

## Article

# Changes in the Intra-Annual Precipitation Regime in Poland from 1966 to 2024

Joanna Wibig \*  and Joanna Jędruszkiewicz 

Department of Meteorology and Climatology, University of Lodz, 90-136 Lodz, Poland;  
joanna.jedrusszkiewicz@geo.uni.lodz.pl

\* Correspondence: joanna.wibig@geo.uni.lodz.pl

## Abstract

Many studies relate to long-term changes in annual precipitation in Poland, yet most of them were statistically insignificant. The primary objective of this research was to investigate the precipitation regime during the year in the context of climate change, which is more crucial than annual averages from the perspectives of agriculture and plant growth, as well as for the industrial sector and human access to clean water. For this reason, we used daily precipitation data from the Institute of Meteorology and Water Management—National Research Institute from 1966 to 2024. Each month of the study was examined for changes in monthly totals, the number of dry and wet days, precipitation intensities, and extremes. In the cold season, a considerable shift in precipitation patterns was found between November and December, which became drier, and January and February, which became wetter with more intense and extreme precipitation. Pronounced changes were also noticed in April and June, when not only the monthly totals but also the number of wet days and precipitation intensity decreased. These two months, together with winter, are essential for plant growth. On the contrary, July became slightly wetter. Interesting changes were also observed in September, including an increase in dry days and more intense rainfall. With the increase in temperature and changes in the advection of air masses, September became more similar to summer than to autumn months. The key factors driving shifts in precipitation regimes during the year were a warmer atmosphere and changes in circulation patterns.



Academic Editor: Stefano Federico

Received: 4 May 2025

Revised: 24 June 2025

Accepted: 1 July 2025

Published: 3 July 2025

**Citation:** Wibig, J.; Jędruszkiewicz, J. Changes in the Intra-Annual Precipitation Regime in Poland from 1966 to 2024. *Atmosphere* **2025**, *16*, 813. <https://doi.org/10.3390/atmos16070813>

**Copyright:** © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

**Keywords:** agriculture; drought; climate adaptation; climate warming; Central Europe

## 1. Introduction

A study of rainfall variability and trends is essential for understanding regional climate tendencies. Both average rainfall and rainfall extremes play a significant role. Precipitation totals and their variability throughout the intra-annual cycle determine the country's water balance and the water resources available to crops during the growing season. Extreme rainfall can lead to soil erosion, flooding, damage to infrastructure, and adverse effects on human health and well-being. On the other hand, a shortage of precipitation can initiate drought development from meteorological, through soil, to hydrological drought. Droughts threaten water availability, lower agricultural productivity, increase the risk of wildfires, and adversely affect the natural environment and various economic sectors, including the energy sector.

Since 1950, annual precipitation totals have increased in Northern Europe and decreased in parts of Southern Europe [1]. Precipitation conditions in Central Europe are

much more complex. Poland, situated between 49°00' N and 54°50' N, similarly to other regions of Central Europe, experiences significant annual rainfall variability, making long-term trends usually statistically insignificant. The initial research on precipitation across Poland was focused on its intra-annual course [2], albeit within different historical borders. Precipitation trends in Poland have long been the subject of study. Furthermore, trends in precipitation strongly depend on the considered period. The increasing trend from 1931 to 1980 was noted by Kożuchowski [3]. Pińskwar et al. [4] have shown regionally consistent, although mostly insignificant, increasing trends in winter and spring precipitation from 1961 to 2017. Studies by Łupikasza and Małarzewski [5] highlighted rising trends in annual totals in the northern half and the eastern part of the country, as well as decreasing trends in the southwestern area; however, these changes did not exceed 3%. The most substantial changes (up to 5%) occurred in autumn across the largest part of the country. In winter, increases of up to 5% were observed in the northern half of the country, while similar decreases were observed in the southern half. During spring and summer, the spatial distribution of positive and negative changes resembled the annual trend, with a maximum of 5% in spring and 3% in summer.

Simple daily intensity index (SDII), defined as precipitation total divided by number of days with precipitation  $\geq 0.1$  mm, was estimated at 3.56 mm in lowland Poland in 1958–2008 [6]. In the annual course, the highest values were recorded in summer (even above 5 mm), and the lowest in winter (2–3 mm). A comparison of the frequency of daily rainfall totals between two periods, 1991–2017 and 1961–1990, reveals an increase in the frequency of days with precipitation above 5.5 mm and a decrease in the number of days with precipitation in the range of 4.0–5.0 mm [4].

Numerous studies have investigated precipitation extremes in Poland [7–10]. These studies indicate that trends are varied and characterised by low statistical significance [7–9]. The low significance is attributed to shifts in precipitation trend direction over time, coupled with significant interannual variability relative to the averages. It has been established that with rising temperatures, the occurrence of days with precipitation exceeding the 95th and 99th percentiles is increasing [10]. An increase in precipitation extremes was also observed in other parts of Central Europe [11], and these trends often coincide with more frequent dry periods [12].

With warming, the dates of thermal seasons in Poland are shifting [13]. Winter, defined as the period with temperatures below 0 °C, is becoming shorter, starting slightly later and ending significantly earlier. Meanwhile, summer, defined as the period with temperatures above 15 °C, is lengthening, starting earlier, and ending later. The durations of the other seasons do not change much, but their timing shifts. This situation contributes to changes in the precipitation regime.

Since most studies focus on long-term precipitation trends on the annual or at least seasonal scales, which are difficult to detect in Central Europe due to high precipitation variability, this study is the first that aims to investigate changes in the precipitation regime on a monthly scale throughout the year. This provides the opportunity to detect changes in access to water that are crucial for humans, agriculture, industry, or energy sectors, which might be blurred in the more extended time-scale studies. We examined changes in selected precipitation characteristics on a monthly scale to estimate the extent to which changes in the precipitation regime follow changes in the thermal seasons. Among the analysed elements, we focused mainly on the variability of monthly precipitation totals, the monthly frequency of days without precipitation, days with precipitation  $\geq 1$  mm, the simple daily intensity index, and days with high precipitation exceeding the 95th percentile of daily precipitation totals on days with precipitation.

## 2. Data and Methods

### 2.1. Data

This study used daily precipitation totals from 48 stations in Poland acquired for 1966–2024 from the Institute of Meteorology and Water Management—National Research Institute (IMWM-NRI) ([https://danepubliczne.imgw.pl/data/dane\\_pomiarowo\\_obserwacyjne](https://danepubliczne.imgw.pl/data/dane_pomiarowo_obserwacyjne), accessed on 15 March 2025). The locations of the stations are given in Figure 1. Synoptic stations without missing data were selected. Data are complete and homogeneous. In the case of snowfall, the precipitation value is given after the snow has melted.

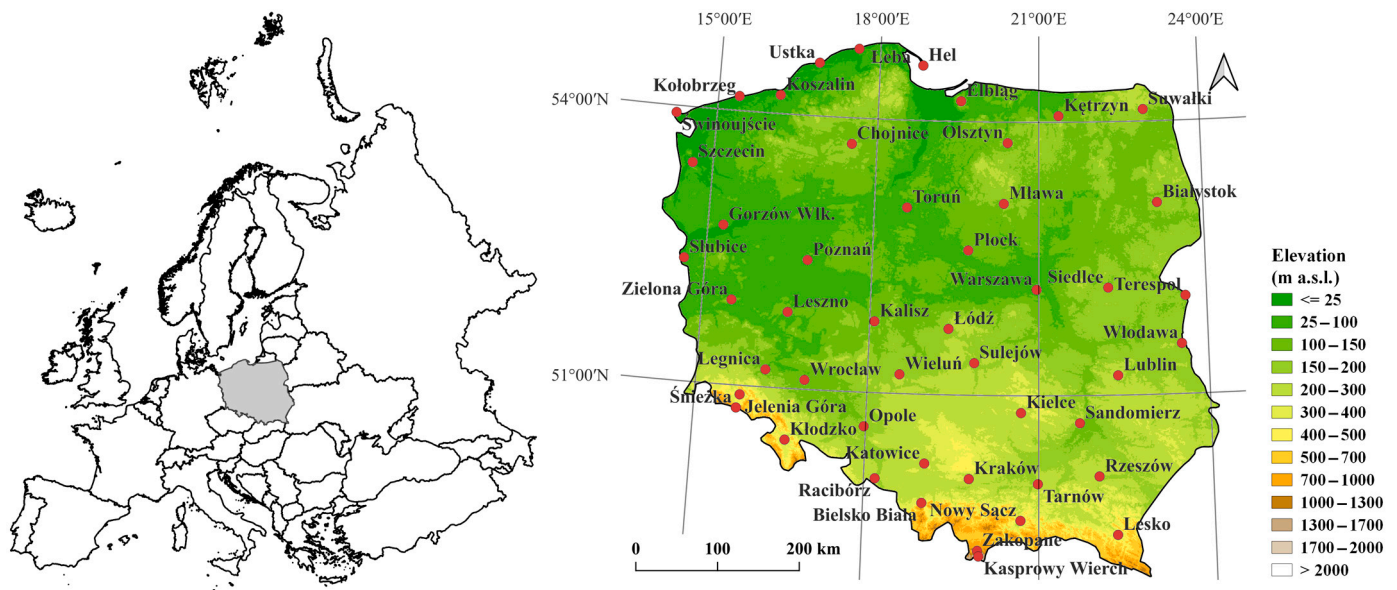


**Figure 1.** The location of the meteorological stations.

### 2.2. Methods

To investigate how the precipitation regime changed throughout the intra-annual cycle, the course of monthly values for precipitation totals, frequency of dry days, frequency of days with precipitation of at least 1 mm, average monthly precipitation abundance, and frequency of days with extreme precipitation were analysed. The standard division of the year into seasons was used. Spring includes March, April, and May; summer is June, July, and August; autumn is September, October, and November; and winter is the period from early December to late February of the following year.

The statistical distributions of average monthly precipitation totals at 48 stations in Poland are illustrated using box and whisker plots created with Grapher 17 software. The boxes span from the 1st to the 3rd quartile, with a bar indicating the median. Whiskers extend from the ends of the box to 1.5 times the interquartile range. Outliers are marked as dots. Additionally, trend coefficients calculated by the Sen–Theil method [14,15] are presented, which estimate a slope as the median of the slopes of all lines connecting each pair of sample points. The Sen–Theil method is resistant to outliers and is more robust to skewed data than simple linear regression. The statistical significance of the trends was assessed at the 0.05% level using the Mann–Kendall test with ties [16,17]. At the same time, the spatial distribution of the monthly totals and trend coefficients for selected months were presented on maps.

Similarly, the monthly frequencies of the number of days without precipitation and with precipitation of at least 1 mm were analysed. Although closely related, they are not complementary to the number of days in a month, because in Poland, a dry day is

considered as a day without precipitation or with precipitation  $< 0.1$  mm. In most European countries, a day with precipitation (hereinafter referred to as a wet day) is defined as a day with precipitation  $\geq 1$  mm, and this criterion was also applied in this work. However, there are still days with precipitation  $\geq 0.1$  mm but  $< 1$  mm, and these were not analysed. The next step was to examine the average monthly precipitation abundance, i.e., the average sum of precipitation on days with at least 0.1 mm of precipitation. This characteristic is known as the simple daily intensity index (hereinafter SDII) [4].

Extreme precipitation was defined as daily precipitation exceeding the 95th percentile of daily precipitation totals on days with precipitation  $\geq 0.1$  mm in the reference period 1971–2000. This value was determined separately for each station. Since the number of days exceeding this value at each station in each month is small, in many cases equal to zero, the sum of the exceedances at all stations in Poland was calculated for each month. Based on this, the trends of extreme precipitation in individual months were calculated. This was the only indicator whose trend was calculated for the entire country of Poland, without considering its spatial distribution.

