

Extreme Precipitation in Poland in the Years 1951-2010

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Abstract. The characteristics of extreme precipitation, including the dominant trends, were analysed for eight stations located in different parts of Poland for the period 1951-2010. Five indices enabling the assessment of the intensity and frequency of both extremely dry and wet conditions were applied. The indices included the number of days with precipitation $\geq 10\text{mm}\cdot\text{d}^{-1}$ (R10), maximum number of consecutive dry days (CDD), maximum 5-day precipitation total (R5d), simple daily intensity index (SDII), and the fraction of annual total precipitation due to events exceeding the 95th percentile calculated for the period 1961-1990. Annual trends were calculated using standard linear regression method, while the fit of the model was assessed with the F-test at the 95% confidence level. The analysed changes in extreme precipitation showed mixed patterns. A significant positive trend in the number of days with precipitation $\geq 10\text{mm}\cdot\text{d}^{-1}$ (R10) was observed in central Poland, while a significant negative one, in south-eastern Poland. Based on the analysis of maximum 5-day precipitation totals (R5d), statistically significant positive trends in north-western, western and eastern parts of the country were detected, while the negative trends were found in the central and north-eastern parts. Daily precipitation, expressed as single daily intensity index (SDII), increased over time in northern and central Poland. In southern Poland, the variation of SDII index showed non-significant negative tendencies. Finally, the fraction of annual total precipitation due to the events exceeding the 1961-1990 95th percentile increased at one station only, namely, in Warsaw. The indicator which refers to dry conditions, i.e. maximum number of consecutive dry days (CDD) displayed negative trends throughout the surveyed area, with the exception of Szczecin that is a representative of north-western Poland.

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report [1] has been describing different changes in atmospheric precipitation totals in relation to geographical regions since the beginning of the 20th century, pointing to an increasing trend, inter alia, in northern Europe. At the same time, the probable upward trend in the distribution of extreme precipitation events over the ever-increasing area of our globe has also been reported. Such news stimulates the analysis of precipitation data with regard to changes in their characteristics, particularly in the case of local-scale extreme precipitation events. The aim of this work was to analyse selected features of extreme precipitation events that occurred in Poland in the period 1951-2010. An increase in frequency and intensity of such events has a high impact on the functioning of society and economy, mainly due to the increased risk of flooding.

The investigations were based on the analysis of daily precipitation totals recorded at eight stations in different regions of Poland (figure 1) that represent various physical-geographical conditions.



Stations located in Szczecin and Hel are representative of coastal zone in which the Baltic Sea strongly affects the climate. Stations in the cities of Poznan and Olsztyn are located in the lake region, with some areas elevated even more than 300 m above sea level, which can affect the precipitation totals. Warszawa, Wroclaw and Wlodawa stations represent the belt of central lowlands at 100-200 m asl, with poorly diversified topography and visibly lower precipitation totals in comparison to other regions. Bielsko-Biala station is typical for the upland region, where the station elevation has a visible effect on the precipitation total and the number of days with precipitation, particularly in the case of heavy precipitation [2]. In the present study, a deliberate decision was made not to analyse extreme precipitation in mountainous areas. The data originated from the homogeneous database of Institute of Meteorology and Water Management - National Research Institute (IMGW-PIB). In the case of Szczecin station, the analysed period was shorter due to missing data from the years 1951-1955.



Figure 1. Location of sampling stations.

