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Variability of atmospheric precipitation in Skierniewice in the years 1923–2022

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Highlights

- Authors analysed precipitation magnitude and variability over 100 years.
- No significant decrease in annual precipitation totals was observed.
- High variability in precipitation during individual months was noted.
- A slight, significant increase in precipitation was recorded only in winter months.

Abstract: The amount and distribution of precipitation directly affect crop growth and yield. Deficits in precipitation during key growth periods (spring and summer) can hinder plant development, reduce yields, and, in extreme cases, cause total crop failure. In this study, the magnitude and variability of atmospheric precipitation in Skierniewice over a 100-year period (1923–2022) were analysed. Pearson's correlation coefficient and the Mann–Kendall test were applied to detect trends in precipitation changes in the time series. The distribution of precipitation in individual years was assessed using the precipitation unevenness index. The analysis of annual precipitation totals for Skierniewice over the study period revealed no significant trend. The study demonstrated that the observed high variability in annual precipitation totals was largely due to the considerable variability in precipitation during individual months. Linear regression analysis showed a slight but statistically significant increase in precipitation in January ($r = 0.34$), February ($r = 0.27$), and December ($r = 0.37$). For the other months, the correlation coefficients were not statistically significant, with values either negative or close to zero. The highest average monthly precipitation (for the study period) occurred in July (82.0 mm), while the lowest was recorded in January (24.3 mm). July also saw the highest total monthly rainfall (214.3 mm in 1960). This month was characterised by the greatest precipitation amplitude, reaching 203.5 mm.

Keywords: climate change, maximum precipitation, precipitation distribution, rainfall

INTRODUCTION

Climate and its variability have a significant impact on various aspects of human activity, ranging from economic operations and living conditions to food security (Ray *et al.*, 2015; Holleman *et al.*, 2020). For many years, literature has suggested that human activity is among the key drivers of recent dynamic climate changes, particularly the rise in air temperatures (Herrero *et al.*, 2016; James *et al.*, 2017). An analysis of air temperature trends conducted by Treder *et al.* (2024) also shows an increase in air temperatures in Skierniewice (Central Poland) over the analysed 100-year period (1923–2022). Rising air temperatures lead to increased water requirements for plants (Dai, Zhao and Chen, 2018). This underscores the importance of analysing whether the observed warming trend influences precipitation patterns.

In agriculture, the amount and distribution of precipitation directly affect the growth and yield of crops. Deficits in precipitation during key growth periods, such as spring or summer, can limit plant development, reduce yields, and, in extreme cases, result in total crop losses (Tryngiel-Gać *et al.*, 2013; Dietz, Zörb and Geilfus, 2021). Conversely, excessive precipitation, especially over short periods, can cause flooding, soil erosion, and hinder field operations such as sowing or harvesting (Rao and Li, 2003; Knapik, 2013). Analysing the magnitude and variability of atmospheric precipitation is crucial in climate and hydrological research, particularly in the context of climate change and its impacts on the natural environment and the economy. Precipitation is one of the most critical components of the water balance, determining water availability for various economic sectors, including agriculture, which is particularly sensitive to variability and uneven precipitation distribution (Jiang *et al.*, 2024). According to Karaczun and Kozyra (2020), Poland is already experiencing the negative effects of climate change. These changes exacerbate the problem of precipitation variability, leading to more frequent extreme events such as droughts or heavy rainfall, as noted by many authors (e.g., Kalbarczyk and Kalbarczyk, 2024). Intense rainfall over short periods can result in local flooding and waterlogging, causing damage to crops and agricultural infrastructure. Such events were observed in Poland in 2024, particularly in the southern Oder River basin, with unprecedented precipitation levels not recorded in the previously analysed periods (Suchanek-Gabzdyl, 2024; *PGW Wody Polskie, 2025*). Climate models suggest that extreme precipitation events will become more frequent in a warming climate. Observations in tropical regions (Allan and Soden, 2008) reveal a clear link between extreme rainfall and temperature, with heavy rains intensifying during warm periods and diminishing during cooler ones. The amplification of extreme rainfall observed by these authors exceeds the then contemporary model predictions, suggesting that projections of future changes in extreme rainfall in response to anthropogenic global warming may be underestimated. Climate models predict significant increases in precipitation intensity but decreases in frequency (Trenberth *et al.*, 2003; Dai *et al.*, 2020). Dai and Bloecker (2018) note that regional and local precipitation is far more variable year-to-year than air temperature, making it challenging to forecast future precipitation scenarios. Assessing long-term climate change trends requires extended measurement data series. Only the analysis of multi-year meteorological data enables an understanding of the range of climatic fluctuations and the identification of their direction and rate of change.

The aim of this study was to analyse the magnitude and variability of atmospheric precipitation in Skierniewice over 100 years, from 1923 to 2022. Skierniewice, located in central Poland, is characterised by a temperate transitional climate, making it an intriguing area for studying precipitation variability in the context of long-term climatic trends. The research includes an analysis of historical precipitation data, identification of long-term trends, and an assessment of seasonal and annual variability. The study also takes into account the occurrence of extreme precipitation values, which may indicate an intensification of climatic phenomena in the region. The results of the analysis can provide valuable insights into local climate change and its potential consequences for the region, including agriculture and water management.

MATERIALS AND METHODS

The source material consisted of precipitation measurements from the period 1923–2022, recorded at a meteorological station located at the SGGW Experimental Field and at a station situated in the Pomological Orchard of the National Institute of Horticultural Research (51.96°N, 20.16°E, 125 m a.s.l.). The distance between the stations is approximately 500 m of open space. Data from the first station were available for the period 1923–2014, and from the second station for the period 2015–2022. Weather data for certain months in 1939, 1940, and 1945 were not available due to wartime disruptions (1939: September–December; 1940: January–May; 1945: January–July). The amplitudes between minimum and maximum precipitation values were determined for individual months over the analysed 100-year period.

