 375
May 2010
< 80
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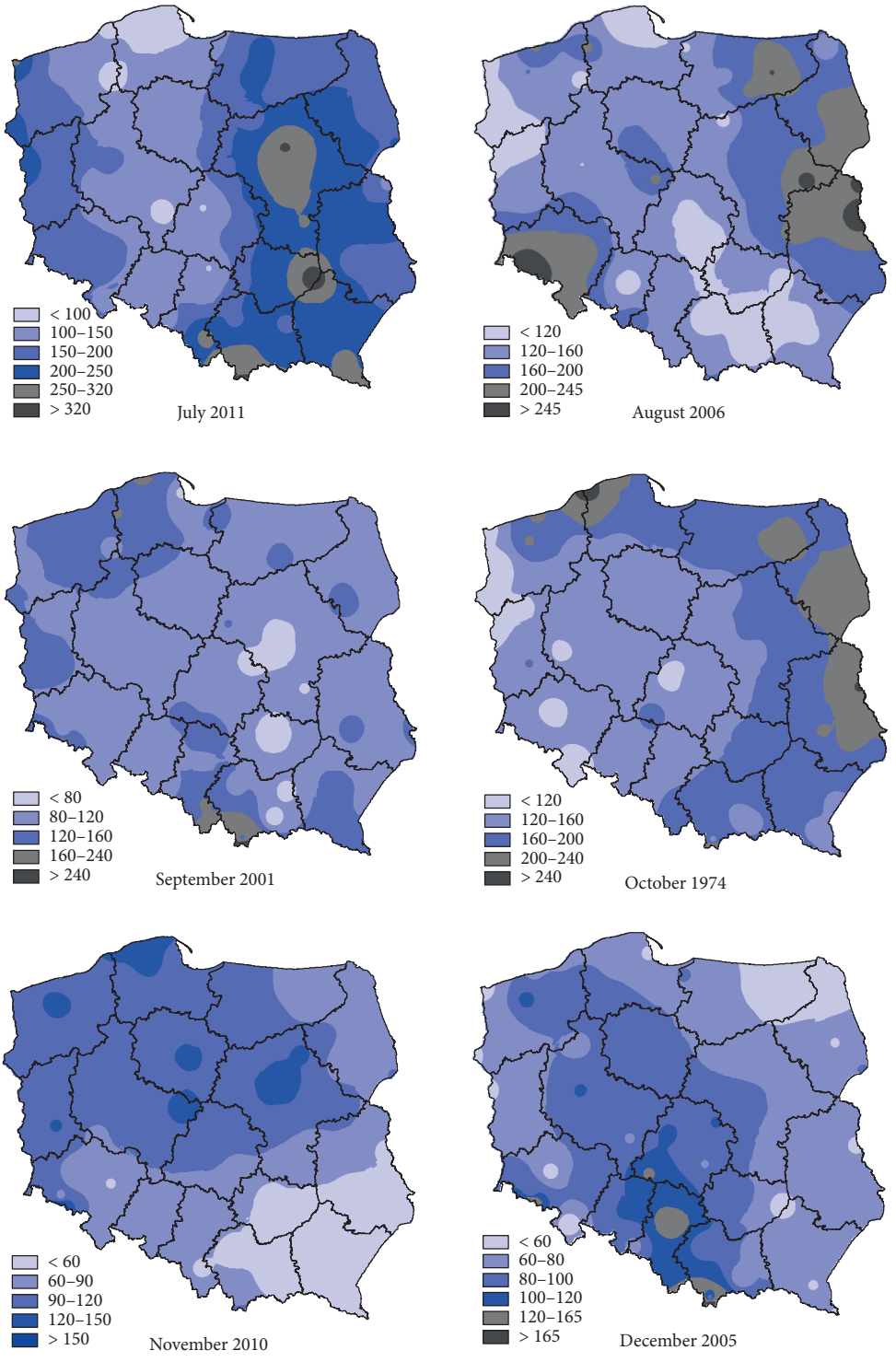
110–140
140–170
170–210
> 210
June 2009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150–200
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July 2011
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120–160
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200–245