Five indices of extreme precipitation that enable the assessment of intensity and frequency of both extremely wet and extremely dry conditions were analysed. The indices included the number of days with precipitation $\geq 10\text{mm}\cdot\text{d}^{-1}$ (R10), maximum number of consecutive dry days (CDD), maximum 5-day precipitation total (R5d), simple daily intensity index (SDII), and the fraction of annual total precipitation due to events exceeding the 1961-1990 95th percentile (R95T). The aforementioned indices were designed prior to the publication of IPCC Third Assessment Report, and are recommended for evaluating the changing characteristics of extreme precipitation events [3]. According to the authors [3], the longest time period without precipitation characterizes changes in the drought occurrence during the warm part of the year. The number of days with precipitation $\geq 10\text{mm}\cdot\text{d}^{-1}$ (R10) and simple daily intensity index (SDII) reflect changes in precipitation, particularly during the wet part of the year. The maximum 5-day precipitation total (R5d), and the fraction of annual total precipitation due to events exceeding the 1961-1990 95th percentile (R95T) appropriately characterize the cases of extreme precipitation.

Temporal trends in the above-mentioned indices were evaluated by means of linear regression, while their statistical significance at the 95% confidence level was assessed with the F-Snedecor test.

2. Results

The annual mean numbers of days with heavy precipitation, R10 [4], for which the daily total is $\geq 10\text{mm}\cdot\text{d}^{-1}$, showed a high spatial variation. In north-western, western and central Poland (Szczecin, Poznan and Warszawa stations), the annual number of such days was not larger than 12 (table 1). On the coast of Poland, on average ca. 13 days with heavy precipitation (R10) per year were noted. The

lake region was characterized by a slightly higher number of days with heavy precipitation, reaching the value of ca. 15. In central lowlands, the values of R10 index were somewhat lower than those calculated for the lake region, varying at the 13-14 days' level. In the upland areas, the numbers of days with heavy precipitation were visibly higher, reaching the annual mean value of ca. 29 days at the sampling station in Bielsko-Biala. The lowest annual mean number of days with heavy precipitation varied from 2 (Poznan) to 6 days (Wroclaw and Wlodawa), and even up to 18 days (Bielsko-Biala). During the analysed time period, the annual maximum number of days with heavy precipitation ranged from 22-28 in the lowlands to 42 in the uplands. The temporal trend analysis of the annual number of days with heavy precipitation (R10) showed the presence of statistically significant increase in the number of such days at stations in Poznan and Warszawa. The statistically significant decrease in R10 index was observed in Wroclaw.

Table 1. The annual mean, maximum and minimum number of days with heavy precipitation (R10) at selected stations in Poland in the years 1951-2010, and the slope values ($\text{day}\cdot 10\text{yrs}^{-1}$) from the fitted regression equations. Statistically significant values are shown in boldface.

Station	Szczecin ^a	Hel	Olsztyn	Poznan	Warszawa	Wroclaw	Wlodawa	Bielsko-Biala
Min	5.0	4.0	6.0	2.0	4.0	6.0	6.0	18.0
Mean	11.9	12.9	14.8	11.4	11.9	13.6	12.7	28.8
Max	22.0	24.0	28.0	22.0	24.0	25.0	25.0	42.0
Trend	0.11	0.10	0.00	0.25	0.50	-0.23	-0.19	-0.29

^a 1956-2010

The 5-day precipitation total (R5d) is considered a good indicator for describing long-lasting extreme precipitation that can cause flooding [5]. The maximum values of the annual mean of 5-day precipitation totals at stations located in the Polish lowlands were very similar, ranging between 25.3 and 31.4 mm in Szczecin and Olsztyn, respectively (table 2). The highest mean values of R5d index were observed in Bielsko-Biala (47.1mm). In the period 1951-2010, the lowest 5-day precipitation totals equalled 2.9 and 11.5 mm in Szczecin and Bielsko-Biala, respectively. These values did not have a distinct spatial distribution, with an exception of visibly higher values at the station located in the uplands. On the other hand, the absolute maximum values of 5-day precipitation total showed a weak pattern. The highest 5-day precipitation totals measured at stations located in western Poland (Szczecin, Poznan and Wroclaw) reached the 85-92 mm level, while those at stations in northern and central Poland were lower (60-70 mm). In Wlodawa, which is representative of eastern Poland, the absolute maximum of 5-day precipitation total reached 101 mm. In Bielsko-Biala, the value of this parameter equalled 164.5 mm.

