JOURNAL OF WATER AND LAND DEVELOPMENT

e-ISSN 2083-4535

Polish Academy of Sciences (PAN) Institute of Technology and Life Sciences – National Research Institute (ITP – PIB)

JOURNAL OF WATER AND LAND DEVELOPMENT
DOI: 10.24425/jwld.2023.147231
2023, No. 59 (X–XII): 76–82

Seasonal precipitation variation in central-eastern Poland

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RECEIVED 22.05.2023 ACCEPTED 22.08.2023 AVAILABLE ONLINE 31.12.2023

Abstract: The purpose of the work is to characterise pluvial conditions in central-eastern Poland from the beginning of the 21st century (2001–2020). The analysis involved seven meteorological stations of the Institute of Meteorology and Water Management – National Research Institute (IMGW-PIB): Białowieża, Legionowo, Pułtusk, Siedlce, Szepietowo, Terespol and Warsaw. The work contains the analysis of the annual and seasonal atmospheric precipitation pattern (summer, winter, spring and autumn) and its temporal and spatial variation throughout a 20-year period. Moreover, the percentage share of precipitation in each season in the annual sum was calculated. In order to analyse precipitation patterns in the study period, the Innovative Trend Analysis (ITA) was applied. The average long-term annual atmospheric precipitation sum ranged from 557 mm at Terespol to 653 mm at Białowieża. The highest seasonal precipitation sum in the studied region was recorded for the summer (218 mm) whereas in spring and autumn, precipitation stayed at a similar level and amounted to 130 and 131 mm, respectively. The lowest precipitation was recorded in winter (109 mm). The highest percentage share of the atmospheric precipitation sum was associated with summer rainfall (from 35 to 38%), whereas the lowest in winter (from 18 to 20%). Comparisons of 2001–2010 and 2011–2020 decades revealed a decline in the share of summer precipitation in the annual sum at most of the stations, and an increase in the share of winter precipitation. The ITA demonstrated that the most significant trends in precipitation change occurred in summer and winter and the directions of the trends were different for each station.

Keywords: atmospheric precipitation, central-eastern Poland, seasonality, tendency for change

INTRODUCTION

The latest sixth IPCC report (2023) shows that man-made climate change affects many weather and climatic extremes all over the world. This has resulted in unfavourable worldwide results as well as losses and damage to nature and humans. The spatial distribution of atmospheric precipitation is a key element of the hydrological cycle. In the 21st century, changes in atmospheric precipitation due to anthropogenic impacts may change water availability which affects both humans and the biosphere (Haddeland *et al.*, 2014; Schewe *et al.*, 2014). Brienen *et al.* (2013) advise caution while drawing conclusions on tendencies in precipitation because they are very sensitive to the time period under consideration. Also research for Ukraine conducted by Ivanov, Palamarchuk and Pyshniak (2009) supports this claim. Earlier international and Polish research explained precipitation tendencies in terms of annual mean (Degirmendžić, Kożuchowski and Żmudzka, 2004; Kożuchowski, 2004; Chadwick, Boutle and Martin, 2013; Knutti and Sedláček, 2013; Skowera, Kopcinska and Kopec, 2014), seasonal fluctuations (Czarnecka and Nidzgorska-Lencewicz, 2012; Kumar *et al.*, 2014; Polade *et al.*, 2014) and extreme event distribution (Kharin *et al.*, 2013; Sillmann *et al.*, 2013; Tongal, 2019; Zhou *et al.*, 2023). Wibig (2009) claims that atmospheric precipitation in Poland did not change greatly in the second half of the 20th century. Żmudzka (2002) has confirmed an insignificant increasing tendency in annual precipitation sums. Grzywna *et al.* (2020) analysed atmospheric precipitation in Poland in 1981–2010 and they found that the average rainfall in the summer and winter half-year was 382 mm (63% of the annual sum) and 224 mm (37%), respectively. The annual precipitation sum averaged 606.66 mm, with a standard deviation of 88.49. Ziernicka, Wojtaszek and Kopcińska (2020) report that the coefficient of variation for annual precipitation sums in Poland was 17% that in 1971–2000. The coefficient increased to 19% in