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August 2006
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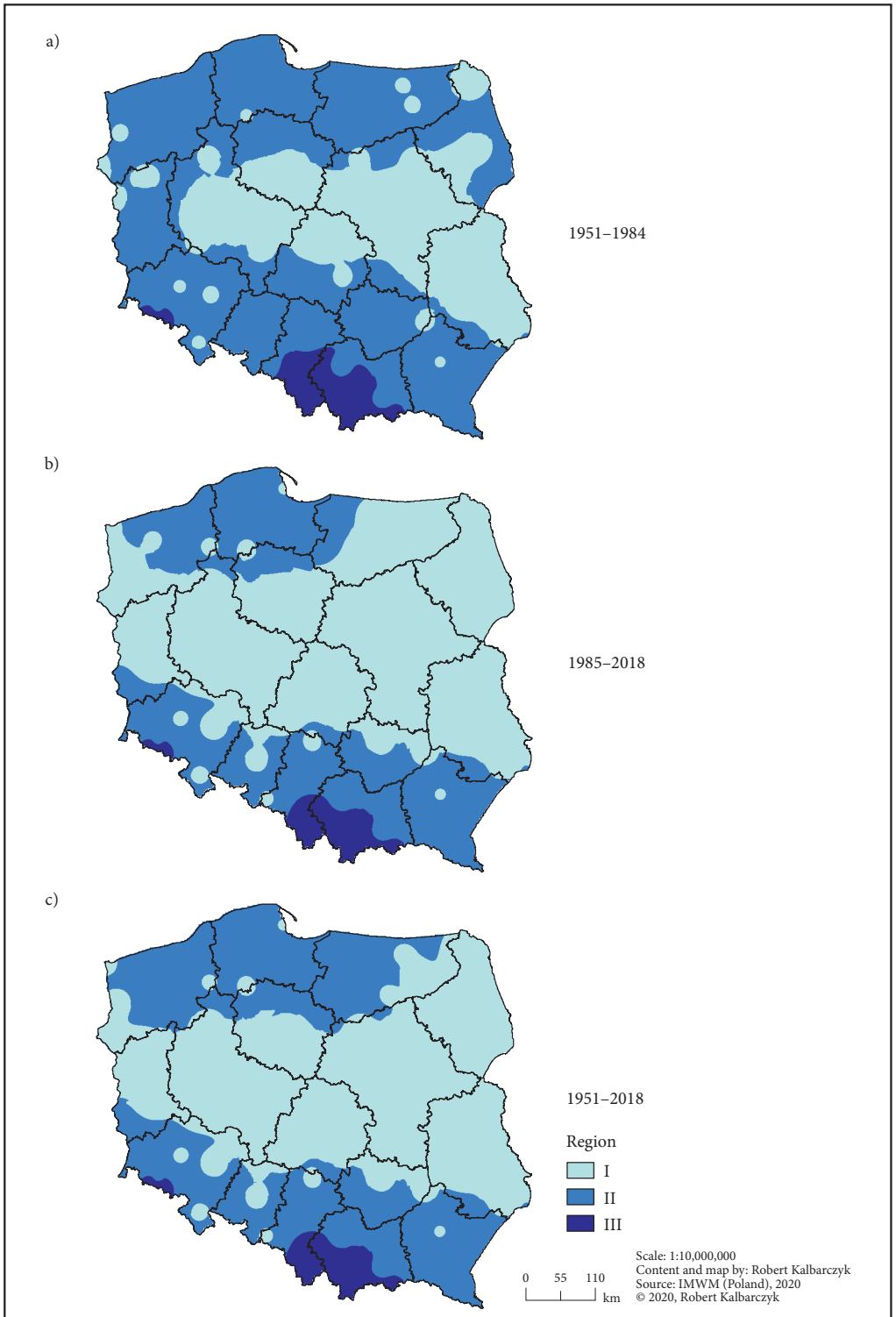
120–160
160–240
> 240
September 2001
< 120
120–160
160–200
200–240
> 240
October 1974
< 60
60–90
90–120
120–150
> 150
November 2010
< 60
60–80
80–100
100–120
120–165
> 165
December 2005