Pearson's r correlation coefficient and the Mann–Kendall test were used to analyse the detection of trends in precipitation amount changes in time series. The Mann–Kendall test evaluates trends in time-series data by comparing all pairs of observations (Wang *et al.*, 2020).

The test statistic S is calculated using the formula:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}(x_j - x_i) \tag{1a}$$

where: n = number of observations in the dataset, x_i, x_j = observations at times i and j, respectively, $\operatorname{sgn}(x_j - x_i)$ = the sign function, defined as:

$$\operatorname{sgn}(x_j - x_i) = \begin{cases} +1 \text{ if } (x_j - x_i) > 0 \\ 0 \text{ if } (x_j - x_i) = 0 \\ -1 \text{ if } (x_j - x_i) < 0 \end{cases} \tag{1b}$$

After calculating the test statistic S, Kendall's τ coefficient was used to measure the strength of the trend:

$$\tau = \frac{2S}{n(n-1)} \tag{2}$$

Values of τ close to 1 or −1 indicate a strong monotonic relationship, while values close to 0 indicate no trend, with $\tau > 0$ being increasing and $\tau < 0$ – decreasing trend.

The distribution of precipitation in individual years was determined using the precipitation unevenness index (I_{PU}) (Kożuchowski and Wibig, 1988). This index helps to assess how uneven the distribution of precipitation is, which is important for understanding the potential impacts on agriculture, water resources, and climate research.

$$I_{PU} = \frac{\sum_1^{12} \left| P_m - \frac{Pa}{12} \right|}{Pa} 100 \tag{3}$$

where: P_m = total monthly precipitation (mm), P_a = annual precipitation (mm).

The amount of precipitation occurring in the individual seasons was defined based on the criterion: March–May – spring, June–August – summer, September–November – autumn, December–February – winter.

Analyses were performed using Excel 2013 spreadsheet (Microsoft USA) and Statistica 13.1 (Dell USA).

RESULTS AND DISCUSSION

TOTAL ANNUAL PRECIPITATION

A characteristic feature of regions with variable or temperate climates is the significant variation in annual precipitation totals from year to year. An analysis of annual precipitation totals for Skierniewice over the period 1923–2022 did not reveal a significant trend in precipitation amounts (Fig. 1). The linear correlation coefficient between the years of measurement and precipitation totals reached only r = 0.18, with no statistical significance. Similarly, the results of the Mann–Kendall test indicate no statistical significance (p = 0.059) in confirming the slight upward trend in annual precipitation totals (τ = 0.13). Thus, both analyses did not confirm the widely held belief in popular media about a decrease in annual precipitation, e.g. InPost (no date). During the same period, however, a clear increase in average air temperature was recorded (Treder *et al.*, 2024), which has resulted in a decline in the climatic water balance.

Literature data indicate that precipitation in Poland is characterised by very high temporal variability, which results in a climatic risk to plant cultivation (Żarski *et al.*, 2014), although statistically significant changes in seasonal precipitation amounts have not been observed. With increasing greenhouse gas emissions in the twenty-first century, projections indicate a rise in annual precipitation across much of Eurasia, tropical Africa, and extratropical North America. In contrast, decreases are expected in many subtropical regions, including the Mediterranean basin, southwestern North America, southern Africa, large parts of Australia, and sections of South America (Zhao and Dai, 2015; Stringer *et al.*, 2021). As noted by Trenberth (2011), while the overall spatial patterns of precipitation remain relatively stable, the intensity changes – dry regions tend to become drier, particularly in the subtropics, while wet regions become wetter, especially in the mid- and high-latitudes. This "wet-get-wetter, dry-get-drier" trend is expected to persist in the coming decades.

VARIABILITY OF MONTHLY PRECIPITATION

The assessment of trends in precipitation increases or decreases for individual months during the study period was conducted using the Mann–Kendall test and by calculating correlation coefficients between precipitation amounts and the respective years of measurement (Fig. 2). The Mann–Kendall test confirmed a statistically significant but weak upward trend in total monthly precipitation for January, February, March and December. The values of the τ coefficient, which measures the strength of the trend, were the highest in January and December – 0.29 and 0.25, respectively, and the lowest in May at 0.15. For the remaining months, no clear monotonic trend was observed (Tab. 1).

These findings are largely supported by linear regression analysis, which showed a slight but statistically significant (p < 0.05) increase in precipitation in January (r = 0.34), February (r = 0.27), and December (r = 0.37). The linear correlation coefficient between the years of the study and March precipitation totals reached 0.2, but was not statistically significant (p = 0.053). For the other months, the correlation coefficients were also not statistically significant, with values either negative or close to zero. The results thus indicate a significant increase in precipitation