2001–2018. On the other hand, Kożuchowski (1985) reports 11% for the entire period of 1881–1980, 10% in the first half of the 20th century, and 12% in the second half. In the 20th century, there was a steady increase in the coefficient of variation of atmospheric precipitation in 10-year periods in Poland. Substantial spatial and temporal variation of atmospheric precipitation yields the necessity of conducting research on a regional scale in order to better understand projected seasonal changes affecting water supply in a given region (Brunetti *et al*., 2002; Fowler and Kilsby, 2003; Kostopoulou and Jones, 2005; Moberg and Jones, 2005; Alexander *et al*., 2007). The description of temporal and regional seasonal fluctuations in precipitation may contribute to better modelling of hydrological systems, which will result in a better water reserve management. Such information is also necessary for a better assessment of the impact of climate change on water reserve systems on a regional scale.

The objective of the work is to characterise seasonal pluvial conditions in central-eastern Poland from the beginning of the 21st century (the years 2001–2020).

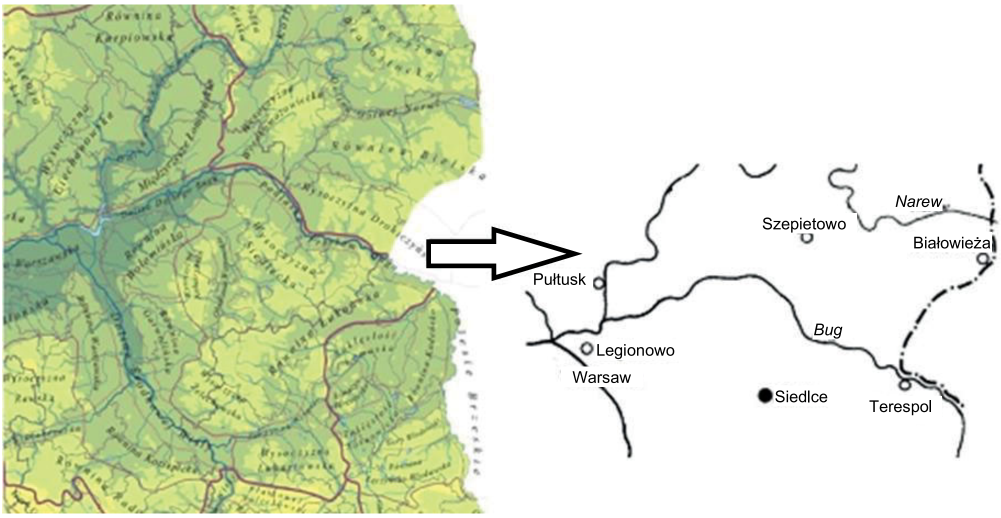


Fig. 1. Study area; source: own elaboration based on Kondracki (1994)

MATERIALS AND METHODS

STUDY MATERIALS

According to Kondracki (1994), the study area encompasses Mazowsze-Podlasie Lowlands, that is Southern Podlasie Lowland and the southern part of Northern Podlasie Lowland which are classified as sub-provinces of Central Polish Lowlands. The Narew River, flowing in the direction of the Vistula River, and its estuary the Wkra form the northern hydrographic boundary of the study area, the Vistula is the western boundary, whereas Bug, which flows into Narew, is the eastern boundary, and the Wieprz River is the south-eastern boundary (Fig. 1). The region's mesoclimate varies substantially due to the lie of the land. Towards the east, the continental features become stronger, them being associated with winter length and temperature during winter months.

The experimental material consisted of meteorological data of daily atmospheric precipitation sums from the following seven IMGW-PIB stations: Białowieża, Legionowo, Pułtusk, Siedlce, Szepietowo, Terespol and Warsaw (Tab. 1, Fig. 1) in 2001–2020.