The analysis of R5d index variation over the analysed time period did not reveal any trends at the stations representing northern (Hel) and north-eastern Poland (Olsztyn). The presence of statistically significant temporal trends in the values of R5d index were noted for the remaining stations, however, the trend directions were not the same. In Warszawa and Wroclaw, a statistically significant decrease in R5d index was observed, which reached the level of 1.8-2.3 $\text{mm}\cdot 10$. At stations located in Szczecin, Poznan and Wlodawa, statistically significant increases in R5d index were noted, ranging from 1.5 to 2 $\text{mm}\cdot 10\text{yrs}^{-1}$. The rate of increase in maximum 5-day precipitation total in Bielsko-Biala exceeded 4 $\text{mm}\cdot \text{yr}^{-1}$.

The mean value of the maximum number of consecutive dry days (CDD) at the analysed stations in the years 1951-2010 was steady, reaching the level from ca. 20 days in Bielsko-Biala to almost 26 days in Warszawa (table 3). The highest values of CDD index ranged from 38 (Bielsko-Biala) to 75 days (Warszawa). Based on the obtained results, it can be concluded that the longest periods of consecutive dry days at the analysed stations in the years 1951-2010 occurred in winter, end of summer and early fall. In general, the maximum values of CDD index did not occur simultaneously,

although the longest period of consecutive dry days in Poznan, Wroclaw and Bielsko-Biala took place in 1959; it ended on the exact same day, namely, October 21st. The station in Bielsko-Biala is characterized by the shortest period of consecutive dry days, most likely due to the fact that it is located in the uplands where the number of days with precipitation is, on average, higher than at the remaining stations [2]. Thus, the probability of extended precipitation-free period in Bielsko-Biala is lower. In Warszawa, the highest value of CDD index was 10-30 days higher than at the remaining stations located in the Polish lowlands. This is most likely related to the local-scale precipitation conditions in the large, highly-urbanized environment.

Table 2. The maximum values of 5-day precipitation total, R5d [mm] at selected stations in Poland in the years 1951-2010, and the slopes of fitted linear regression lines [mm·10yrs⁻¹]. Statistically significant values are shown in boldface.

Station	Szczecin ^a	Hel	Olsztyn	Poznan	Warszawa	Wroclaw	Wlodawa	Bielsko-Biala
Min	2.9	5.3	8.6	8.8	4.7	3.3	3.4	11.5
Mean	25.3	26.0	31.4	27.9	26.9	29.0	30.4	47.1
Max	91.0	60.6	68.2	84.5	70.0	92.1	101.0	165.4
Trend	1.55	-0.44	-0.21	1.78	-1.79	-2.33	1.99	4.15

^a 1956-2010

Stations located in north-eastern, central and southern Poland were characterized by significant negative trends in the number of consecutive dry days (CDD). The trend rates varied from -0.46 (Bielsko-Biala) to -0.88 day·10yrs⁻¹ (Warszawa), which translates into a decreased length of maximum periods without precipitation and the lowered risk of post-drought period occurrence. A similar tendency, i.e. lowered values of CDD index were observed in Hel, however, the trend was not statistically significant. The positive trends in the distribution of CDD index were observed in Szczecin and Wlodawa, although only in the case of Szczecin, the trends were statistically significant, reaching the level of 0.45 day·10yrs⁻¹.

Table 3. The mean maximum and absolute maximum of the number of consecutive dry days, CDD [days], including the dates of occurrence, for selected stations in Poland in the years 1951-2010, and the slopes of fitted linear regression lines [day·10yrs⁻¹]. Statistically significant values are shown in boldface.