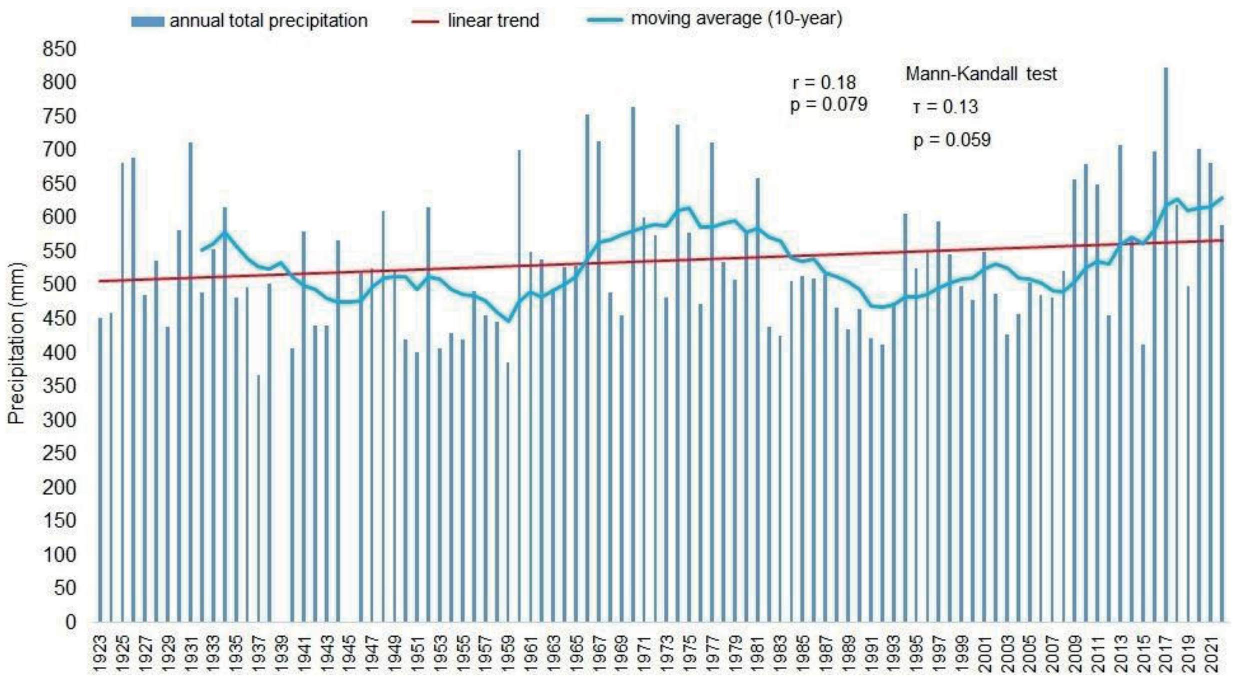

Fig. 1. Total annual precipitation in Skierniewice (1923–2022); r = correlation coefficient, p = significance level, τ = Kendall's coefficient; source: own study

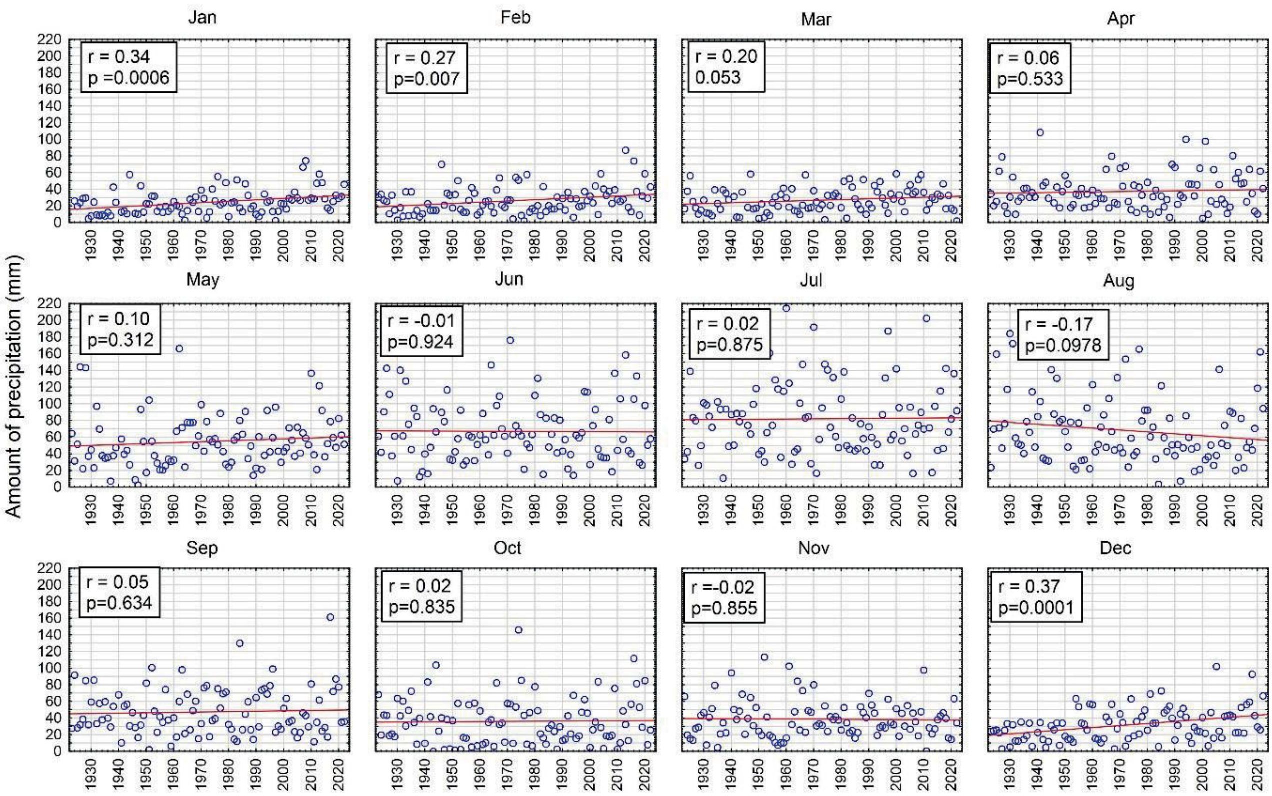

Fig. 2. Monthly precipitation variability in Skierniewice (1923–2022); *r* and *p* as in Fig. 1; source: own study