Table 1. Geographic coordinates of synoptic and climatic IMGW-PIB stations in central-eastern Poland

Station	Geographic coordinates		H_s m a.s.l.
	φ°	λ°	
Białowieża	52°42'	23°51'	164
Legionowo	52°24'	20°58'	93
Pułtusk	52°44'	21°06'	95
Terespol	52°04'	23°37'	131
Siedlce	52°11'	22°16'	146
Szepietowo	52°51'	22°33'	150
Warsaw	52°13'	21°01'	113

Explanations: φ° – latitude, λ° – longitude, H_s – elevation above sea level. Source: https://danepubliczne.imgw.pl/.

STUDY METHODS

The work includes the analysis of annual and seasonal (summer, winter, spring, autumn, warm half year, cold half year) atmospheric precipitation sums as well as their temporal and spatial variation during a 20-year period (2001–2020). Annual atmospheric precipitation sequences consisted of data from December of the previous year to November of a given year. Seasonal precipitation sums were determined for the following seasons of the year: spring (March–May), summer (June–Aug.), autumn (Sept.–Nov.) and winter (Dec.–Feb.). Moreover, the percentage share of each seasonal precipitation in the annual sum as well as its variation were determined. In order to analyse the trend in precipitation change throughout the study period, the Innovative Trend Analysis was applied (Şen, 2020). To this end, the data sequence was divided into two sub-series for 2001–2010 and 2011–2021. Trend strength (*D*) and slope (*S*) were calculated according to the Equations (1) and (2):

$$D = \frac{1}{n}\sum \frac{10(\bar{y}_i - \bar{x}_i)}{\bar{x}_i} \quad (1)$$

$$S = \frac{2(y_i - x_i)}{n} \quad (2)$$

where: D = trend indicator, S = trend slope, n = number of observations of each sub-series, $\bar{y}_i$, $\bar{x}_i$ = means for the first and second sub-series.

In order to determine trend significance, a confidence interval was used at the significance level of α = 0.05, following the Equation (Şen, 2021):

$$CL_{(1-\alpha)} = 0s_{\mathrm{crit}} \pm б_{(s)} \quad (3)$$

where: $CL_{(1\text{-}\alpha)}$ = percent of significance level, s_{crit} = standard deviation value, $\pm б_{(s)}$ = slope of standard deviation. In this work the significance level was 5%.

RESULTS AND DISCUSSION

In 2001–2020, in central-eastern Poland, the highest average annual precipitation sums were recorded for Białowieża (653 mm) and Pułtusk (593 mm), and the lowest for Terespol (557 mm) (Tab. 2). As a result of various geographic factors and atmospheric circulation, a parallel of altitude distribution of atmospheric precipitation occurred in the study area. In central-eastern Poland, summer precipitation was twice as high as in winter. The highest precipitation sums during the summer period were recorded at Białowieża (237 mm) and Pułtusk (230 mm), them being the lowest at Terespol (206 mm). In the majority of stations (Siedlce, Terespol, Legionowo, Pułtusk, Szepietowo), spring precipitation was higher compared to autumn. When comparing 2001–2010 and 2011–2020, it was found that in the second decade summer precipitation was lower at most stations but winter precipitation was higher. No major differences were found between spring and autumn precipitation in the two decades. Additionally, after conducting their research in Wielkopolska (Greater Poland) in 1981–2014, Szyga-Pluta (2018) found the highest average seasonal precipitation sums in summer (200.1 mm). These were 76.8, 85.7 and 90.9 mm higher compared to spring, autumn and winter precipitation. According to Tomczyk and Bednorz (eds.) (2022), average spring, summer, autumn and winter precipitation sums in central eastern Poland amounted to 150, 250, 150 and 100 mm in 1991–2020.

In all stations (except Legionowo), the highest variation was observed in winter precipitation, while the lowest in autumn (Tab. 3). Coefficients of variation ranged from 37 to 43% in winter and from 22 to 27% in autumn. Different results were recorded by Szyga-Pluta (2018) for Wielkopolska in 1981–2014; in individual months, high values of this coefficient predominated (above 40%), the highest value being calculated for October (56.4%).