All maps were prepared in Surfer 20 using the kriging method of interpolation.

### 3. Results

#### 3.1. Monthly and Annual Precipitation Totals

The spatially averaged annual precipitation in Poland from 1966 to 2024 was 661.2 mm. The lowest annual precipitation total was recorded in Central Poland, where it did not exceed 550 mm over an extended area; the minimum of 503.7 mm was recorded in Kalisz. Precipitation increased toward the north, where the highest values exceeded 700 mm along the coast, and also toward the south. The higher precipitation in the north is related to the inflow of more humid air masses from the Baltic Sea, its location on the track of Baltic cyclones and fronts, and the more varied terrain of the lake districts. In contrast, increased precipitation in southern Poland is mainly due to the orographic effect of uplands and mountain ranges. Among the considered stations, the highest annual total of 1765.9 mm was recorded at Kasprowy Wierch (1991 m a.s.l.). Values above 1000 mm were only observed in the mountains (Figure 2). The multi-year changes in annual precipitation across Poland were generally small. The average decrease was almost 2 mm per decade. However, the number of stations showing a decrease in precipitation (28, with two exceeding the statistical significance level) was similar to those showing an increase (20, with nine statistically significant). The largest decreases were observed at the mountain stations of Kasprowy Wierch and Śnieżka (1602 m a.s.l.), both exceeding 36 mm per decade. The most substantial increase in precipitation was recorded in Elbląg with 22 mm per decade. The spatial distribution of these trends is illustrated in Figure 2.

On an annual scale, low precipitation totals were observed from November to April, with the lowest value in February. The highest values occurred from June to August, with a maximum in July (Figure 3). At the same time, precipitation variability was significantly lower in the cold season than in the summer months. All outliers in the upper part of the distribution represent monthly precipitation totals at mountain stations.

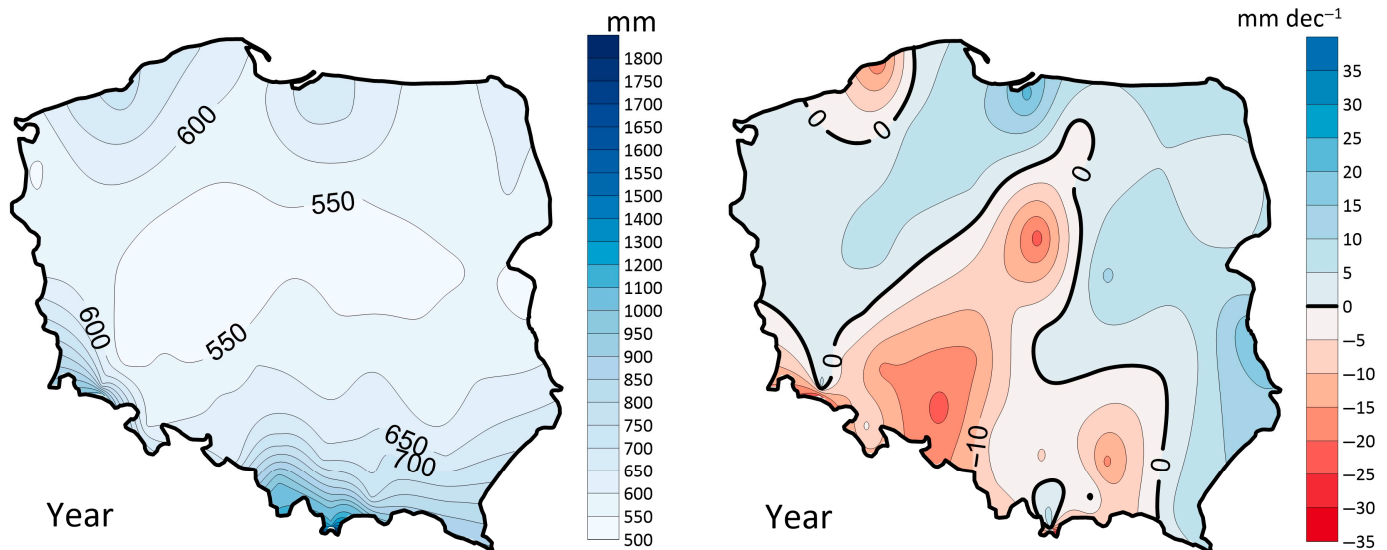


**Figure 2.** Spatial distribution of mean annual precipitation totals in Poland in 1966–2024 (on the left) and trend coefficients (on the right).

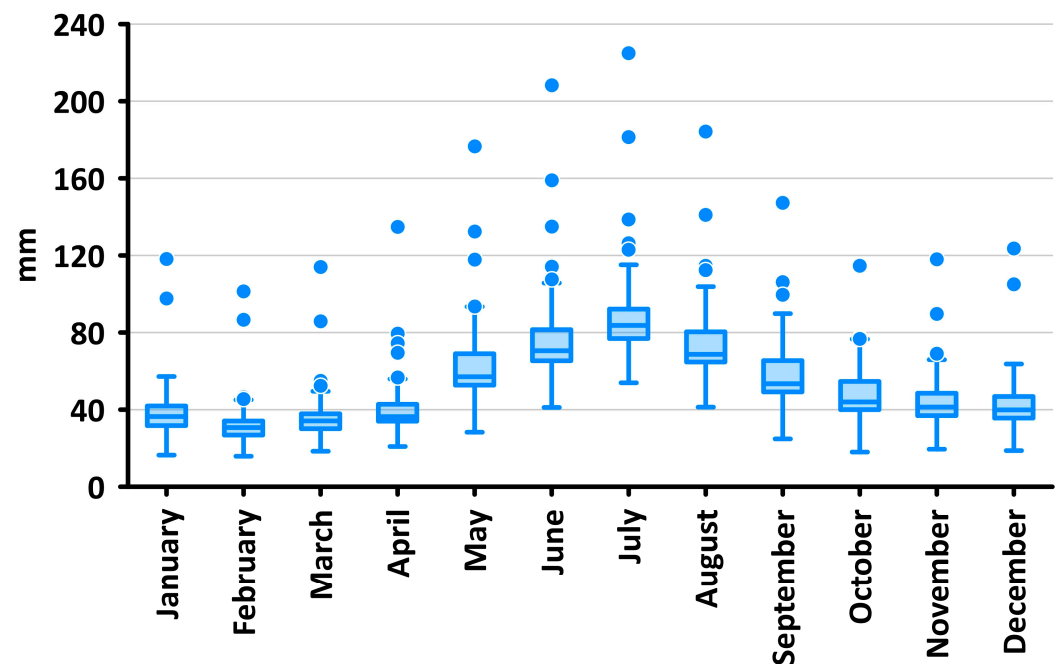


**Figure 3.** Statistical distributions of monthly average precipitation totals at 48 stations in Poland in 1966–2024.

In the spatial distribution of monthly precipitation totals, the lowest values were always found in Central Poland, and the highest in the southern part. Differences mainly occurred in the north and west of the country. In autumn, the distribution closely resembled the annual pattern. During winter months, precipitation increased from Central to Northwestern Poland. In spring, the area of lowest precipitation extended from central Poland to the northern border. The increase typical of other seasons, especially in the Lake District and along the coast, was not visible. This increase occurred in summer but was less pronounced than in autumn and winter (Figure 4).

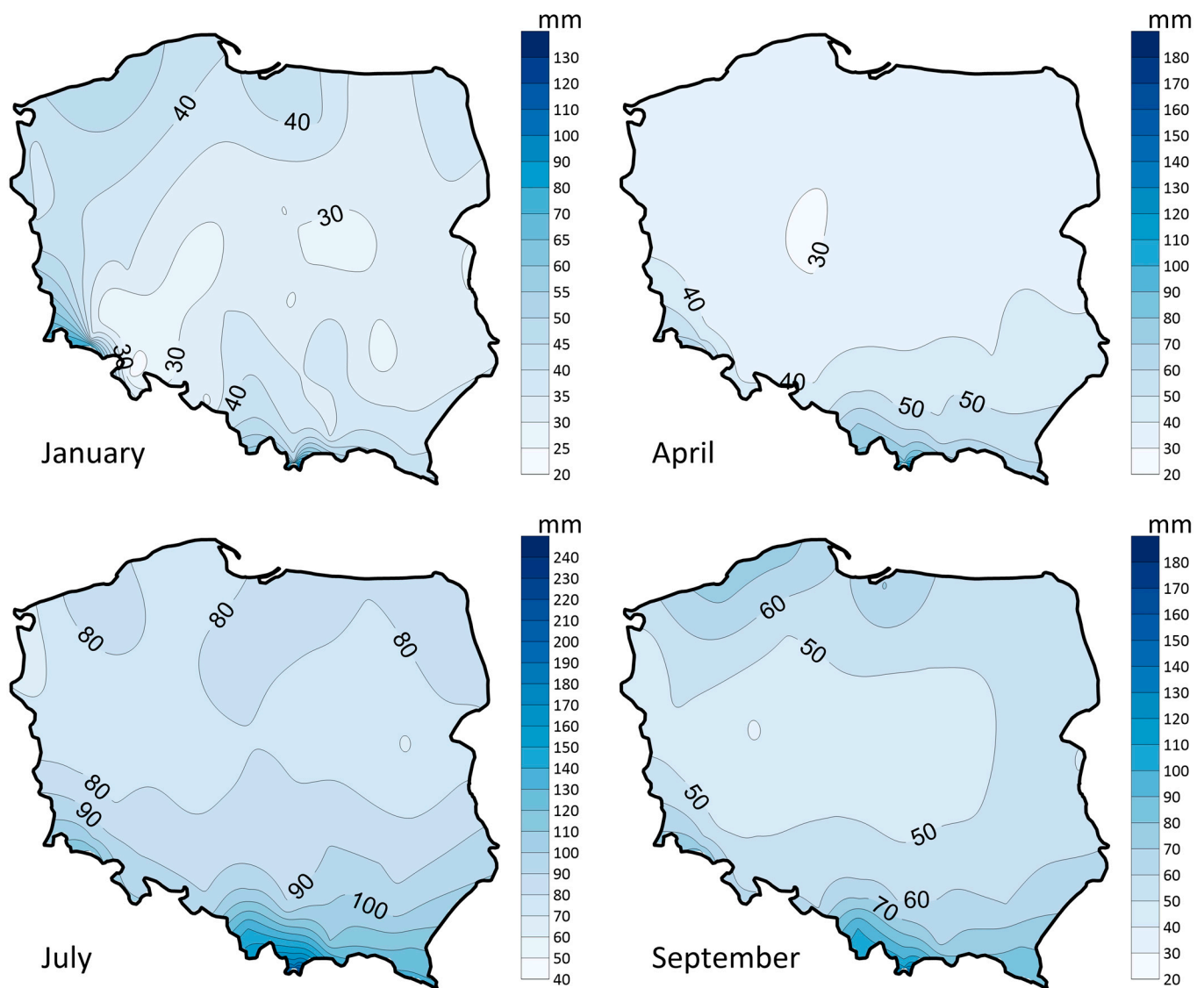


**Figure 4.** Spatial distribution of monthly precipitation sums in Poland in 1966–2024 in selected months.

Precipitation trends showed significant variation across different months (Figure 5). Increases in precipitation were most notable in January and February, observed at 42 stations in January (16 of which showed statistically significant increases) and 43 in February (significant at 22 stations). In contrast, decreases in precipitation totals prevailed in April (at 42 stations, statistically significant at 11), June (at 43 stations, with 14 significant), and November (at 45 stations, with 12 significant). In the remaining months, the number of stations where increases were observed was similar to the number of stations where decreases were recorded, and their statistical significance was low. Notably, areas of increases and decreases were distinct and regionalised. For instance, in July, August, and December, the north was characterised by an increase while the south experienced a decrease, whereas in September, this pattern was reversed (Figure 6).