Table 1. Mann–Kendall test of total monthly precipitation in Skierniewice for the 100-year period

Parameter	Value											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
S	1459	1021	781	272	725	–33	57	–540	49	50	143	1258
Zs	4.34	3.04	2.32	0.81	2.16	–0.10	0.17	–1.61	0.14	0.15	0.42	3.74
Trend	incr.	incr.	incr.	none	incr.	none	none	none	none	none	none	incr.
τ	0.29	0.21	0.16	0.05	0.15	–0.01	0.01	–0.11	0.01	0.01	0.03	0.25
p-value	0.0000	0.0024	0.0202	0.4196	0.0311	1.0759	0.8675	1.8916	0.8863	0.8840	0.6724	0.0002

Explanations: *S* = test statistic, *Zs* = standardised value, incr. = increase, τ = Kendall's coefficient.
Source: own study.

during the winter months, while no such increase, or even a downward trend, is observed in the other months. Similar analyses were taken by other authors. Nidzgorska-Lencewicz, Mąkosza, and Czarnecka (2024), based on monthly precipitation measurements between 1991 and 2020, observed an increase in the share of winter precipitation in the annual total in some areas of the West Pomeranian Voivodship (a province in northwestern Poland). The authors noted that at three synoptic stations (Świnoujście, Koszalin, Szczecin), the mean annual and calendar winter precipitation totals were higher in the period 1991–2020, while the calendar summer totals were lower compared to those recorded during 1951–2010. In the study by Banaszkiewicz, Grabowska and Dymerska (2011), an analysis of precipitation levels in northeastern Poland was conducted based on data from 1951–2000. Significant upward trends were observed in winter, spring and autumn, along with decreasing trends in summer. The decline in summer precipitation totals was also confirmed in the study by Skowera (2014), based on data for the period 1971–2010, as well as in the study by Żmudzka (2009), based on data from 1951–2000.

At the regional scale, for the area under observation (Łódź region), Siedlecki and Pawlak (2004) calculated the average annual precipitation total to be 578 mm. The highest seasonal total occurred in summer (221 mm), while the lowest was recorded in winter (105 mm), during the period 1903–2003. In Łódź, located approximately 50 km from the study area, monthly precipitation variability was analysed based on data from 1904–2006. According to Kaźmierczak (2019), in this region, statistically insignificant declines in annual precipitation were observed, amounting to 0.306 mm per year, with the largest decreases noted in summer.

Trends in atmospheric precipitation totals in the Łódź Voivodship were also analysed by Radziun (2019) for the period 1961–2016. In winter, changes ranged from –0.28 to 0.82 mm per year. Statistically significant winter trends were recorded, among others, in Skierniewice (0.57 mm·year^{-1}). In summer, the author observed the largest negative deviation from the multi-year average in Skierniewice, reaching −73% in 1992.

Selected characteristics of precipitation for individual months are presented in Table 2. The highest average monthly precipitation (for the study period) was recorded in July (82.0 mm), while the lowest was in January (24.3 mm). July also recorded the highest total monthly rainfall (214.3 mm in the year 1960). This month was characterised by the greatest precipitation amplitude, reaching as much as 203.5 mm. The lowest amplitude (56.7 mm) was observed in March.

Very low total precipitation can occur in any month of the year. A complete lack of precipitation was recorded in January 1923 and October 1943. Particularly unfavourable for agriculture is the possibility of very low rainfall during the plant growing season.

The increase in winter precipitation, while summer precipitation remained at a similar level, led to a decrease in the value of the index measuring intra-annual precipitation variability (I_{PU}) – Figure 3. Despite the trend toward a more balanced annual distribution of precipitation, the most uneven distributions during the entire study period were recorded in the years 1984 and 2011, with I_{PU} values of 82.17 and 80.13, respectively, indicating very high annual precipitation unevenness. Generally, an increase in the uniformity of annual precipitation distribution, given the seasonal requirements of crop cultivation, may have unfavourable effects on agriculture.

MAXIMUM DAILY PRECIPITATION

The data analysis did not reveal any upward trend in the intensity of maximum daily precipitation (r = −0.03) – Figure 4. The highest daily precipitation amounts recorded in a single year occurred in 1962 and 1970, with 79.3 mm and 78.7 mm, respectively, while the lowest amounts were recorded in 1983, 1991, and 1993 (<20 mm). Intense rainfall events are generally ineffective for agricultural purposes (Klamkowski, Treder and Tryngiel-Gać, 2014), but they can pose serious threats to the natural environment, technical infrastructure (roads, bridges, railways), and urban and rural settlements.

When examining monthly maximum daily precipitation, a statistically significant increasing trend was observed only for the winter months of February (r = 0.21) and December (r = 0.25) – Figure 5. Numerous studies have analysed the occurrence of extreme precipitation events in different regions of Poland. For instance, the analysing daily precipitation data for the period 1951–2020 of Kalbarczyk and Kalbarczyk (2024) showed a significant increase in extreme daily precipitation events for the whole country in September (for the adopted thresholds of above 30, 50, and 70 mm) and in May (for a threshold of >100 mm). Kaźmierczak and Wdowikowski (2016), based on observations from Legnica covering the years 1961–2010, reported an increasing trend in the height of maximum daily precipitation, despite a decline in both total annual precipitation and the number of precipitation days. The authors continued their research (Wdowikowski, Kaźmierczak and Ledvinka, 2016), assessing maximum daily precipitation totals using several