Summer precipitation in central-eastern Poland in the study period constituted from 35 to 38% of the annual sum, whereas winter precipitation accounted for 17 to 20% (Fig. 2). The percentage share of spring and autumn precipitation in the annual sum was similar and ranged from 21 to 24%. In 2001–2018, the percentage share of summer precipitation in for the whole area of Poland ranged from 34 to 44%, while winter precipitation from 12 to 24%, spring precipitation from 15 to 26%, and autumn precipitation from 20 to 30% (Ziernicka-Wojtaszek and Kopcińska, 2020). Czarnecka and Nidzgorska-Lencewicz (2012) claim that the dominance of summer precipitation over winter precipitation is mainly due to the intensity of the summer rainfall (rain from convection clouds) and rather than its frequency.

Table 2. Seasonal atmospheric precipitation sums in the years 2001–2010, 2011–2020, and 2001–2020

Station	Spring	Summer	Autumn	Winter	Annual
2001–2010					
Białowieża	139	248	150	133	670
Legionowo	136	193	125	117	571
Pułtusk	129	212	123	113	577
Siedlce	118	210	124	100	552
Szepietowo	142	205	123	100	570
Terespol	121	218	118	95	552
Warsaw	117	227	125	104	573
2011–2020					
Białowieża	134	227	148	128	637
Legionowo	120	226	128	111	585
Pułtusk	134	249	123	110	616
Siedlce	148	211	130	108	597
Szepietowo	138	223	129	105	595
Terespol	128	195	120	96	539
Warsaw	121	212	126	112	571
2001–2020					
Białowieża	136	237	149	131	653
Legionowo	128	210	127	114	579
Pułtusk	132	230	123	111	596
Siedlce	148	211	130	108	597
Szepietowo	140	214	126	102	582
Terespol	124	206	119	96	545
Warsaw	119	219	126	108	572

Source: own study.

Comparisons of 2001–2010 and 2011–2020 decades revealed that at 4 out of 7 stations (Warsaw, Szepietowo and Pułtusk) recorded an increase in the share of spring and autumn rainfall in the annual sum. It was true for spring precipitation only at Warsaw, Terespol, Pułtusk, Szepietowo. There was a clear decline in the share of summer precipitation in the annual sum (Fig. 3) accompanied by an increase in the share of winter precipitation (except Siedlce and Legionowo). Three out of seven stations (Warsaw, Legionowo and Pułtusk) recorded an increase in the share of spring and autumn rainfall in the annual sum. It was true for spring precipitation only at Terespol. Additionally, Szwed (2019), who analysed series of data for seasonal precipitation in Poland for the years 1951–2013, found that, particularly in the south of Poland, there was a tendency for a decline in the share of

Table 3. Minimum and maximum values, and coefficients of variation (*CV*) in seasonal atmospheric precipitation

Station	Parameter	Spring	Summer	Autumn	Winter
Białowieża	min	82	84	90	45
	max	208	358	194	266
	CV	23	31	22	37
Legionowo	min	61	81	51	41
	max	232	438	162	261
	CV	37	43	27	41
Pułtusk	min	81	67	51	45
	max	200	315	128	215
	CV	27	32	22	43
Siedlce	min	67	118	41	41
	max	238	316	143	249
	CV	30	27	24	46
Szepietowo	min	63	134	48	54
	max	233	357	148	229
	CV	27	29	22	37
Terespol	min	81	67	51	45
	max	200	315	128	215
	CV	27	32	22	43
Warsaw	min	68	87	39	17
	max	204	406	139	255
	CV	30	35	24	42

Source: own study.

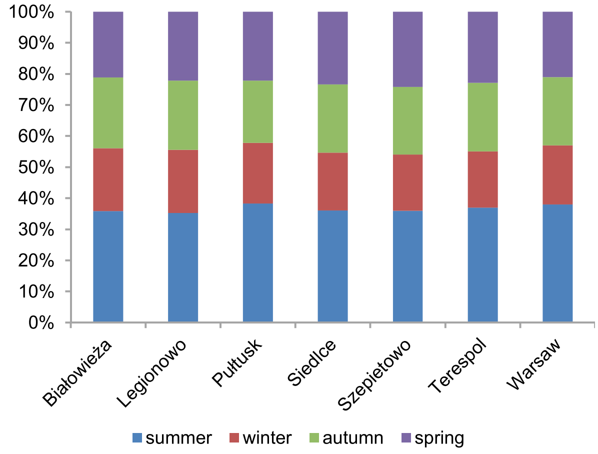


Fig. 2. Percentage share of seasonal precipitation in the annual sum; source: own study