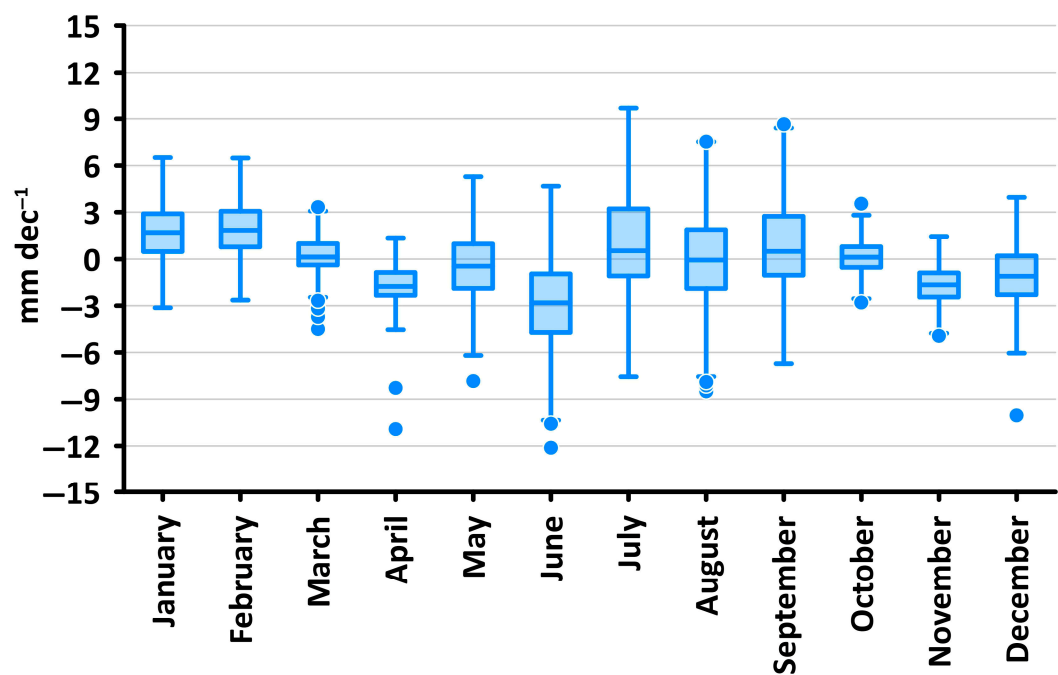


Figure 5. Statistical distributions of monthly precipitation sum trend coefficients at 48 stations in Poland in 1966–2024.

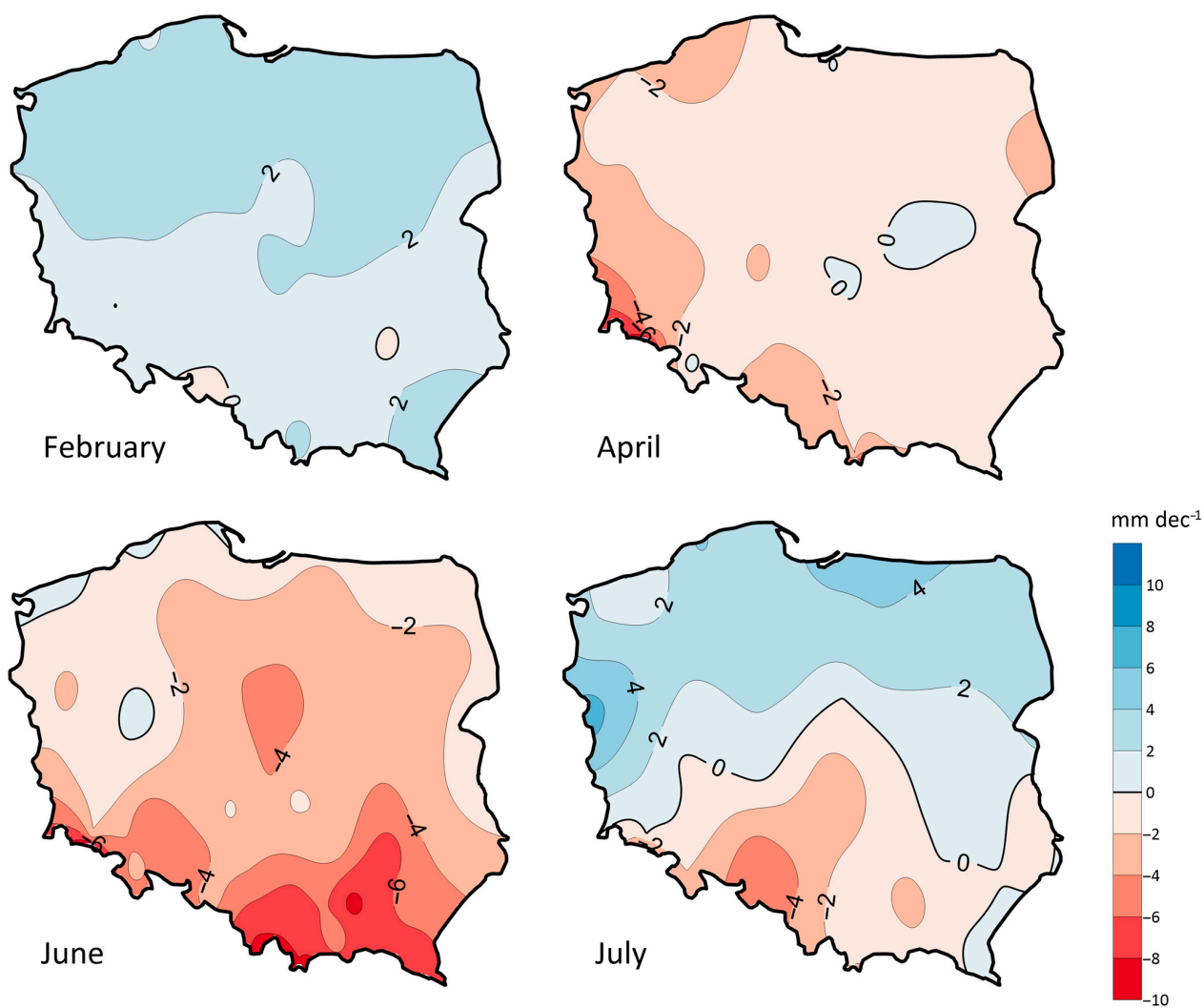


Figure 6. Cont.

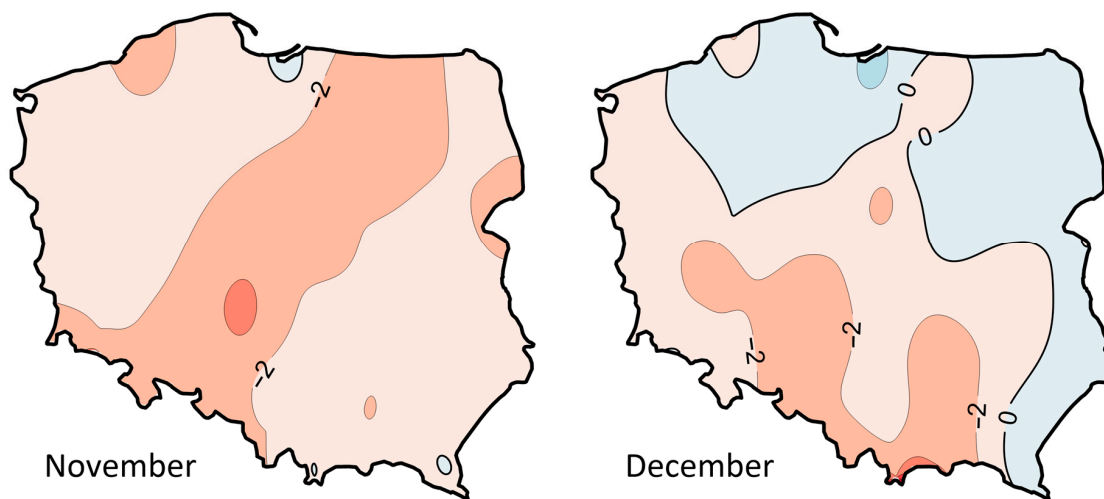


**Figure 6.** Spatial distribution of long-term changes in monthly precipitation totals in Poland in 1966–2024 in selected months.

### 3.2. Dry Days

The frequency of dry days had a clear intra-annual cycle. They were least common during the cold season (from November to February, with a minimum in February) and early summer (June and July). Dry days were primarily observed in spring, late summer, and early autumn (with a maximum in August) (Figure 7). Outliers were only found at the lower ends of the distributions and appeared at mountain stations (with the minimum always at Śnieżka) and in the foothills.

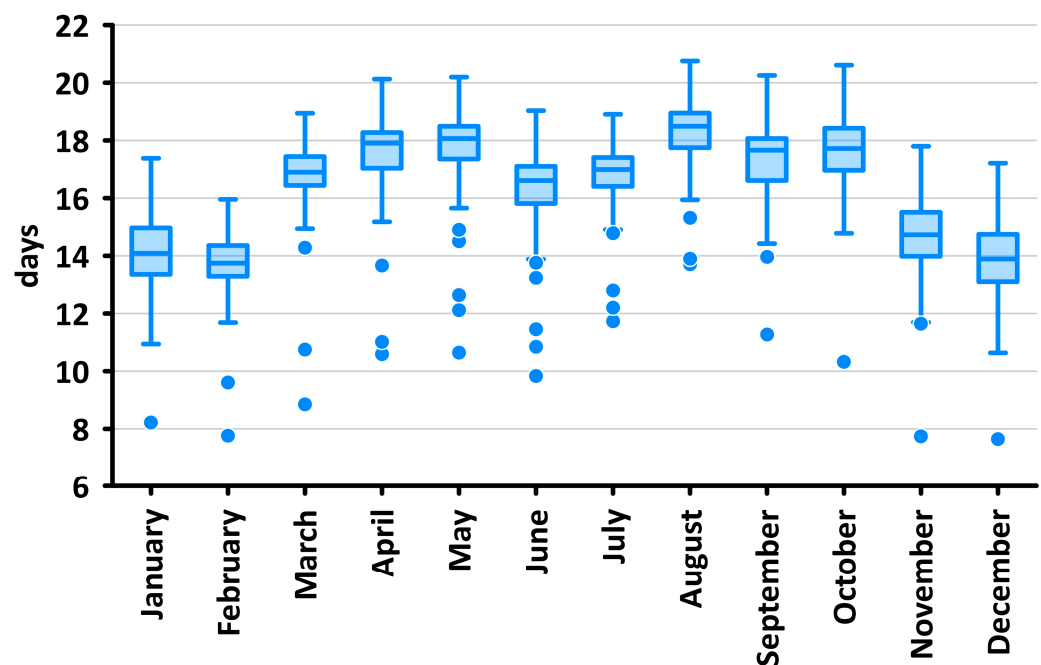


**Figure 7.** Statistical distributions of monthly average dry days frequencies at 48 stations in Poland in 1966–2024.

The intra-annual cycle was also evident in the spatial distribution of dry days in Poland (Figure 8). From November to January, the fewest dry days (<13 days) were observed in the north, especially along the middle coast, while the most frequent dry periods (>15 days) occurred in southwestern Poland, excluding high-mountain stations. In February

and March, the highest number of dry days was observed in central Poland, decreasing in both directions toward the north and south. From April to June, many dry days were recorded on the coast and in central Poland ( $>17$  days), while the fewest occurred in the southern part of the country ( $<15$  days). July, August, and September were characterised by a maximum of dry days in Central Poland ( $>18$  days), and similar to February and March, their frequency diminished toward the north and south. In October, the region with the highest number of dry days shifted southward.