Table 2. Selected characteristics of monthly precipitation (mm) in Skierniewice (1923–2022)

Characteristic	Value											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean	24.3	26.6	26.9	37.4	54.9	66.9	82.0	68.0	47.5	36.2	38.7	31.8
Min. (year)	0 (1923)	2.2 (1976)	2.2 (2022)	5.1 (2000)	2.6 (1947)	7.8 (1930)	10.8 (1937)	3.5 (1984)	2 (1951)	0 (1943)	0.5 (2011)	3.1 (1968)
Max. (year)	74.5 (2008)	87.1 (2013)	58.9 (2000)	108.5 (1941)	166.1 (1962)	176.1 (1971)	214.3 (1960)	184.1 (1930)	161.4 (217)	146.2 (1974)	113.6 (1952)	102.0 (2005)
Amplitude	74.5	84.9	56.7	103.4	163.5	168.3	203.5	180.6	159.4	146.2	113.1	98.9

Source: own study.

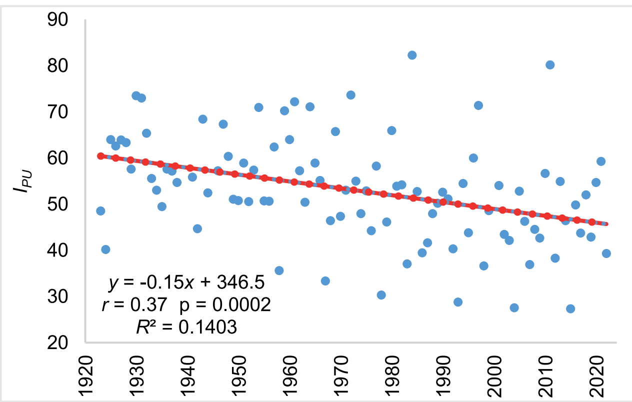

Fig. 3. Annual precipitation unevenness index (I_{PU}) for Skierniewice (1923–2022); R^2 = determination coefficient, r and p as in Fig. 1; source: own study

stations located in the Nysa Łużycka River basin. Increasing trends were found at most of the measurement points.

In the Łódź region, which includes the current study area, precipitation patterns were analysed by Rzepa (2004), who examined the highest daily precipitation totals from 1903 to 2003. The author noted that the highest daily total recorded in Łódź (about 50 km from the study site) occurred in the summer of 1939, reaching 103.5 mm. According to Radziun (2019), who analysed data from 1961 to 2016, the variability of precipitation differed depending on the season. The ranges for spring and autumn were the most similar, while the greatest variability, medians, and maximum daily totals were observed in summer. The lowest values were recorded in winter, indicating a continental precipitation regime, as previously described by Kożuchowski and Wibig (1988).

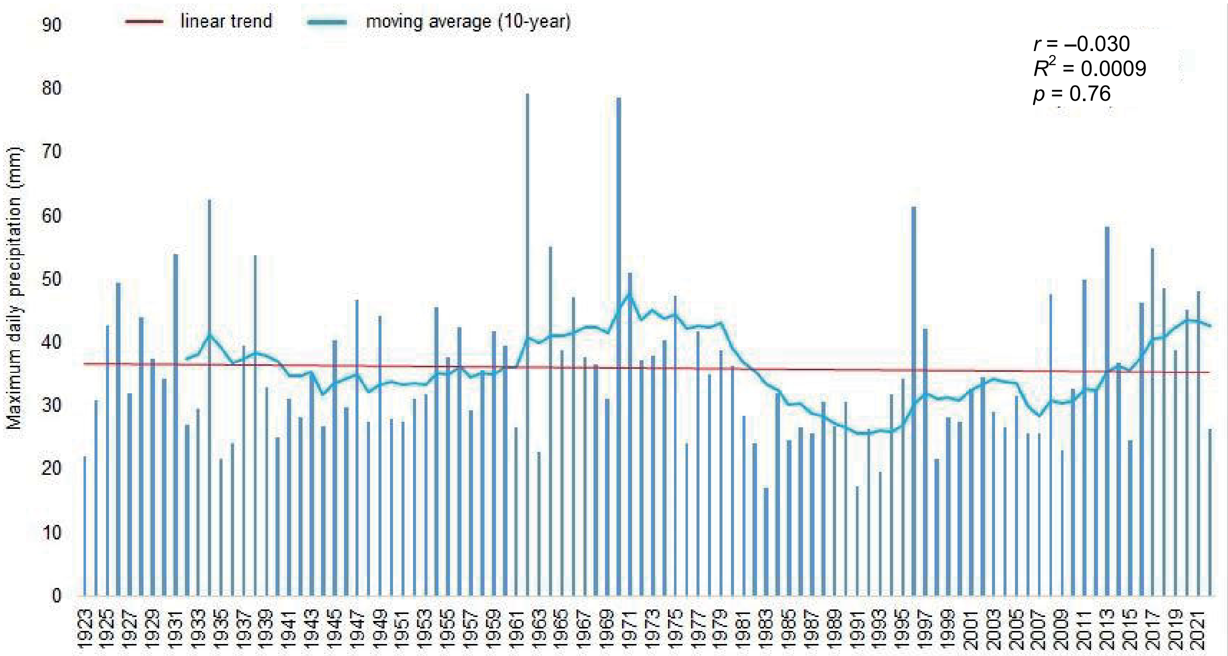

Fig. 4. Maximum daily precipitation in Skierniewice (1923–2022) in the year; R^2 = determination coefficient, *r* and *p* as in Fig. 1; source: own study