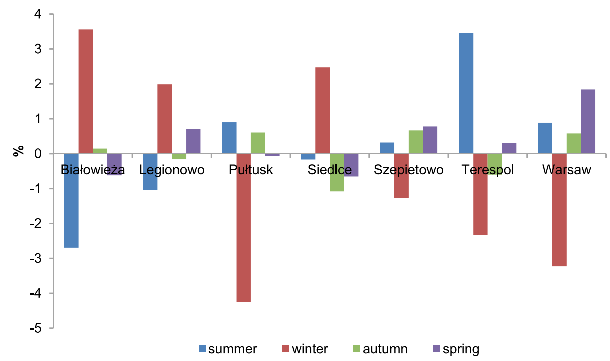
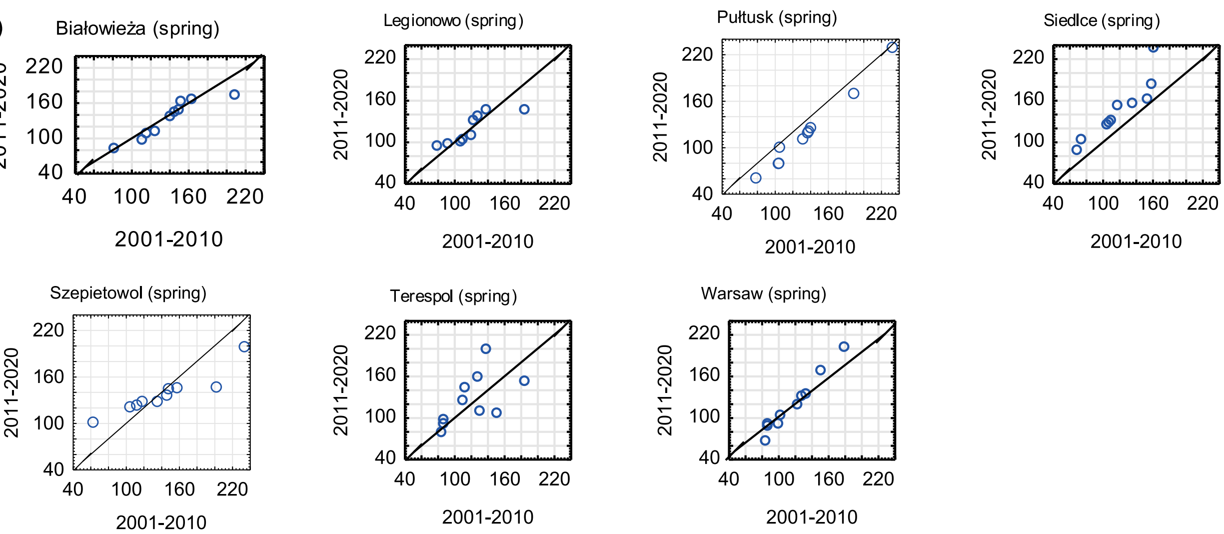


Fig. 3. Differences in the share of seasonal precipitation in the annual sum between the decades 2011–2020 and 2001–2010; source: own study

summer precipitation in the annual sum, whereas in the north-western areas there was a tendency for an increase in winter precipitation. For the eastern and south-eastern parts of Poland, no changes in the winter precipitation sum were observed. Increases or stabilization in the winter precipitation sum lead to an increase in their share in the annual precipitation sum, particularly noticeable in the west. Additionally, Bochenek (2012), who conducted research in Szymbark for over 40 years (1971–2010), noticed changes in precipitation sums and a decline in summer precipitation in the annual sum. Skowera, Kopcińska and Kopeć (2014) claim that the most equivocal are the changes in the share of summer to winter precipitation, and that they are region-related.