In most regions across the country, long-term trends in dry days were statistically insignificant, mainly due to high year-to-year variability. However, the trends did show a high degree of spatial coherence and are therefore worth mentioning. Figure 9, which illustrates the statistical distribution of trend coefficients, indicates no change in the number of dry days for February, May, and October. The first, second, and third quartiles of the trend coefficients in Poland were nearly zero. In January and July, months that already have a low number of dry days, decreases dominated. In August, the number of decreases and increases was equal; however, their spatial distribution showed an upward trend in the southern part of the country and a downward trend in the northern part (Figure 10). The remaining six months were mostly characterised by an increase in dry days, which was most noticeable in southern Poland in December.

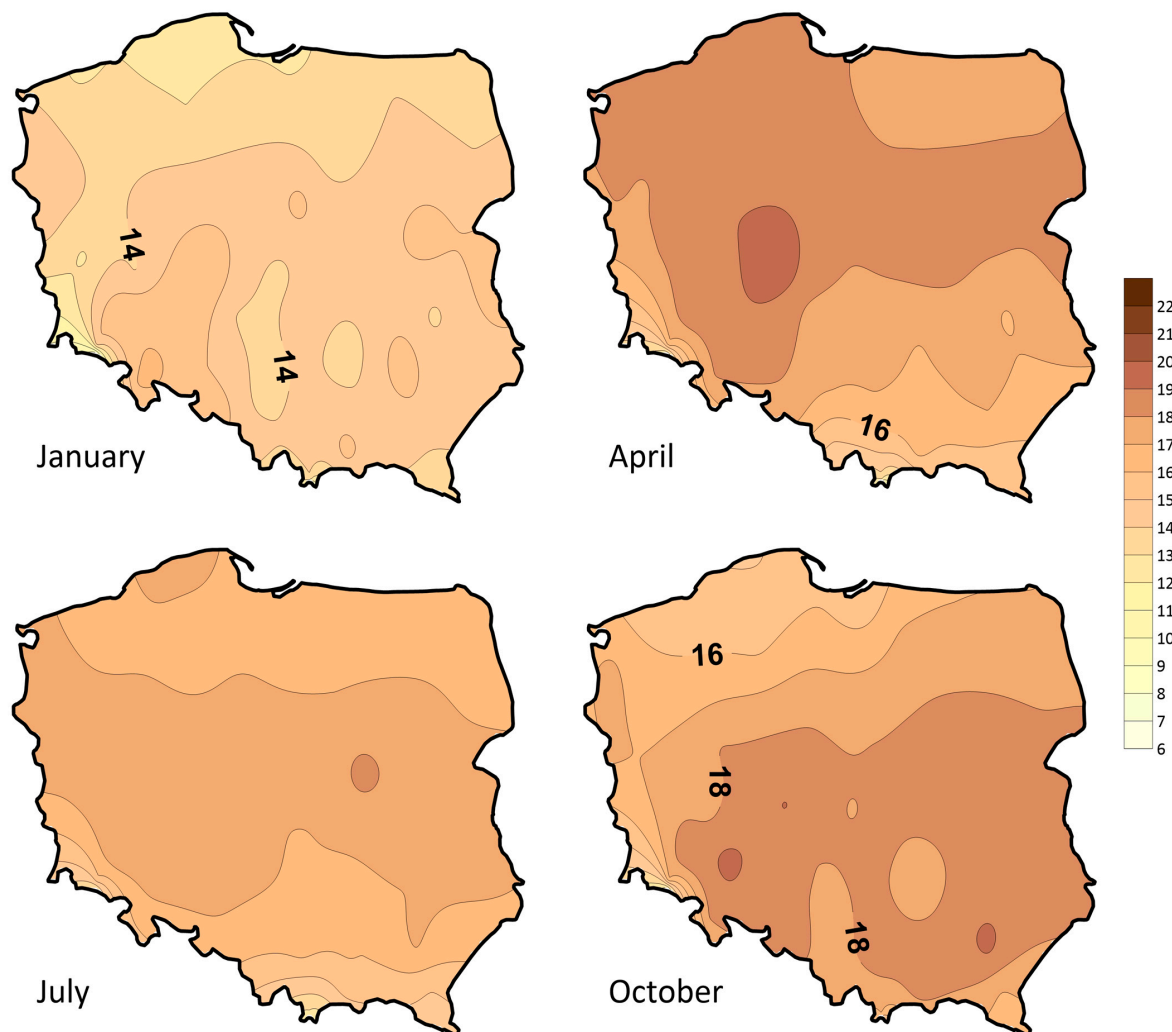


**Figure 8.** Spatial distribution of mean monthly frequency of dry days in Poland in the period 1966–2024 in selected months.

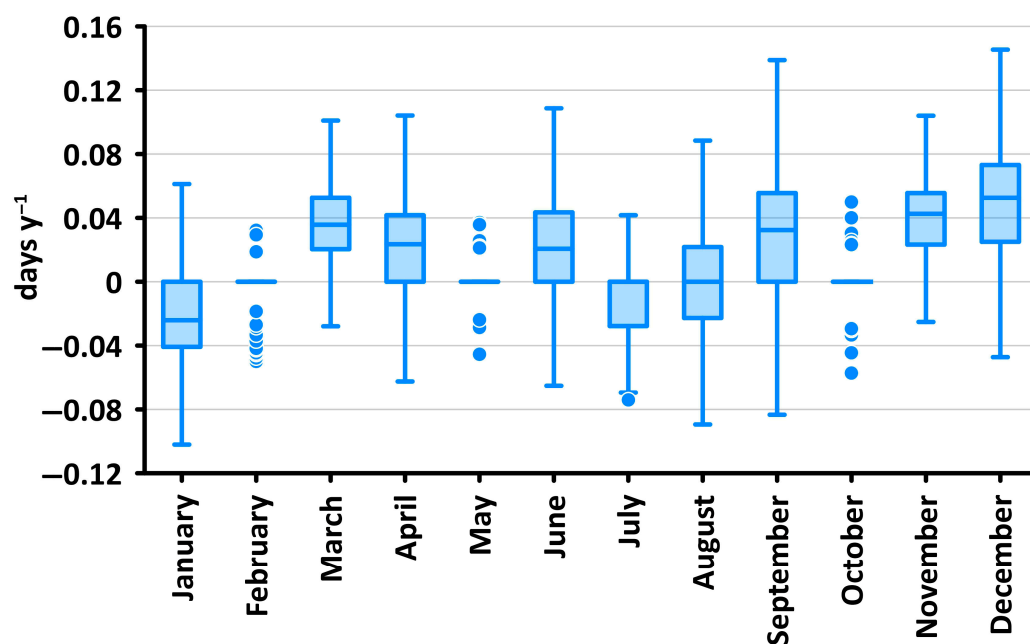


**Figure 9.** Statistical distributions of dry days trend coefficients at 48 stations in Poland in the years 1966–2024.

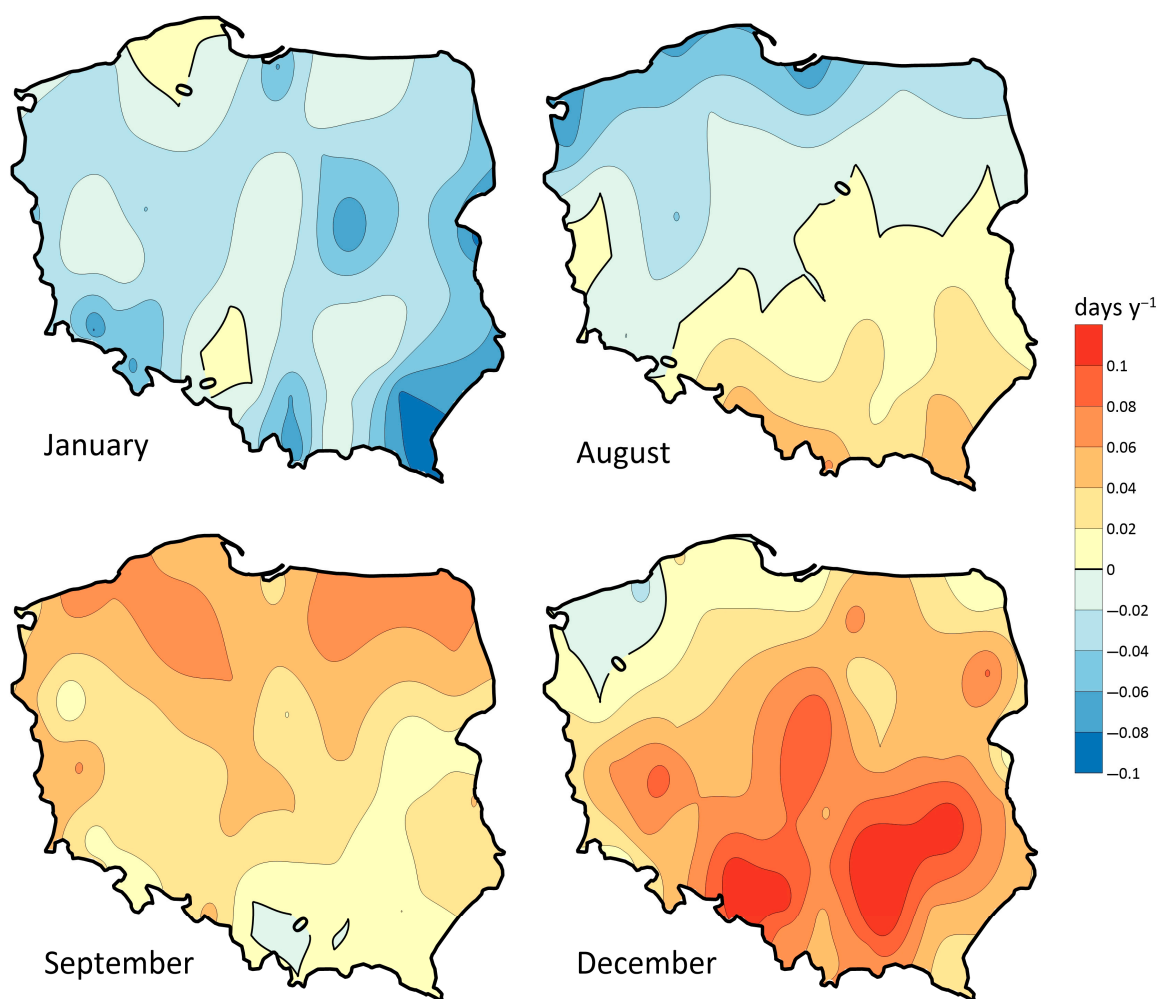


**Figure 10.** Spatial distribution of long-term changes in monthly dry days frequency in Poland in 1966–2024 in selected months.

### 3.3. Wet Days

The frequency of days with precipitation  $\geq 1$  mm (hereinafter referred to as wet days) in the intra-annual cycle had two maxima and two minima. The first and the highest maximum occurred in December and January, with a median of almost 17 wet days in Poland. A significantly lower frequency of wet days was observed in February and March, with a median of around 14. In the following months, a further decrease was observed. In April, the frequency of wet days reached a minimum with a median of about 12. Over the next three months, the number of wet days increased, reaching a secondary maximum in July with a median of about 14. In August and September, there was a second minimum, slightly higher than in April. Afterward, the number of wet days increased gradually until December (Figure 11). The spatial variation in wet day frequency was lowest in February, March, and July, and highest in September. Outliers appeared only in the upper part of the distribution. In mountain and foothill areas, the frequency of wet days considerably exceeded the country's average. Outside these regions, the greatest number of wet days in autumn and winter occurred along the Baltic Sea coast in Northwestern Poland and in the Lake District. In spring, the fewest wet days were recorded in Central and Northwestern Poland (along the Baltic Sea coast). In spring, the fewest wet days occur in Central and Northwestern Poland (along the Baltic coast), and in summer only in Central Poland, while the number of wet days increased again on the coast (Figure 12).