a)
1951–1984
b)
1985–2018
c)
1951–2018
Region
I
II
III
0 55 110
km
Scale: 1:10,000,000
Content and map by: Robert Kalbarczyk
Source: IMWM (Poland), 2020
© 2020, Robert Kalbarczyk

In autumn and winter months, the standard precipitation deviation was higher than in the spring and summer months and fluctuated from approximately 15 to 46 mm in Region I, from approximately 18 to 52 mm in Region II, with the lowest values in February and the highest in July; in Region III it oscillated from ~38 mm in March to ~93 mm in July.

4 Discussion

In Poland in the multi-year period the annual precipitation totals have changed significantly only in some areas of the country. In the south-east, central-east and north-west Poland, precipitation increased significantly, while the sum of precipitation was only locally reduced in south-west Poland. An increase in precipitation totals was confirmed only regionally. The observed significant positive increase in Pr in March had the biggest spatial range. The high increase in precipitation in March and the slight increase in annual precipitation totals in Poland in 1951–2013 were also confirmed by Szwed (2018).

A decrease in monthly precipitation totals was also frequent in some regions. Regional differences related to the trends of precipitation totals and the number of days with precipitation are a very common phenomenon. In Slovakia, regional differences in the temporal distribution of precipitation were shown by Labudová, Faško and Ivaňáková (2015); in Czechia, some regional differentiation in annual precipitation totals of daily maxima was also found (Květoň and Žák 2008). Some examples of regional differences in precipitation variability can also be found in studies by, for example, Skowera, Kopcińska and Kopeć (2014), Tošić et al. (2016), Kivinen et al. (2017) and Pathak et al. (2018).

In the examined 1951–2018 period, differences between the lowest and highest values of annual and monthly precipitation totals and the long-term average (norm) were very high. The highest annual precipitation total in Poland was recorded in 2010 and constituted ~135% of the norm. The highest monthly precipitation total constituted from about 164% in June (2009) to as much as about 355% in October (1974) of the multi-year monthly values. The lowest annual precipitation total in Poland, which was recorded in 1982, constituted ~72% of the multi-year annual precipitation. In particular months, precipitation totals constituted from as little as about 6% of the monthly norm in October 1951 to about 51% of the norm in June 1976. Although undertaken quite often, studies on values that deviate from the norm are still a challenge for researchers (Hundecha and Bárdossy 2005; Młyński, Cebulska and Wałęga 2018; Kalbarczyk and Kalbarczyk 2020b). Differences in the extent of atmospheric precipitation in Poland are primarily explained by the effect of certain types of atmospheric circulation; high importance is attributed to cloud cover (Degirmendžić, Kożuchowski and Żmudzka 2004; Żmudzka 2009; Twardosz, Niedźwiedź and Łupikasza 2011; Młyński, Cebulska and Wałęgaet 2018). For extreme phenomena it is difficult to prove the significance of a trend and regularities in the development of a given phenomenon (Pfeifer et al. 2015; Zeyaeyan et al. 2017). The observed differences in temporal distribution of precipitation totals between particular years result in irregular periods of drought and excessive precipitation, whose negative social and economic effects cannot be prevented (Kundzewicz, Radziejewski and Pińskwar 2006; Dumrul and Kilicarslan 2017; Brázdil et al. 2019). According to some researchers, the frequency of droughts in Poland is increasing and will continue rise until the end of the century (Kalbarczyk 2010; Kuchar and Iwański 2013; Somorowska 2016). Similar predictions concerning the increased intensification of drought conditions until 2100 have been made for, among others, California (Pathak et al. 2018), South Europe and North Africa (Caloiero, Caloiero and Frustaci 2018), and Thuringia in summer (Krause and Hanisch 2007). On the other hand, North Europe is expected to experience increased precipitation (Szwed et al. 2010). It is also reported that in spring Poland may expect an increase in precipitation (Mezghani et al. 2017).