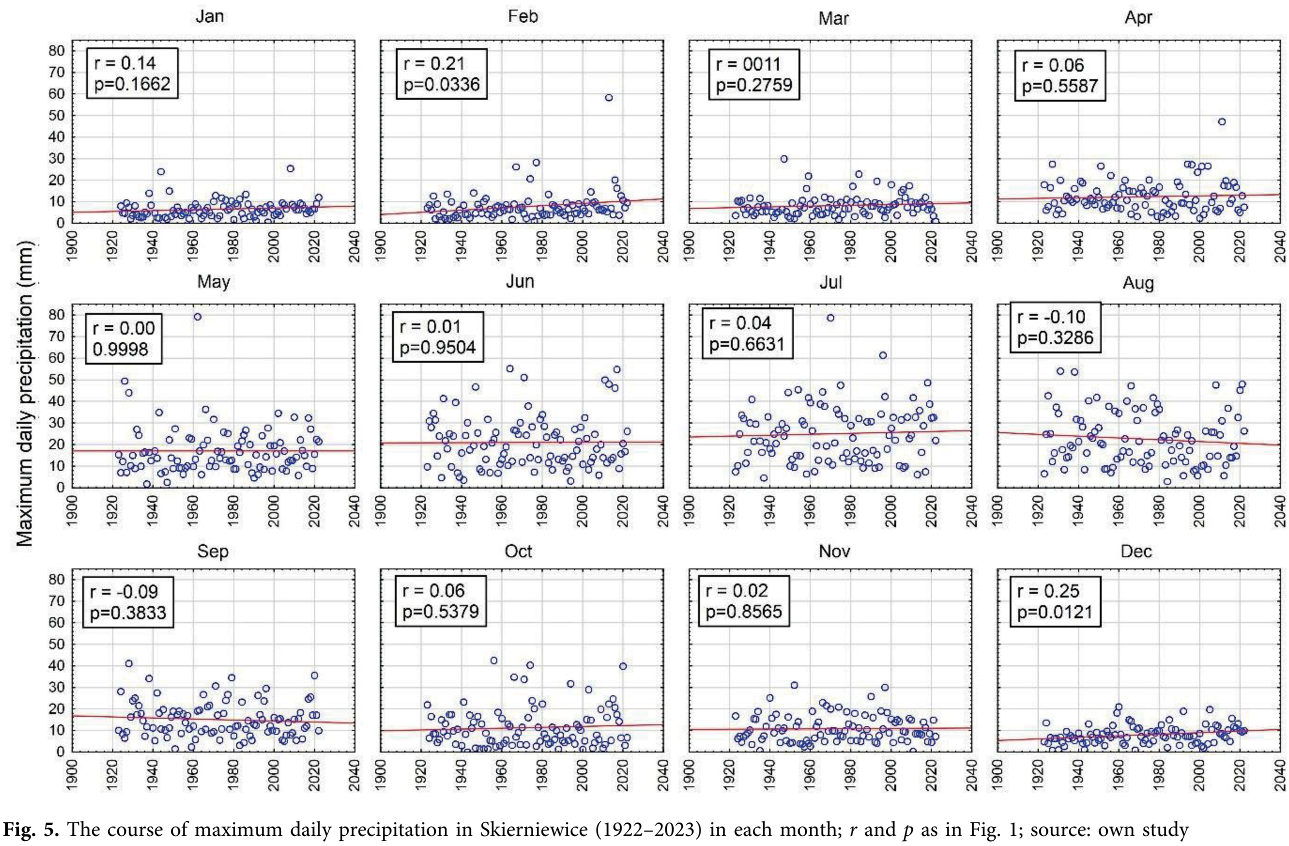

Fig. 5. The course of maximum daily precipitation in Skierniewice (1922–2023) in each month; *r* and *p* as in Fig. 1; source: own study

According to Szwed (2019), climate change in Poland is evident in the changing annual sums of precipitation. While these sums have been gradually increasing, more notably, there have been shifts in the seasonal and monthly distributions of precipitation. The most significant increases have been observed during the colder half of the year (especially in March). Additionally, a decreasing contribution of summer precipitation (June–August) to the annual total has been noted.

Monitoring of daily total precipitation has also been studied outside Poland. For example, Blanchet, Molinié, and Touati (2018) found significant increasing trends in daily rainfall maxima (since 1985) in some areas of southern France. In Switzerland, changes in rainfall intensity and distribution were also evaluated. A wintertime increase of up to 30% was observed for the period 1901–2000, while no statistically significant trends were found for the remaining seasons

(Schmidli and Frei, 2005). Furthermore, Scherrer *et al.* (2015), analysing precipitation data from 1901 to 2014 in Switzerland, observed increases in heavy precipitation intensity, expressed as the annual maximum daily precipitation, with a mean change of about 10% per 100 years.

SEASONAL DISTRIBUTION OF PRECIPITATION

The variability in monthly precipitation described above contributes to extremely high variability in the amount of precipitation occurring in different seasons. Although the average summer precipitation accounts for approximately 213 mm, which represents 39.9% of the total annual precipitation, the recorded extremes highlight this inconsistency. The minimum summer precipitation was only 55 mm in 1992, while the maximum reached as high as 410 mm in 1931 (Fig. 6).

An analysis of seasonal precipitation reveals a very slight yet statistically significant increasing trend in spring precipitation ($r = 0.2$), along with a strong upward trend in winter precipitation ($r = 0.51$) – Figure 7. No significant trends were found for summer and autumn. The rise in winter precipitation, coupled with the absence of a similar trend in summer, has led to a statistically significant increase in the percentage share of winter precipitation in the annual total ($r = 0.39$, $p = 0.000$) and a decrease in the percentage share of summer precipitation ($r = -0.27$, $p = 0.006$) – Figure 8.