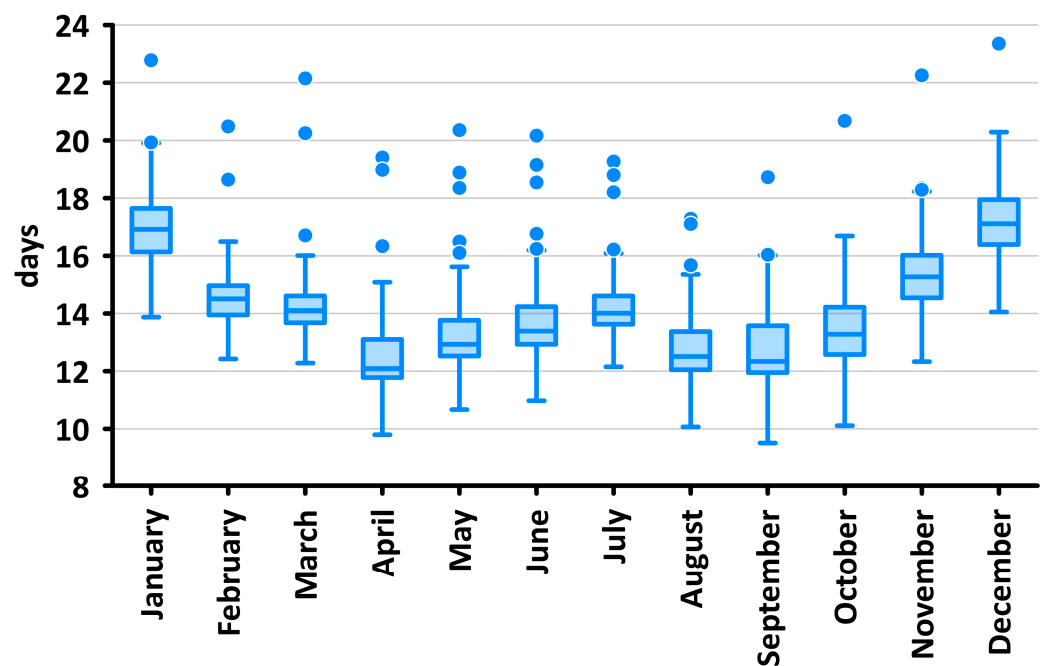


**Figure 11.** Statistical distributions of monthly mean frequency of wet days at 48 stations in Poland in 1966–2024.

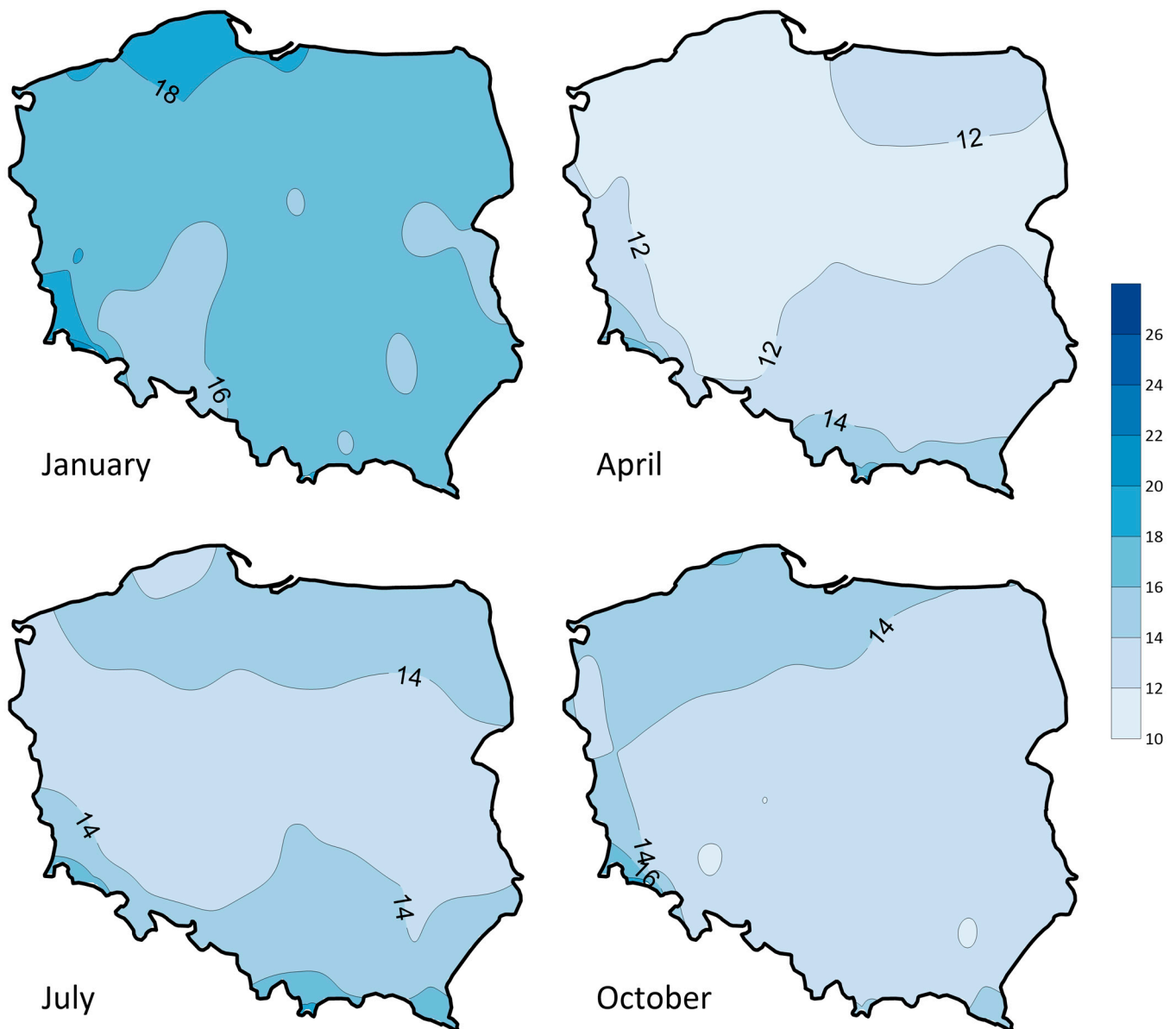


**Figure 12.** Spatial distribution of mean monthly frequency of wet days in Poland in 1966–2024 in selected months.

Throughout the year, the frequency of wet days decreased. However, during certain months, we observed a distinct differentiation in trends. January was the only month where the median of trend coefficients was clearly positive (Figures 13 and 14). In February and July, both the first and second quantiles were equal to zero, indicating that at least 25% of the trend coefficients were 0. In May and October, at least 50% of the trend coefficients were equal to zero. The decrease in the number of wet days was apparent in six months: March, April, June, September, November, and December. The most substantial decline was observed in December and November.

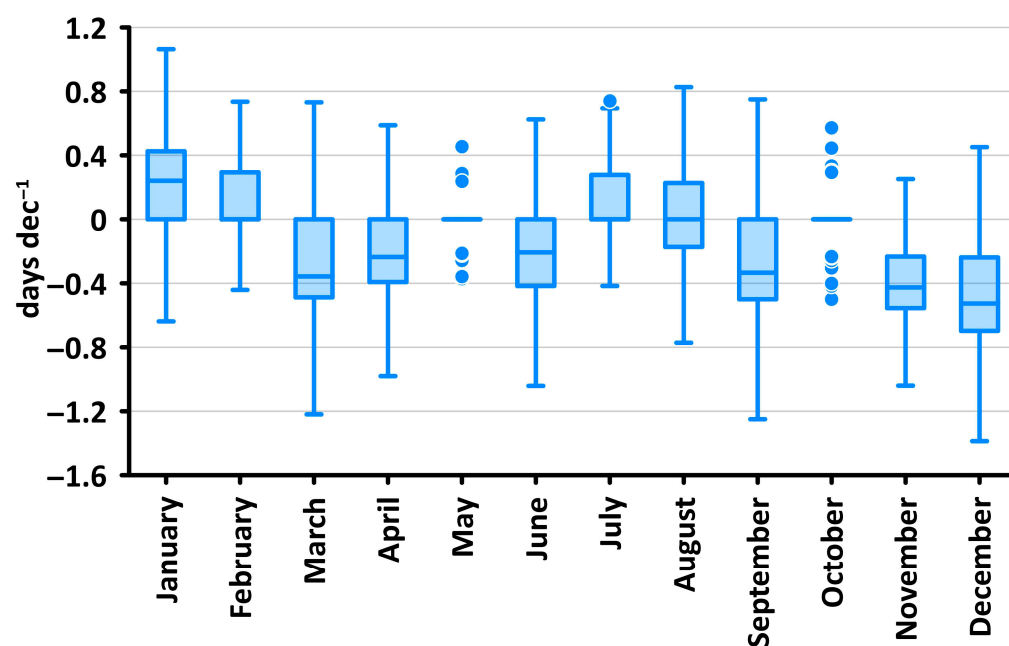


**Figure 13.** Statistical distributions of trend coefficients of monthly mean frequency of wet days at 48 stations in Poland in 1966–2024.