Spatial distribution of annual precipitation totals in Poland shows a clear regularity. The lowest precipitation is characteristic of the central part of the country and increases northwards and southwards, with maximum values in the southernmost mountain areas. The determined precipitation regions display a fairly close similarity to the pluviothermal regions of Poland presented in Schmuck's (1965) as well as in Ziernicka-Wojtaszek and Zawora's (2008); the fundamental difference is the range of the lowest precipitation region reaching also the north-east of the country. In the Köppen's classification nearly the whole Poland is located in the Dfb zone, only a small fragment in the south is included in the climatic zone Dfc (Beck et al. 2018). Thus, the present regionalization provides additional information about spatial differences of precipitation in Poland. In particular months and seasons, spatial distribution of precipitation totals slightly diverge from this regularity; however, the areas with the lowest precipitation totals are continually

located in the strip of central lowlands with a shift to the west or east of the country. The highest monthly Pr values in the examined multi-year period occurred in various parts of the country, most frequently in the south of Poland. This kind of spatial distribution of precipitation in Poland is consistent with previous research studies conducted on the basis of different multi-year periods, as well as research on the early decades of the 20th century (Twaróg 2016; Szwejkowski et al. 2017; Szwed 2018); this indicates stable regularities of Poland's spatial distribution of precipitation.

The determined precipitation regions may be useful for climatic risk management and preparation of regional and local adaptation plans aimed at balancing the effects of climate change (Twaróg 2016; Kalbarczyk and Kalbarczyk 2020a).

5 Conclusion

In Poland, average annual precipitation totals in 1951–2018 were only ~634 mm and fluctuated from <550 mm in the central part of the country to >1300 mm in the south. The lowest average monthly precipitation (Pr), was observed in February and was about 2.9 times as low as the highest average values observed in July. The highest variability of Pr, both annual and monthly, usually occurred in the areas of the highest precipitation totals, primarily in the south of Poland.

In 1951–2018, in most parts of Poland apart from the south-west, annual precipitation totals rose year by year, but a significant increase of at least at a level of $\alpha \leq 0.1$ was found only in small areas in the north-west, central-west and south-east. This increase was caused by the rising Pr in March which occurred mainly in northern and central Poland.

Extreme annual precipitation totals in Poland occurred in 1982 and 2010. They constituted about 72% and 134% of the norm, respectively. The lowest monthly Pr, which constituted only ~6% of the norm, was recorded in October 1951; the highest monthly Pr, which constituted as much as ~355% of the norm, was recorded in October 1974.

In the months of the lowest Pr (dry months), the average number of days without precipitation varied from about 22 days in June 1976 to 29 days in October 1951; in the months of the highest Pr (wet months), it varied from 6 days in January 2007 to 11 days in July 2011, April 1970 and February 2002. In the months with the lowest precipitation, the average number of days with precipitation of >5 mm and the average number of days with precipitation of >10 mm were mostly observed in June and amounted to 2.8 and 1.2 days, respectively. Spatial distribution of the lowest and highest Pr in particular months of the year in comparison with average multi-year values differed not only in precipitation totals but also in spatial distribution, which mostly resembled a latitudinal arrangement in the case of dry months or an irregular arrangement in wet months.

Three precipitation regions were distinguished in Poland on the basis of precipitation variability in each of the different multi-year periods: 1951–1984, 1985–2018, and 1951–2018. The lowest and least variable Pr values were classed as Region I, which in 1951–1984 covered the central-east part of Poland, whereas in 1985–2018 it was in the central, north-west and north-east parts of the country. The highest and most variable Pr was classed as Region III, which in all the analyzed multi-year periods was in the south-west and south Poland. The results may prove useful while planning water management measures, as well as in the management of flood risks and prevention of drought effects.

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