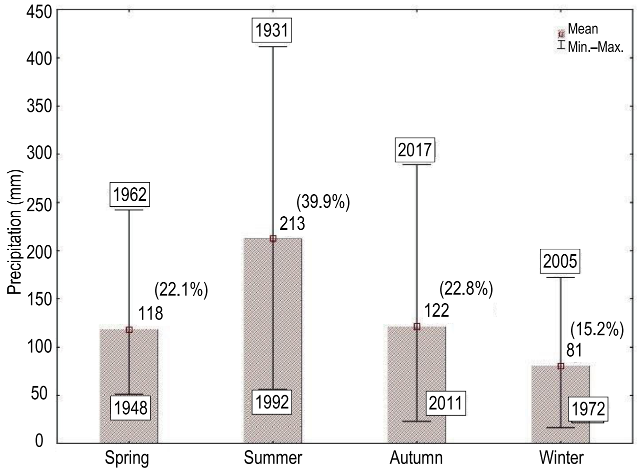

Fig. 6. Precipitation distribution in Skierniewice (1923–2022) in different seasons of the year; source: own study

Czarnecka and Nidzgorska-Lencewicz (2012), based on an analysis of data from 1951–2010, concluded that there was a slight trend of increased precipitation during the spring and autumn seasons across most of Poland, while the share of summer precipitation in the total annual precipitation was decreasing. Moberg and Jones (2005) conducted a large-scale continental analysis of precipitation variability, based on daily precipitation data from several dozen meteorological stations across Europe

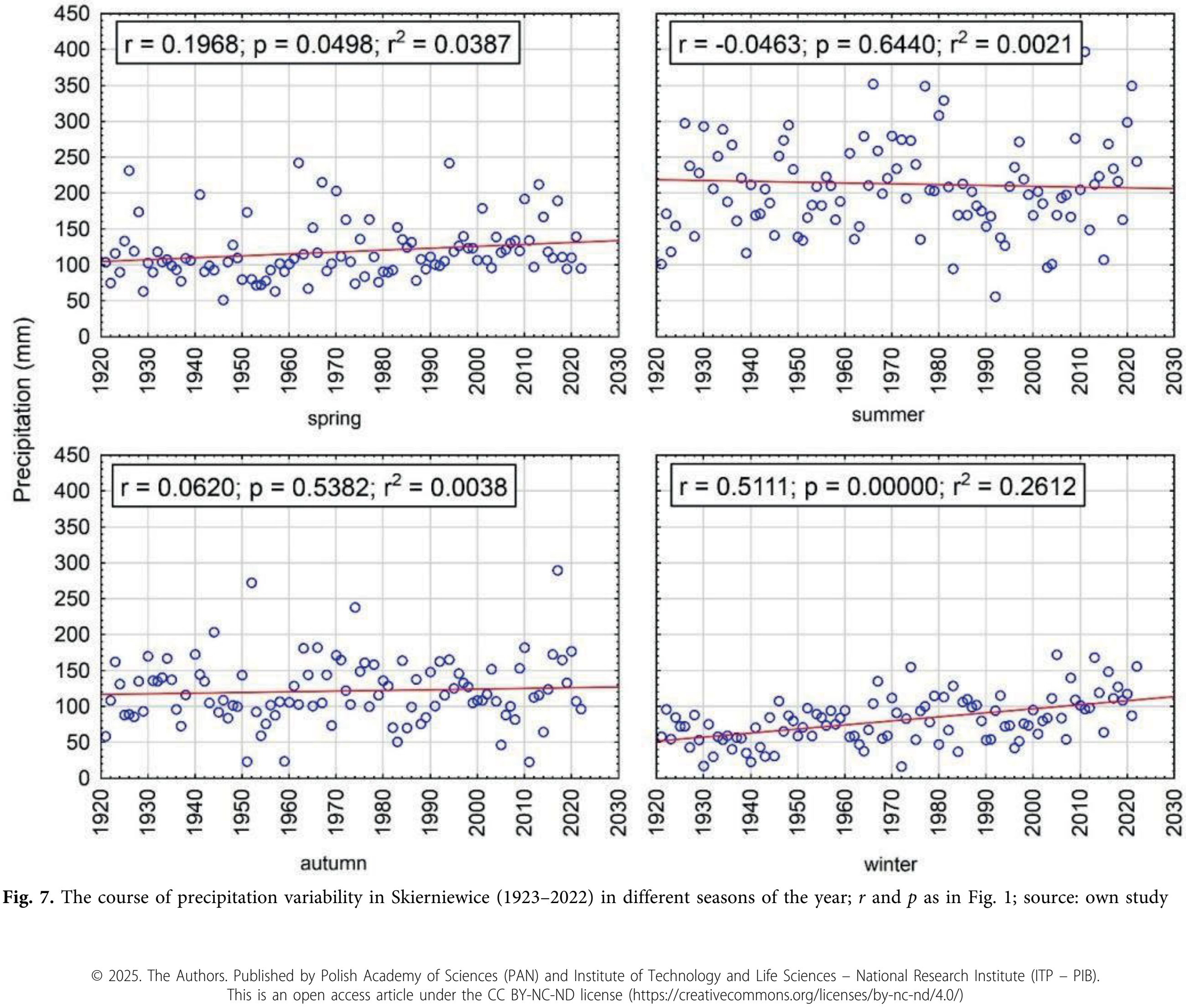

Fig. 7. The course of precipitation variability in Skierniewice (1923–2022) in different seasons of the year; *r* and *p* as in Fig. 1; source: own study