Station	Szczecin ^a	Hel	Olsztyn	Poznan	Warszawa	Wroclaw	Wlodawa	Bielsko-Biala
Mean	24.1	22.9	23.9	24.2	25.7	24.1	25.4	20.1
Max	50.0	53.0	58.0	46.0	76.0	65.0	65.0	38.0
Time period	27.12.95 - 14.02.1996	28.11.1972 - 19.01.1993	10.01.1972 - 7.03.1972	06.09.1959 - 21.10.1959	18.08.1951 - 1.11.1951	18.08.1959 - 21.10.1959	16.12.1996 - 18.02.1007	14.09.1959 - 21.10.1959
Trend	0.45	-0.04	-0.48	-0.81	-0.88	-0.84	0.17	-0.46

^a 1956-2010

The index of mean daily precipitation intensity, defined as the 24-hr accumulated amount of precipitation measured on the day with the precipitation ≥ 1 mm (SDII), was rather steady at the

stations located in the Polish lowlands, assuming the values from 5.0 (Szczecin) to 5.6 mm (Wroclaw) (table 4). In Bielsko-Biala, the SDII index was visibly higher, reaching the value of 7.5 mm. The minimum values of SDII index at all the analysed stations were characterized by low variation, with the index values ranging from 3.4 (Poznan) to 5.3 mm (Bielsko-Biala). The maximum values of SDII index varied from 6.6 to 7.5 mm in the Polish lowlands, while in Bielsko-Biala, the SDII value reached almost 11 mm.

Changes in the SDII index values in the years 1951-2010 displayed a distinct spatial pattern. At stations located in northern and central Poland, the values of single daily intensity index increased at a statistically significant rate of 0.04-0.08 mm·10yrs⁻¹. In the case of stations located in southern Poland, the SDII index showed non-significant negative tendencies.

Table 4. The mean, maximum and minimum values of simple daily intensity index, SDII [mm] at selected stations in Poland in the years 1951-2010, and the slopes of regression lines [mm·10yrs⁻¹]. Statistically significant values are shown in boldface.

Station	Szczecin ^a	Hel	Olsztyn	Poznan	Warszawa	Wroclaw	Wlodawa	Bielsko-Biala
Min	4.0	3.6	3.8	3.4	4.0	4.2	4.1	5.3
Mean	5.0	5.1	5.3	5.1	5.2	5.6	5.3	7.5
Max	6.5	6.6	6.8	6.9	6.7	7.3	7.4	10.9
Trend	0.07	0.08	0.04	0.06	0.06	-0.02	-0.01	-0.01

^a 1956-2010

The value of 95% quantile is a characteristic used in numerous publications [3, 5, 6, 7] for establishing the threshold value above which a daily precipitation total is considered to be extreme. At stations located in the Polish lowlands, the values of 95% quantile ranged around ca. 15 mm, which placed them between the moderately heavy (≥ 10 mm) and heavy (≥ 20 mm) precipitation in accordance with the conventional classification of daily precipitation totals [4] (table 5). In Bielsko-Biala, the value of 95% quantile was visibly higher, reaching 24.1 mm. Despite considerable variation in the 95% quantile values for daily precipitation totals at the analysed stations, the fraction of annual total precipitation due to extreme events (R95T) was rather steady. Extreme precipitation events contributed from ca. 21 to ca. 25% of annual precipitation totals in Poznan and Bielsko-Biala, respectively. Extreme precipitation events, as defined above, may not occur at all in specific years. In such cases, the value of R95T index equals 0%. In years with the 24-hr accumulated amount of precipitation above the 95% quantile or with one day of extreme rainfall exceeding the 99% quantile, the share of extreme precipitation in the annual total may reach up to 40-50%.

Table 5. The mean, maximum and minimum values for the fraction of extreme precipitation, R95T (defined as being above the 95% quantile calculated for the normal season 1961-1990) [%] in the annual precipitation total at selected stations in Poland in the years 1951-2010, and the slopes of fitted linear regression lines [%·10yrs⁻¹]. Statistically significant values are shown in boldface.