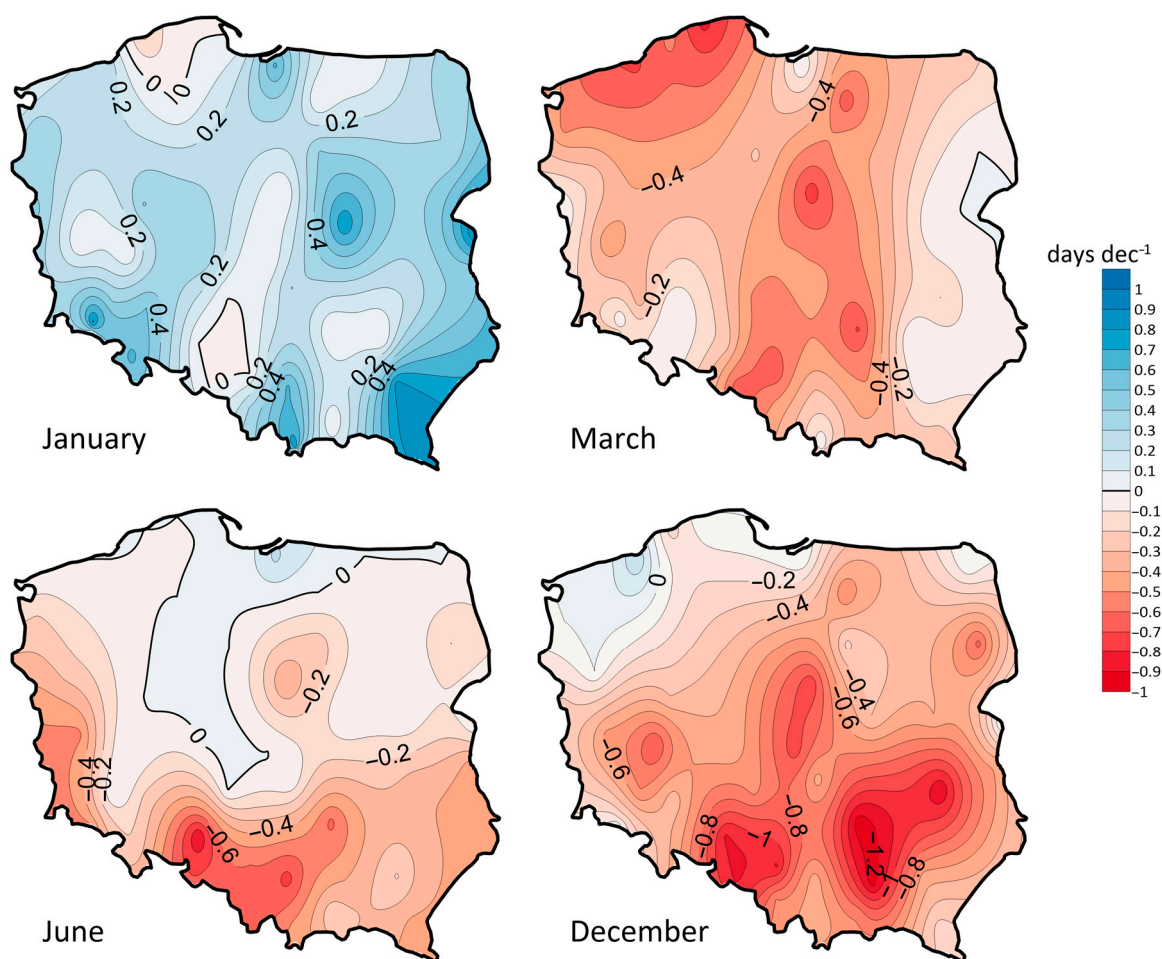


**Figure 14.** Spatial distribution of long-term changes in monthly wet days in Poland in 1966–2024 in selected months.

### 3.4. Simple Daily Intensity Index

In Poland, SDII had a distinct intra-annual cycle, typical of continental climates, with a maximum in summer, specifically in July, and a minimum in winter, particularly in February. During the summer months, the median SDII in Poland exceeded 5 mm, reaching 6.02 mm in July (Figure 15). In winter, the median SDII in Poland only slightly exceeded 2 mm (2.06 in February, 2.12 in January, and 2.27 in December). The lowest average monthly SDII at an individual station was 1.60 mm in January in Kłodzko, while the highest was 11.38 mm in July at Kasprowy Wierch, a mountain station situated at an altitude of 1991 m a.s.l.

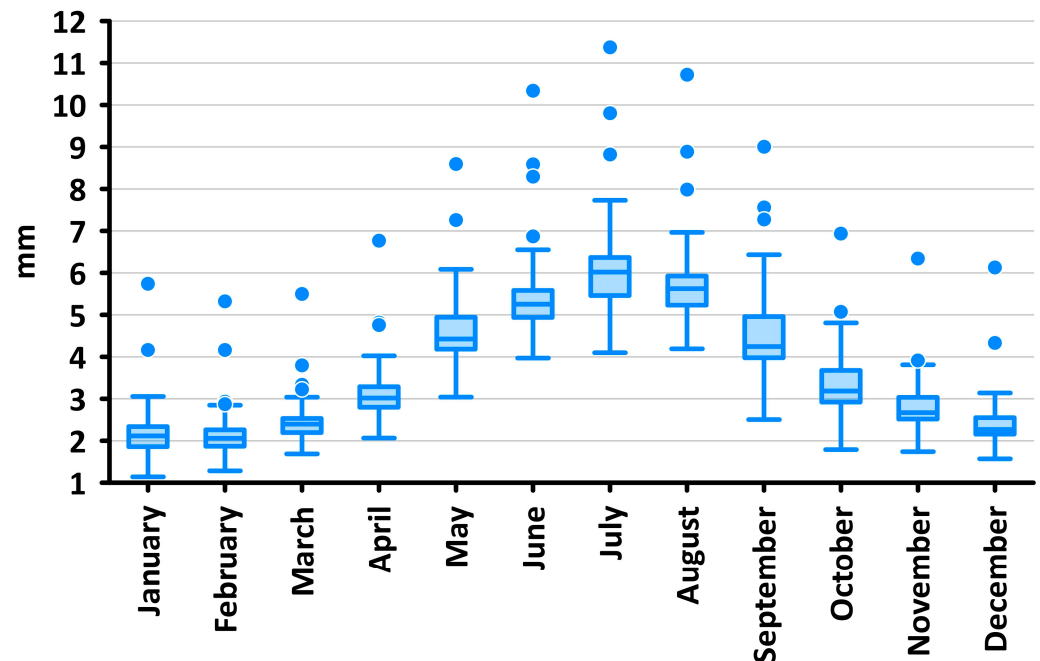


**Figure 15.** Statistical distributions of monthly average SDII values at 48 stations in Poland in 1966–2024.

The spatial distribution of SDII in Poland (Figure 16) indicates that the highest values were recorded in the southern part of the country, especially in the mountain and foothill regions where higher daily totals were due to the orographic effect. At the end of summer (August) and winter (February), the lowest SDII values were observed in the central lowland area. In contrast, the northern regions, particularly near the coast and small hills of the lake districts, tended to have slightly higher SDII values. During spring and the first half of summer, low SDII values covered the coast. This can be attributed to the changing differences in air temperature between the sea and land in the annual cycle.

The long-term trends in monthly SDII values were mostly statistically insignificant, primarily due to the high year-to-year variability. However, several regularities can be observed. SDII increases were observed from January to March and in September, while it decreased in April, June, and November (Figure 17).

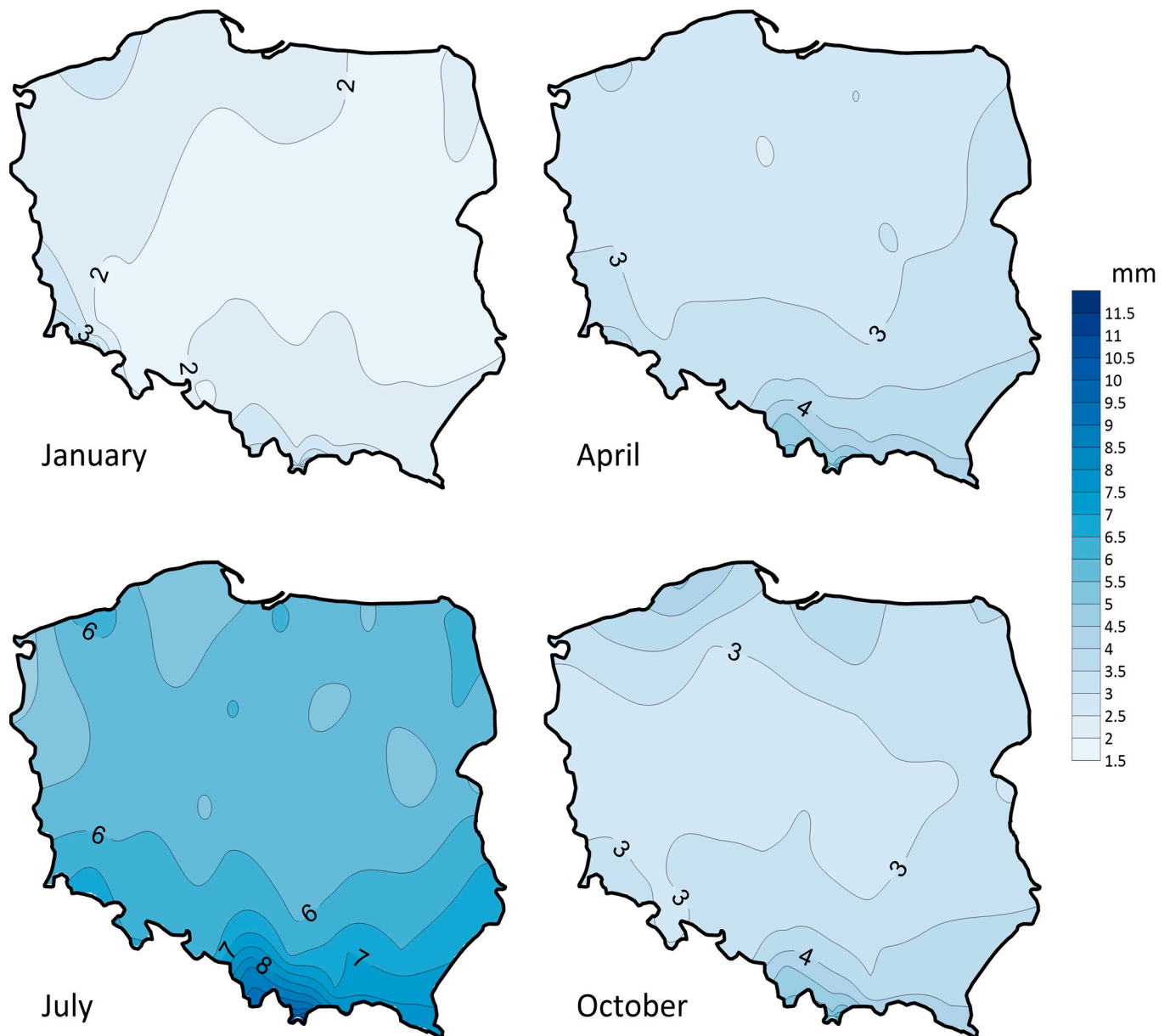


**Figure 16.** Spatial distribution of mean monthly SDII in Poland in 1966–2024 in selected months.

Although the long-term changes were mostly statistically insignificant, they were spatially consistent (Figure 18). After the increase observed from January to March, there was an abrupt shift to a decrease in SDII in April. A decrease in the SDII was also visible in June and November. However, in months when comparable numbers of stations indicated decreases and increases in the SDII, they often appeared in compact regions. For example, in July, SDII increased in the southern part of Poland and decreased in the northern part. Conversely, in December, the SDII increased in the south and west, and decreased in the rest of the country.

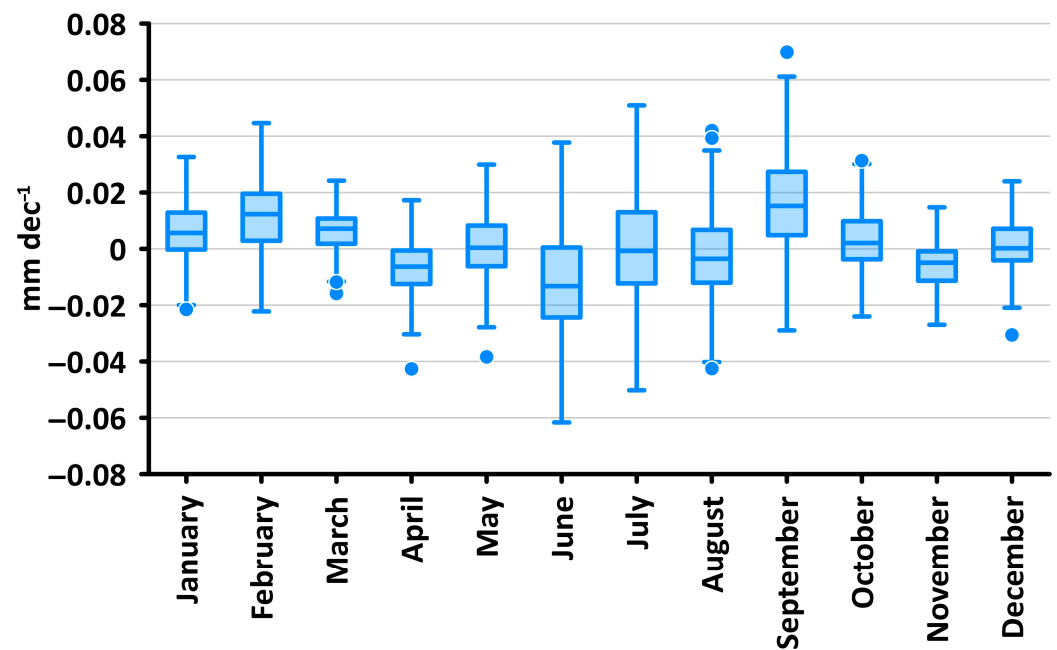


Figure 17. Statistical distributions of SDII trend coefficients at 48 stations in Poland in 1966–2024.