Results of the ITA application (Fig. 4) demonstrate that for the majority of stations points representative data are located on or very close to the 1:1 line, which suggests there were only slight changes in seasonal precipitation sums in 2011–2020 compared to

a)



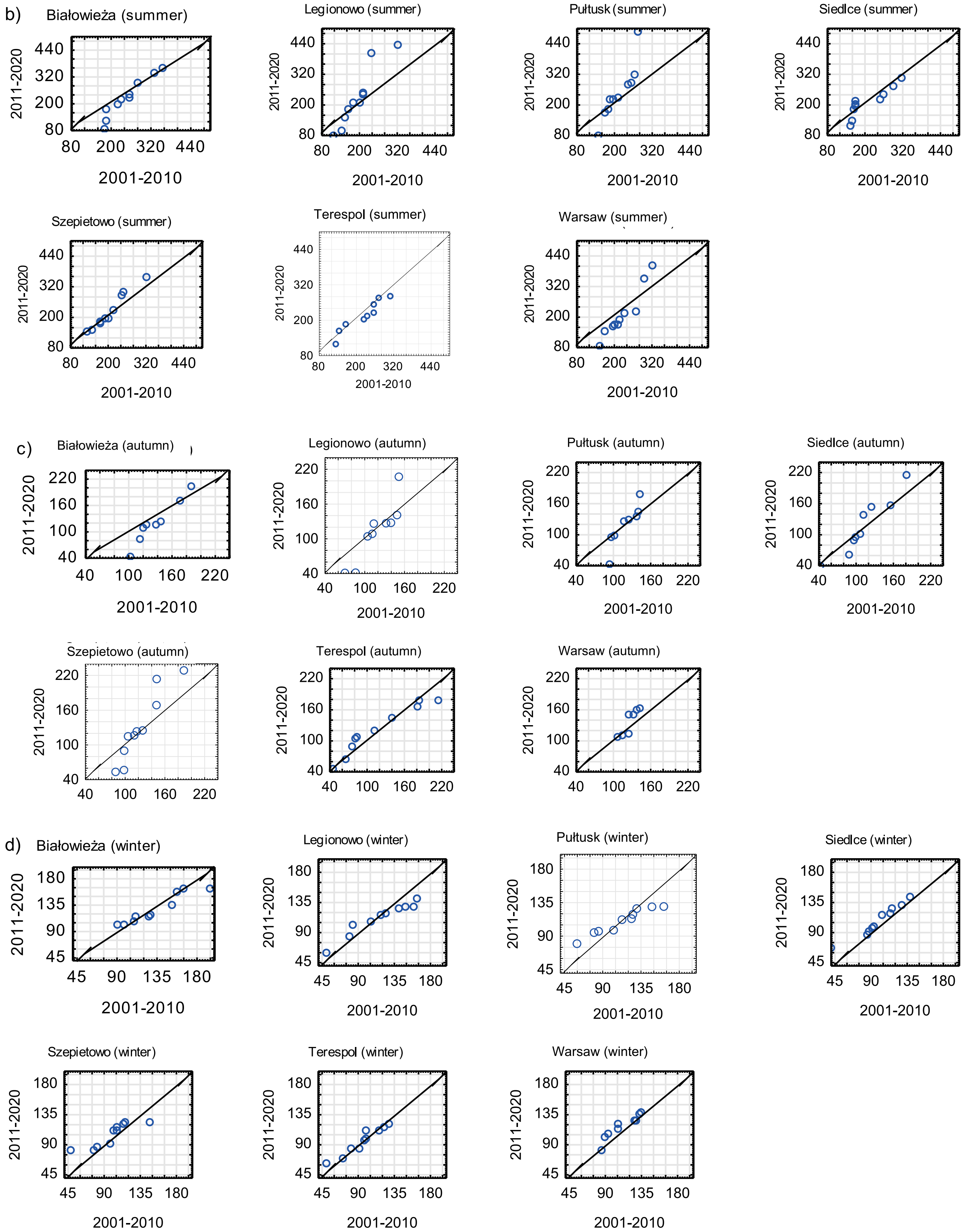


Fig. 4. ITA results for precipitation sums in 2001–2020 in: a) spring, b) summer, c) autumn, d) winter; source: own study