Station	Szczecin ^a	Hel	Olsztyn	Poznan	Warszawa	Wroclaw	Wlodawa	Bielsko-Biala
95% quantile	14.16	15.09	16.00	15.30	16.41	18.72	15.70	24.10
Min	4.38	0.00	3.59	0.00	4.23	0.00	0.00	3.50
Mean	22.51	22.67	21.78	20.94	21.60	22.61	24.42	24.90
Max	42.68	43.31	41.28	47.95	40.39	44.53	47.19	50.28
Trend	-0.27	0.24	-0.01	0.00	0.68	-0.10	0.26	0.09

^a 1956-2010

The analysis of changes in R95T index at the analysed stations in the years 1951-2010 did not show any statistically significant trends, with an exception of Warszawa. For this particular station, a positive trend was found whose value was increasing, on average, by 0.68% per 10 yrs.

3. Discussion and conclusions

The discussion on the characteristics of extreme precipitation in Poland should be conducted in relation to the variable spatial distribution of annual precipitation totals and the associated trends. The spatial distribution of annual precipitation totals corresponds to the hypsometric image of Poland. The annual precipitation totals in the coastal belt and lake region equal >550 mm, while in the central coastal region, they reach over 700 mm. The central lowlands are characterized by rainfall values below $550 \text{ mm}\cdot\text{yr}^{-1}$. In southern Poland and the mountains, the annual precipitation totals exceed 600 and 700 mm, respectively [8]. The trend directions of annual precipitation totals show a high spatial variability. In the second half of the 20th century and at the beginning of the 21st century, a statistically significant increase in the annual amount of precipitation was observed in northern, north-western and south-eastern Poland. At the same time, a statistically significant decrease in annual rainfall occurred in south-western Poland. In the remaining areas, the trends had various directions and were statistically non-significant [9].

As in the case of annual precipitation totals, the characteristics of extreme precipitation and the associated trends showed a high spatial variability.

The annual mean number of days with precipitation $\geq 10 \text{ mm}\cdot\text{d}^{-1}$ (R10) in the years 1951-2010 was close to the values observed in the second half of the 20th century [8]. In the Polish lowlands, the value of this parameter did not exceed 15 days, while in the uplands and mountains, it ranged from 20 to 40 days. The trend analysis of R10 index revealed the presence of statistically significant increase in its value at stations located in Poznan and Warszawa, while in Wroclaw, a decrease was noted. The obtained results are consistent with those reported for stations located in Poznan and Wroclaw from the period 1971-2002 [10]. Also, the authors demonstrated that the number of days with precipitation $\geq 10 \text{ mm}\cdot\text{d}^{-1}$ (R10) remained unchanged in the northern part of Poland. However, a visible change in the trend direction was noted in Warszawa, with a negative trend for the period 1971-2002, and a positive one for the longer time period, mainly due to the increased number of days with precipitation $\geq 10 \text{ mm}\cdot\text{d}^{-1}$ (R10) after 1991. A similar pattern of changing trends in extreme precipitation, the latter being defined as the daily amount of rainfall above the 90% quantile, was recorded in Poland in the years 1951-2008 [9].

The analysis of changes in the distribution of R5d index during the analysed period did not show any trends at stations located in northern (Hel) and north-eastern Poland (Olsztyn). Similar results were reported by [11] who showed the general lack of trend with regard to the R5d index in the area of Poland located north of the 52nd parallel. A decrease in the Rd5 values in central and south-western Poland has also been confirmed by [10]. On the other hand, an increase in the Rd5 values in north-western, western, southern and eastern Poland slightly contradicts the previously cited results, particularly those obtained for Wlodawa and Bielsko-Biala by [11]. For these two stations, the report [11] provides evidence for the presence of statistically significant negative trends in the distribution of R5d index in the period 1951-2006. At the same time, the report by [10] corroborates the results of the present study. This finding indicates that in the case of R5d index, the selected time period has a strong influence on the results of trend analysis.