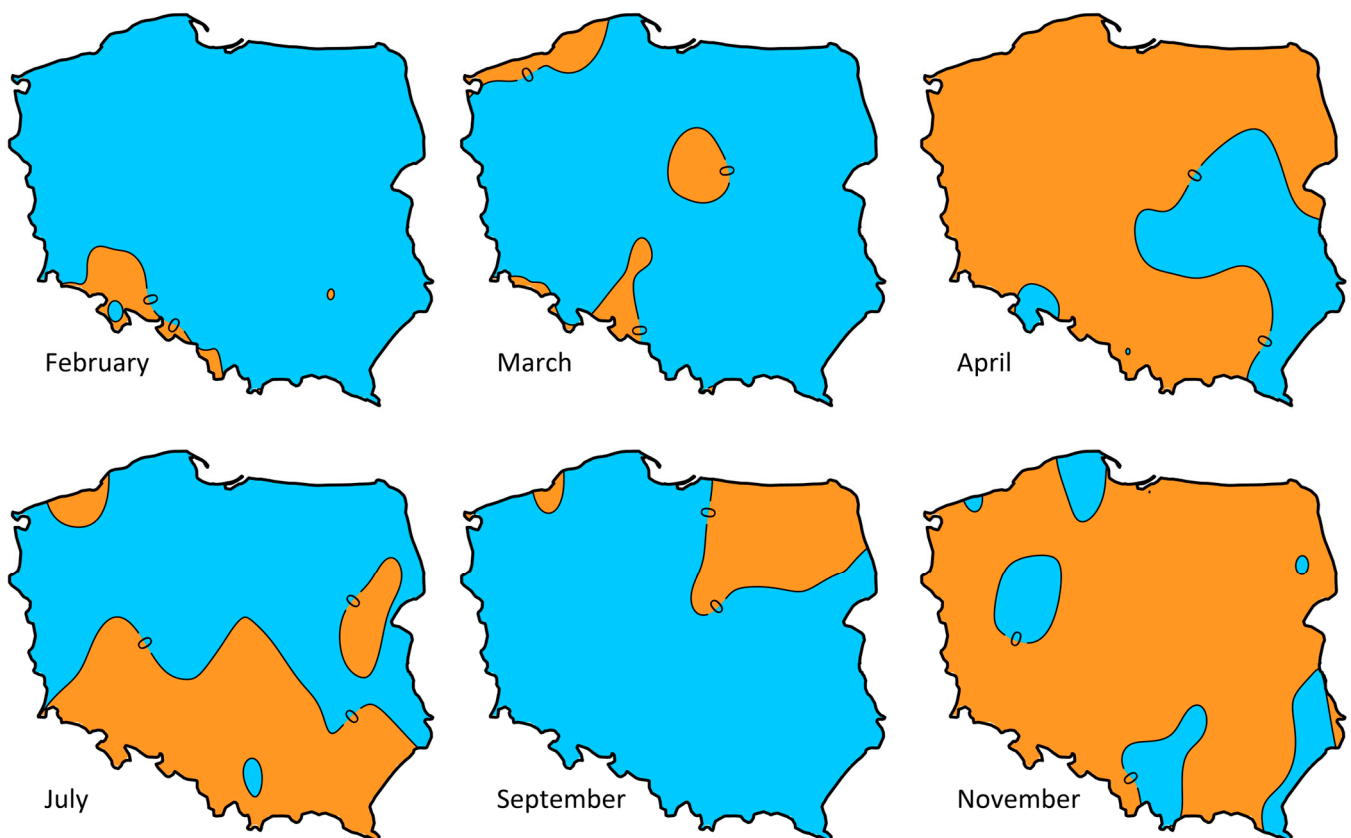


Figure 18. Spatial distribution of long-term changes in monthly SDII in Poland in 1966–2024 in selected months. SDII is increasing/decreasing in blue/orange areas.

### 3.5. Extreme Precipitation

To analyse how the frequency of extreme precipitation varied across different months, the 95th percentile of daily precipitation totals on days with precipitation was calculated for the reference period of 1971–2000 (Figure 19). Subsequently, the frequency with which this percentile was exceeded was counted for each month, along with the

total precipitation observed on those days when it was exceeded. Since, apart from the summer months, exceedances are quite rare, the results were aggregated across all stations. Then, trends in these values and the decadal percentage changes were assessed. The monthly mean values and percentage changes over the 10-year period are presented in Table 1. Significant trends were obtained for four months. In February and September, the frequency of extreme precipitation increased by 9.1% and 6.1% per decade, respectively, while the total amount of extreme precipitation rose by 8.8% and 6.8% per decade, respectively. In April and June, the frequencies of extreme precipitation decreased by 10.5% and 6.8% per decade, respectively, while the totals of extreme precipitation declined by 11.3% and 7.2% per decade, respectively. In the remaining months, changes in both values were statistically insignificant.

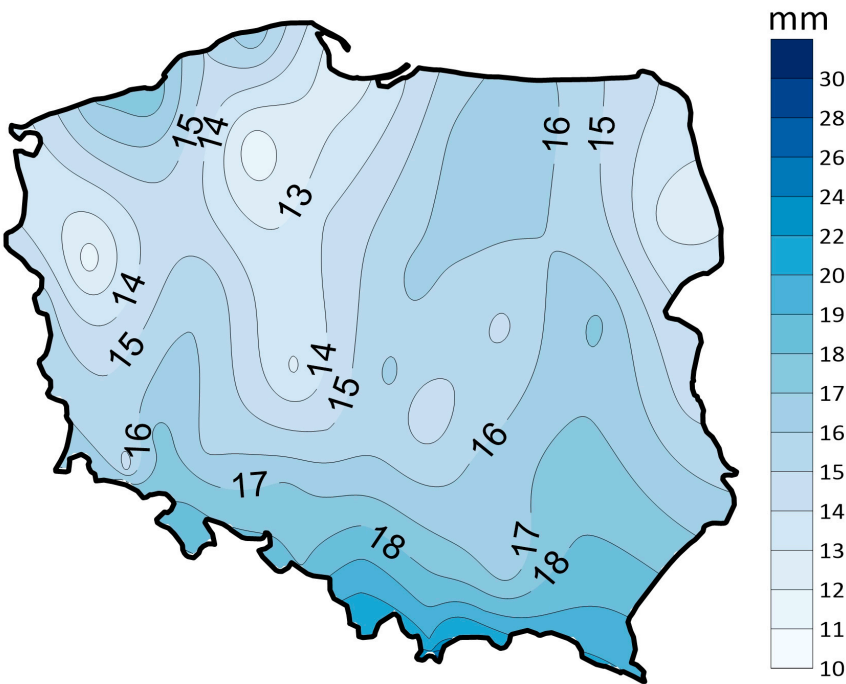


**Figure 19.** The 95th percentile of daily precipitation total in the reference period 1971–2000 in Poland.

**Table 1.** Exceedances of the 95th percentile of precipitation aggregated across all stations: average values for 1966–2024, trend in percentages per decade, average precipitation totals exceeding the 95th percentile of precipitation, and their trend in percentages per decade. Statistically significant values are bolded.

| Month     | Mean Number of Events | Percentage Change of the Number of Events per Decade | Average Precipitation in mm | Percentage Change of Precipitation per Decade |
|-----------|-----------------------|------------------------------------------------------|-----------------------------|-----------------------------------------------|
| January   | 5.4                   | 0.0                                                  | 113                         | 0.0                                           |
| February  | 3.9                   | <b>9.1</b>                                           | 83                          | <b>8.4</b>                                    |
| March     | 5.6                   | 4.9                                                  | 118                         | 5.4                                           |
| April     | 14.1                  | <b>−10.5</b>                                         | 324                         | <b>−11.3</b>                                  |
| May       | 37.5                  | −1.9                                                 | 931                         | −2.7                                          |
| June      | 53.8                  | <b>−6.8</b>                                          | 1434                        | <b>−7.2</b>                                   |
| July      | 68.4                  | 1.5                                                  | 1950                        | 0.8                                           |
| August    | 56.8                  | 1.1                                                  | 1560                        | 0.9                                           |
| September | 35.4                  | <b>6.1</b>                                           | 903                         | <b>6.8</b>                                    |
| October   | 22.3                  | 2.5                                                  | 510                         | 3.0                                           |
| November  | 13.9                  | 0.0                                                  | 290                         | −1.2                                          |
| December  | 6.9                   | 0.0                                                  | 143                         | 0.6                                           |

#### 4. Discussion

The mean annual precipitation recorded across 48 stations in Poland from 1966 to 2024 was 662.2 mm. During this time, no statistically significant changes were observed. Similar results include 605 mm across 12 stations for 1901–1980 [18], 640 mm for 1951–2018 [5], and 678.6 mm for 1991–2020 were obtained in other studies [19]. These differences mainly result from the varying number of stations used in the averaging process, along with substantial interannual variability. Likewise, no notable seasonal trends in precipitation totals were identified for the entire country. However, a shift in the precipitation regime was found on a monthly scale.

We selected three parts of the year that become significantly drier (April, June, and November–December) and two that become wetter (January–February and July).

In January and February, monthly precipitation totals increased due to a decrease in the number of dry days (in January); an increase in the number of wet days (with precipitation  $\geq 1$  mm); and an increase in the SDII, which indicates higher average totals on days with precipitation, also known as precipitation abundance. In February, there was an additional increase in the number of days with precipitation above the 95th percentile, along with higher totals on those days. This probably results from rising temperatures, which often lead to higher maximum precipitation totals [20,21]. Another possible reason is the increased frequency of polar maritime warm air masses, which favour precipitation in Poland [22]. Although precipitation amounts increased, it does not improve the hydrological budget. Problems arise when, in a warmer atmosphere, snowfall is replaced by rainfall, and the water quickly drains away instead of being stored in the snow cover. This conversion has been well-documented for Poland [5,23], as well as in other parts of Central Europe [24].

In the springtime, only April is a month of crucial changes in the precipitation regime. There is a reduction in monthly precipitation totals, the number of wet days, and the Simple Daily Intensity Index (SDII), while precipitation above the 95th percentile remains unchanged. Conversely, the frequency of dry days has increased. Recently, drier conditions in April (characterised by a warmer atmosphere, reduced precipitation, higher evapotranspiration, lower soil moisture, and lower river flow) have been observed not only in Poland but also in Germany and other countries in Central Europe [25]. The significantly drier air in April is attributed to a significant increase in temperature and pressure of water vapor saturating the air in this month [26] and the complete disappearance of snow cover in March in Poland's lowland regions [23]. Furthermore, these changes are also driven by northward shifts in the cyclone track and more common and persistent anticyclonic weather patterns. More frequent blocking observed in Central Europe may be partly attributed to the influence of Arctic Amplification and a lower meridional temperature gradient, which weakens the zonal jet and increases the planetary wave amplitude. In March and May, Poland, like other areas of Central Europe, remains without considerable change in precipitation and circulation. In March, in Poland, the increase in the number of dry days and the decrease in the frequency of wet days were balanced by the increase in SDII. Considerable climate change in spring, with regard to temperature increases (which lead to more intensive evapotranspiration) and a significant decrease in precipitation (in April), disrupts the hydrological cycle. The most pronounced decrease in maximum discharge in Poland from 1951 to 2020 was observed in early spring ( $>80\%$  of the gauge stations), primarily in April (in the eastern and central parts of the country), and also in March (in southern and central Poland) [27]. This poses a great challenge to agriculture and plant growth, as they have limited access to the water supply at such a critical starting point in their development.