2001–2010. The largest number of significant changes in season precipitation sums (in four seasons) was recorded for Warsaw, Siedlce, Legionowo; the lowest for Terespol (only in summer) (Tab. 4). The tendency for change in precipitation in individual seasons revealed that the largest number of significant values occurred in summer and winter. However, the direction of changes in summer and winter precipitation was different depending on the station. At Warsaw, Terespol, Siedlce and Białowieża stations, the

Table 4. Values of the slope of trends obtained by ITA, and critical values (*CL*) for seasonal precipitation sums at individual stations

Station	Parameter	Spring	Summer	Autumn	Winter
Białowieża	trend slope	–0.45	–2.14*	–0.23	–0.43*
	CL	0.53	0.89	0.50	0.38
Legionowo	trend slope	–1.60*	3.32*	0.30	–0.64*
	CL	0.27	1.23	0.72	0.36
Pułtusk	trend slope	0.50	3.65*	0.07	–0.30*
	CL	0.85	1.57	0.55	0.28
Siedlce	trend slope	2.97*	0.06	0.67*	0.76*
	CL	0.73	1.28	0.65	0.26
Szepietowo	trend slope	–0.43	1.72*	0.60	0.54*
	CL	0.61	0.52	0.67	0.49
Terespol	trend slope	0.67	–2.31*	0.17	0.06
	CL	1.35	1.10	0.59	0.25
Warsaw	trend slope	0.38*	–1.50*	0.08	0.81*
	CL	0.26	0.90	0.79	0.35

Explanation: * = significant at $\alpha = 0.05$.
Source: own study.

summer precipitation sums significantly declined, whereas at Pułtusk, Szepietowo and Legionowo they actually increased. In winter, an increase was recorded for Warsaw, Szepietowo and Siedlce, and a decline for Legionowo, Pułtusk and Białowieża. Spring precipitation displayed a significant positive tendency for Warsaw and Siedlce, whereas negative for Legionowo. Autumn precipitation revealed a significant (positive) variation at the Siedlce Station only. Osuch *et al.* (2016) believe that projections for the future indicate further unfavourable changes in seasonal precipitation patterns. In a warmer season, precipitation is likely to be on the decline, with raising levels in the colder season. In effect, the shift of precipitation from warmer to colder seasons will continue. However, the results showed that the spatial pattern depended on the climate model, time scale under consideration, and the bias correction.

CONCLUSIONS

1. In the long-term study period, the annual precipitation sum in central eastern Poland was 588 mm. Average seasonal atmospheric precipitation sums for spring (March–May), summer (June–Aug.), autumn (Sept.–Nov.) and winter (Dec.–Feb.) amounted to 130, 218, 131 and 109 mm respectively.
2. The analysis of seasonal precipitation sums over 2001–2010 and 2011–2020 decades demonstrated that in the latter decade summer precipitation at most stations was lower, whereas winter sums were higher. Winter precipitation in the study period showed the highest variability (V = 43%). No major differences were found between spring and autumn precipitation in the two decades. Their variation over the study period was 29 and 23% respectively.
3. The Innovative Trend Analysis demonstrated that the largest number of significant changes in seasonal precipitation sums occurred in summer and winter. However, the direction of changes in both summer and winter precipitation differed according to stations. Spring precipitation displayed a significant positive trend for Warsaw and Siedlce only, whereas negative for Legionowo. Autumn precipitation showed a significant positive tendency at Siedlce only.

REFERENCES

Alexander, L.V. *et al.* (2007) "Trends in Australia's climate means and extremes: a global context," *Australian Meteorological Magazine*, 56(1), pp. 1–18.

Bochenek, W. (2012) "Ocena zmian warunków opadowych na Stacji Naukowo-Badawczej IGiPZ PAN w Szymbarku w okresie 40 lat obserwacji (1971–2010) i ich wpływ na zmienność odpływu wody ze zlewni Bystrzanki [Evaluation of precipitation at the IG&SO PAS research station in Szymbark during 40-year period (1971–2010) and its impact on the variability of water runoff from the Bystrzanka stream basin]," *Woda-Środowisko-Obszary Wiejskie*, 12(2), pp. 29–44. Available at: https://www.itp.edu.pl/old/wydawnictwo/woda/zeszyt_38_2012/artykuly/Bochenek.pdf (Accessed: May 10, 2023.05.10).