The mean maximum period without precipitation (CDD) ranged from ca. 20 (Bielsko-Biala) to almost 26 days (Warszawa), which indicates the occurrence of post-drought periods [12]. In 1951-2010, the highest values of CDD index varied from 38 (Bielsko-Biala) to 75 days (Warszawa). The obtained results are close to those reported by the IMWM-NRI team [13], namely, that the maximum period without precipitation in Poland in 1961-2010 ranged from less than 24 (south-western Poland) to over 40 days (eastern Poland and central coastal area). The extended precipitation-free period in Warszawa was most likely affected by the specific conditions of cloud formation and precipitation that occur in large urban agglomerations [14]. Warszawa is a large city characterized by increased air

humidity and high number of condensation nuclei, therefore, it has conditions that stimulate precipitation. However, there is a well-documented evidence [15] that the precipitation zone moves outside the eastern leeward boundary of the city due to the shift of rain-bearing clouds away from Warszawa by dominant western and south-western winds. These might be the underlying reasons for the occurrence of mean maximum and absolute maximum periods without precipitation in this location. As shown in the present work, the decreasing values of CDD index at the analysed stations (with an exception of Szczecin) indicate that the risk of post-drought period occurrence is diminishing in Poland. The obtained results on the CDD index are also in agreement with those reported by [10] for the period 1971-2002.

The investigations of simple daily intensity index (SDII) on annual basis in Poland [16] for the period 1951-1980 showed that the obtained values were lower compared to those calculated for the period 1951-2010, namely, mean annual values between 3.4 (western and central Poland) and over 5 mm (uplands and mountains) *versus* 5.0-7.5 mm. This finding results from the fact that the values of SDII index in [16] were calculated from the daily totals of days with precipitation ≥ 0.1 mm, while in the present study, the daily totals of days with precipitation ≥ 1.0 mm were used. Thus, a different approach to data analysis produced higher precipitation intensities at stations located in the Polish lowlands. It is noteworthy that a statistically significant increase in the values of SDII index in northern and central Poland did not coincide with a change in the values of Rd5 index. It is therefore likely that the threat due to extreme precipitation in this area will result from the increased probability of 1-day extreme rainfall rather than from extremely heavy and long-lasting precipitation, which has been suggested by others [9], [17].

No statistically significant trends were found in the temporal distribution of R95T index. The obtained results confirmed the outcome of an earlier study [18], where the lack of statistically significant temporal trends of this precipitation index had been reported for central Europe. Warszawa is a special exception because a statistically significant temporal trend in the distribution of the fraction of annual total precipitation due to events exceeding the 95th percentile was found, with a trend rate of $0.68\% \cdot 10\text{yrs}^{-1}$. Considering the increased values of R10 index in Warszawa, this means that the influence of daily extreme precipitation totals on the annual precipitation total is on the rise in this city.

Trends in extreme precipitation in Poland in the years 1951-2010 are characterized by a high spatial variability and big differences among the analysed stations, which suggests that local conditions have a large impact on the formation of precipitation area at those stations. In general, the frequency of days with precipitation $\geq 10\text{mm} \cdot \text{d}^{-1}$ (R10) remains stable, with an exception of central Poland (stations in Poznan and Warszawa). An increase in the maximum values of R5d index in north-western and south-eastern Poland is connected to the temporal trends in annual precipitation totals. The same applies to a decrease in the maximum values of R5d index in central and south-western Poland. The maximum length of precipitation-free period (CDD) decreased in the entire study area (with an exception of Szczecin), which is an advantageous tendency in the areas of Poland displaying both positive and negative trends in annual rainfall totals. In northern Poland, the increasing values of SDII index corresponded to an increase in the annual precipitation totals. The determinants and variability of extreme precipitation in Poland require further in-depth investigation.

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