In June, the precipitation changes were similar to those in April, increasing the imbalance in the hydrological system. Monthly precipitation decreased, along with an increase in dry days. The frequency of wet days and the SDII also declined. Similar to April, June is a month when the frequency of days with precipitation above the 95th percentile and the total precipitation on such days decreased. In this case, the dry air results from conditions of the previous two months, when April was dry, and precipitation in May remained unchanged, but the rising temperature caused an increase in evaporation. Low soil moisture, higher temperatures, and more frequent blocking exacerbated dry events in Poland. These patterns pose challenges for Polish agriculture, where even a slightly drier-than-usual year results in considerable decreases in yield. Adaptation strategies should include introducing drought-resistant crop varieties that require less water during the growing season, as well as improving irrigation systems. A lower level of groundwater can also harm ecosystems and limit households' access to clean water. Drier conditions create an additional problem for the cooling systems of power plants and other industrial sectors.

In July, humidity conditions improved slightly, with increases in monthly precipitation totals and the number of wet days, while the frequency of dry days decreased. The SDII and the number of days with very high precipitation remained unchanged. More frequent precipitation may result from an increase in the frequency of warm and tropical polar-maritime air masses. In August, the average precipitation in Poland remained unchanged, but contrasting patterns appeared, with a slight increase in the north and a decrease in the south regions.

Major changes were visible in September, which became more of a summery month than an autumnal one. Total precipitation did not change, but its regime did. There were more dry and fewer wet days, while SDII increased. Additionally, the number of days with precipitation above the 95th percentile and the total precipitation on those days increased. These shifts are attributed to rising temperatures and more frequent tropical air advections this month, which bring more moisture, indicating a warmer Mediterranean Sea. In October, no significant changes in the precipitation regime were observed.

Considerable changes in the precipitation regime were detected in November and December. A decrease in monthly precipitation totals was noted in December, resulting from an increase in the frequency of dry days and a decrease in wet days, whereas in November, this was attributed to a decrease in SDII. November and December, which until now have been considered as months of rotten, rainy, and cloudy weather, changed their character, and the rainy weather shifted to January and February, which until recently have been characterised by high-pressure, frosty but sunny and dry weather [28].

Except for the temporary scale, some attention needs to be paid to the regional aspect, especially Central Poland. This region has the lowest annual precipitation in the country due to several factors, including its distance from the sea and low altitude variability. However, at the same time, this area experiences the most pronounced decrease in precipitation and the number of wet days (except in January and February), as well as an increase in the number of dry days. If this situation persists for a longer time, it might have very negative consequences, primarily for agriculture, as it is one of the most essential food production areas in the country, but also for social access to clean water.

## 5. Conclusions

Poland is situated in the transition region between the wetter north and the drier south. This results in high intra-annual variability and mostly insignificant changes in annual precipitation. However, far more important are changes in the precipitation regime throughout the year, which are the primary concern of this study and bring a novel aspect to the climate study of Central Europe. The monthly precipitation characteristics provide

new insights into the hydrological system balance, which has significant implications for ecosystems, agriculture, energy, and industrial sectors, as well as human health and well-being. We found considerable shifts on the monthly scale in precipitation patterns, which is a response to climate change (increasing temperature, decreasing snow cover, and changes in the circulation patterns). Generally, wetter conditions that were previously observed at the end of the year (November–December) shifted to the beginning of the year (January–February). This might positively affect winter water storage and groundwater replenishment in spring, if not for the warmer winters that lead to more rainfall instead of snowfall. The rainwater is quickly discharged through the river network system into catchment areas. Another fundamental change was noted in April and June, when the area became much drier at the critical moment of vegetation growth due to temperature increases, lower soil moisture, and anticyclonic weather conditions. This, combined with a less efficient supply of melting snow, poses a real challenge for agriculture, horticulture, gardening, and the general vegetation development and food supply. More drier days were also observed in September, which, in the warmer conditions with more intensive rainfall, were more reminiscent of summer than autumn. Furthermore, an increasing number of heavy rainfall events in August and September may increase the risk of floods (e.g., a great flood in Central Europe, including Poland, in September 2024). On the contrary, the wetter conditions, except winter, were found in July due to a higher frequency of warm and tropical polar-maritime air masses. In summary, an increase in temperature has a considerable impact on the precipitation regime throughout the year, contributing to drier springs, earlier summers, and later autumns, as well as increased precipitation in winter. These changes have a direct impact on the river outflow, which increases in winter after higher precipitation in January and February and decreases in spring and summer following the dry months of April and June. Nevertheless, it needs to be emphasised that not only the temperature that alters this regime, but also the changes in circulation patterns and advection of air masses, of which July is an example.

**Author Contributions:** Conceptualisation, J.W.; methodology, J.W.; software, J.W.; validation, J.W.; formal analysis, J.W. and J.J.; investigation, J.W. and J.J.; resources, J.W.; data curation, J.W.; writing—original draft preparation, J.W. and J.J.; writing—review and editing, J.W. and J.J.; visualisation, J.W.; supervision, J.W. project administration, J.W. funding acquisition J.W. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the National Science Center (NCN) (grant number 2023/51/B/ST10/01926).

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** The Polish meteorological data were taken from the Institute of Meteorology and Water Management—National Research Institute (IMWM-NRI) ([https://danepubliczne.imgw.pl/data/dane\\_pomiarowo\\_obserwacyjne](https://danepubliczne.imgw.pl/data/dane_pomiarowo_obserwacyjne), accessed on 15 February 2025).

**Acknowledgments:** We would like to thank the Institute of Meteorology and Water Management—National Research Institute for providing the data used in this study, and the anonymous reviewers for their valuable comments.

**Conflicts of Interest:** The authors declare no conflicts of interest.

## References

1. Barros, V.R.; Field, C.B.; Dokken, D.J.; Mastrandrea, M.D.; Mach, K.J.; Bilir, T.E.; Chatterjee, M.; Yuka, K.L.E.; Estrada, O.; Genova, R.C.; et al. Climate Change 2014 Impacts, Adaptation, and Vulnerability Part B: Regional Aspects. In *Working Group II Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK, 2014.

2. Kosińska-Bartnicka, S. Opady w Polsce (Wysokość Częstość i Charakter Klimatyczny) [Precipitation in Poland (Totals, Frequency and Climatological Character)]. *Pr. Meteorol. i Hydrol.* **1927**, *5*, 3–93.
3. Koźuchowski, K. Wiekowe Zmiany Rocznych Sum Opadów w Polsce. *Czas. Geogr.* **1983**, *LIV*, 231–237.
4. Pińskwar, I.; Choryński, A.; Graczyk, D.; Kundzewicz, Z.W. Observed Changes in Extreme Precipitation in Poland: 1991–2015 Versus 1961–1990. *Theor. Appl. Climatol.* **2019**, *135*, 773–787. [[CrossRef](#)]
5. Łupikasza, E.; Małarzewski, Ł. Precipitation Change. In *Climate Change in Poland: Past, Present, Future*; Falarz, M., Ed.; Springer Climate: Cham, Switzerland, 2021; pp. 349–373.
6. Koźuchowski, K. Obfitość Opadów w Polsce w Przebiegu Rocznym. *Przegląd Geofiz.* **2015**, *60*, 27–38.
7. Łupikasza, E. Seasonal Patterns and Consistency of Extreme Precipitation Trends in Europe, December 1950 to February 2008. *Clim. Res.* **2017**, *72*, 217–237. [[CrossRef](#)]
8. Łupikasza, E.B.; Hänsel, S.; Matschullat, J. Regional and Seasonal Variability of Extreme Precipitation Trends in Southern Poland and Central-eastern Germany 1951–2006. *Int. J. Climatol.* **2010**, *31*, 2249–2271. [[CrossRef](#)]
9. Łupikasza, E. Spatial and Temporal Variability of Extreme Precipitation in Poland in the Period 1951–2006. *Int. J. Climatol.* **2009**, *30*, 991–1007. [[CrossRef](#)]
10. Pińskwar, I. Complex Changes of Extreme Precipitation in the Warming Climate of Poland. *Int. J. Climatol.* **2022**, *42*, 817–833. [[CrossRef](#)]
11. Zeder, J.; Fischer, E.M. Observed Extreme Precipitation Trends and Scaling in Central Europe. *Weather. Clim. Extrem.* **2020**, *29*, 100266. [[CrossRef](#)]
12. Hänsel, S.; Hoy, A.; Brendel, C.; Maugeri, M. Record Summers in Europe: Variations in Drought and Heavy Precipitation During 1901–2018. *Int. J. Climatol.* **2022**, *42*, 6235–6257. [[CrossRef](#)]
13. Czernecki, B.; Miętus, M. The Thermal Seasons Variability in Poland, 1951–2010. *Theor. Appl. Climatol.* **2017**, *127*, 481–493. [[CrossRef](#)]
14. Theil, H. A Rank-Invariant Method of Linear and Polynomial Regression Analysis. In *Henri Theil's Contributions to Economics and Econometrics*; Raj, B., Koerts, J., Eds.; Advanced Studies in Theoretical and Applied Econometrics; Springer: Berlin/Heidelberg, Germany, 1992; Volume 23, pp. 345–381.
15. Sen, P.K. Estimates of the Regression Coefficient Based on Kendall's Tau. *J. Am. Stat. Assoc.* **1968**, *63*, 1379–1389. [[CrossRef](#)]
16. Mann, H.B. Mann Nonparametric Test Against Trend. *Econometrica* **1945**, *13*, 245–259. [[CrossRef](#)]
17. Gilbert, R.O. *Statistical Methods for Environmental Pollution Monitoring*; Wiley: New York, NY, USA, 1987.
18. Jokiel, P.; Koźuchowski, K. Zmiany wybranych charakterystyk hydroklimatycznych Polski w bieżącym stuleciu. [Changes in selected hydro-climatic characteristics in Poland]. *Dok. Geogr.* **1989**, *6*, 1–94.
19. Tomczyk, A.; Bednorz, E. *Atlas Klimatu Polski (1991–2020)*; Bogucki Wydawnictwo Naukowe: Poznań, Poland, 2022.
20. Lenderink, G.; van Meijgaard, E. Increase in Hourly Precipitation Extremes Beyond Expectations from Temperature Changes. *Nat. Geosci.* **2008**, *1*, 511–514. [[CrossRef](#)]
21. Wibig, J.; Piotrowski, P. Impact of the Air Temperature and Atmospheric Circulation on Extreme Precipitation in Poland. *Int. J. Climatol.* **2018**, *38*, 4533–4549. [[CrossRef](#)]
22. Bartoszek, K.; Kaszewski, B.M. Changes in the Frequency and Temperature of Air Masses over East-central Europe. *Int. J. Climatol.* **2022**, *42*, 8214–8231. [[CrossRef](#)]
23. Wibig, J.; Jędruszkiewicz, J. Recent Changes in the Snow Cover Characteristics in Poland. *Int. J. Climatol.* **2023**, *43*, 6925–6938. [[CrossRef](#)]
24. Hynčica, M.; Huth, R. Long-term Changes in Precipitation Phase in Europe in Cold Half Year. *Atmos. Res.* **2019**, *227*, 79–88. [[CrossRef](#)]
25. Nagavciuc, V.; Kumar, R.; Rakovec, O. On the Curious Case of the Recent Decade, Mid-spring Precipitation Deficit in Central Europe. *Npj Clim. Atmos. Sci.* **2020**, *3*, 49. [[CrossRef](#)]
26. Krawczyk, E. Long-Term Changes in the Relative Humidity in Poland in 1966–2020. *Int. J. Climatol.* **2025**, *45*, e8706. [[CrossRef](#)]
27. Brzezińska, W.; Wrzeziński, D. Maximum River Runoff in Poland Under Climate Warming Conditions. *Quaest. Geogr.* **2025**, *44*, 85–105. [[CrossRef](#)]
28. Wibig, J. Dry and Wet Spells in Poland in the Period 1966–2023. *Water* **2024**, *16*, 1344. [[CrossRef](#)]

**Disclaimer/Publisher's Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.