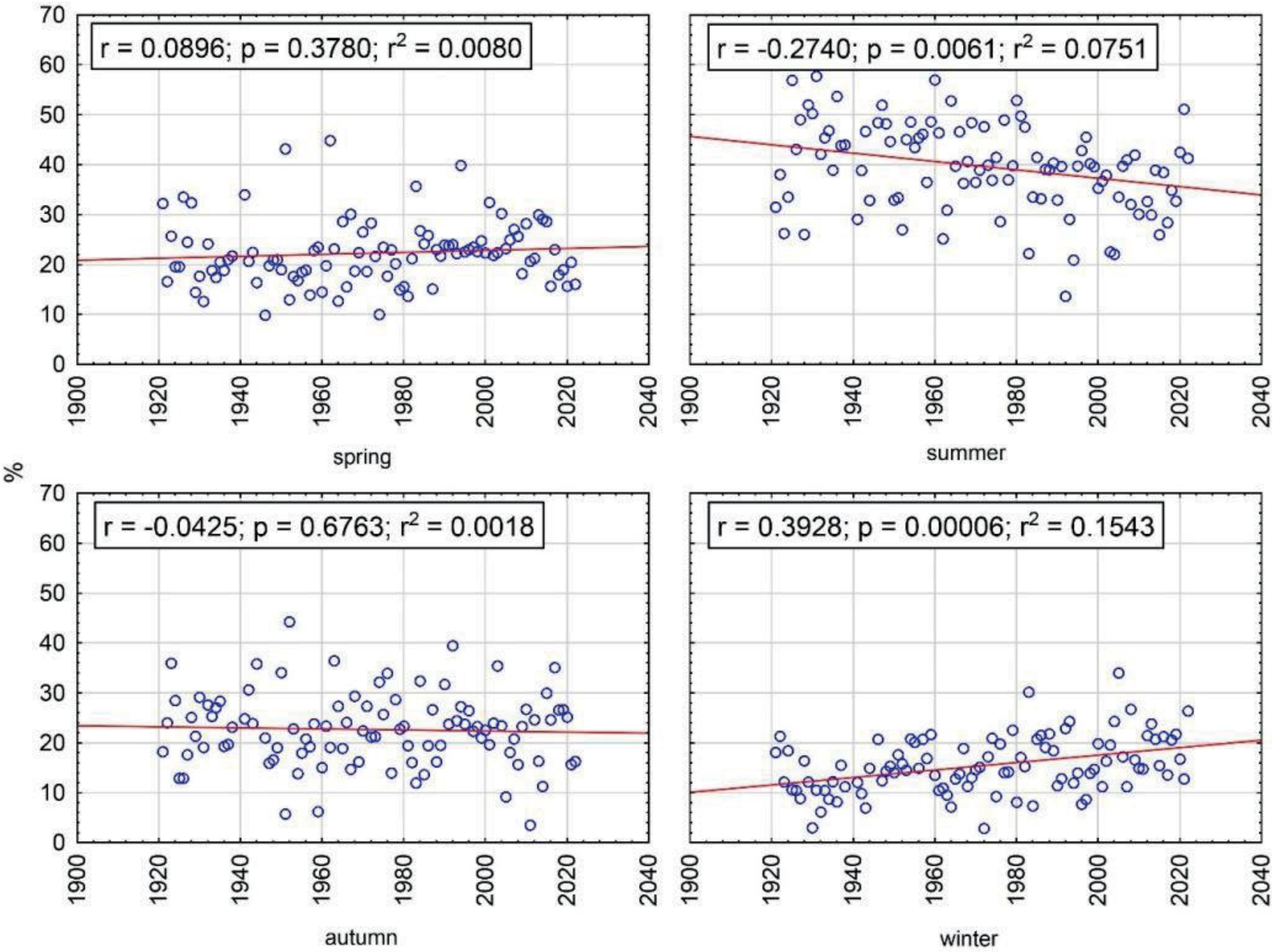

Fig. 8. Percentage share of seasonal precipitation in Skierniewice (1923–2022) in the annual sum; *r* and *p* as in Fig. 1; source: own study

during the 20th century. They found increasing trends in precipitation intensity primarily during winter. In summer, they observed slightly decreasing trends in Scandinavia and slight increases in Central and Western Europe. A rise in winter precipitation, with negligible or no trends in other seasons (based on multi-decade data), was observed in countries like Germany (Hänsel, Petzold and Matschullat, 2009), United Kingdom (Osborn and Hulme, 2002), and Switzerland (Schmidli and Frei, 2005).

In our study, on average, spring precipitation accounts for 22.1% of the annual total, while winter contributes only 15.2%. However, since the winter season does not overlap with the vegetation period, the demonstrated trend of increasing winter precipitation has little practical impact on the climatic water balance.

CONCLUSIONS

The analysis of historical precipitation data in Skierniewice enhances the understanding of water condition variability in the region and enables an assessment of how these changes affect local horticulture and agriculture. The findings may support the development of adaptive strategies, such as the introduction of more drought-tolerant crop varieties, the expansion of irrigation systems, or improved water resource management. The analysis of annual precipitation in Skierniewice over the period 1923–2022 did not reveal a significant long-term trend. A key observation regarding monthly variability is the statistically significant increase in winter precipitation, with no such increase – or even a downward trend – recorded in the remaining months. This pattern, given the seasonal nature of crop cultivation, may be considered disadvantageous for agricultural production. In the context of central Poland, where agriculture plays a vital role in the regional economy, understanding the impact of both the amount and distribution of precipitation is particularly important.

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CONFLICT OF INTERESTS

All authors declare that they have no conflicts of interest.

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