Brienen, S. *et al.* (2013) "Regional centennial precipitation variability over Germany from extended observation records," *International Journal of Climatology*, 33(9), pp. 2167–2184. Available at: https://doi.org/10.1002/joc.3581.

Brunetti, M. *et al.* (2002) "Droughts and extreme events in regional daily Italian precipitation series," *International Journal of Climatology: A Journal of the Royal Meteorological Society*, 22(5), pp. 543–558. Available at: https://doi.org/10.1002/joc.751.

Chadwick, R., Boutle, I. and Martin, G. (2013) "Spatial patterns of precipitation change in CMIP5: Why the rich do not get richer in the tropics," *Journal of Climate*, 26(11), pp. 3803–3822. Available at: https://doi.org/10.1175/JCLI-D-12-00543.1.

Czarnecka, M. and Nidzgorska-Lencewicz, J. (2012) "Wieloletnia zmienność sezonowych opadów w Polsce [Multiannual variability of seasonal precipitation in Poland]," *Woda-Środowisko-Obszary Wiejskie*, 12, pp. 45–60. Available at: https://www.itp.edu.pl/old/wydawnictwo/woda/zeszyt_38_2012/artykuly/Czarnecka%20Nidzgorska.pdf (Accessed: May 10, 2023).

Degirmendžić, J., Kożuchowski, K. and Żmudzka, E. (2004) "Changes of air temperature and precipitation in Poland in the period 1951–2000 and their relationship to atmospheric circulation," *International Journal of Climatology: A Journal of the Royal Meteorological Society*, 24(3), pp. 291–310. Available at: https://doi.org/10.1002/joc.1010.

Fowler, H.J. and Kilsby, C.G. (2003) "A regional frequency analysis of United Kingdom extreme rainfall from 1961 to 2000," *International Journal of Climatology: A Journal of the Royal Meteorological Society*, 23(11), pp. 1313–1334. Available at: https://doi.org/10.1002/joc.943.

Grzywna, A. *et al.* (2020) "The analysis of spatial variability of precipitation in Poland in the multiyears 1981–2010," *Journal of Water and Land Development*, 46, pp. 105–111. Available at: https://doi.org/10.24425/jwld.2020.134202.

Haddeland, I. *et al.* (2014) "Global water resources affected by human interventions and climate change," *Proceedings of the National Academy of Sciences*, 111(9), pp. 3251–3256. Available at: https://doi.org/10.1073/pnas.1222475110.

IPCC (2023) *AR6 Synthesis Report: Climate Change 2023*. Intergovernmental Panel on Climate Change. Available at: https://www.ipcc.ch/report/sixth-assessment-report-cycle/ (Accessed: May 15, 2023).

Ivanov, S., Palamarchuk, J. and Pyshniak, D. (2009) "Precipitation statistics in Ukraine: Sensitivity to informational sources," in P.Ya. Groisman, S.V. Ivanov (eds.) *Regional aspects of climate-terrestrial-hydrologic interactions in non-boreal Eastern Europe*. Netherlands: Springer, pp. 23–32.

Kharin, V.V. *et al.* (2013) "Changes in temperature and precipitation extremes in the CMIP5 ensemble," *Climatic Change*, 119, pp. 345–357. Available at: https://doi.org/10.1007/s10584-013-0705-8.

Knutti, R. and Sedláček, J. (2013) "Robustness and uncertainties in the new CMIP5 climate model projections," *Nature Climate Change*, 3(4), pp. 369–373. Available at: https://doi.org/10.1038/nclimate1716.

Kondracki, J. (1994) *Geografia Polski: mezoregiony fizyczno-geograficzne [The geography of Poland: physical geographical mezoregions]*. Warszawa: Wydawnictwa Naukowe PWN.

Kostopoulou, E. and Jones, P.D. (2005) "Assessment of climate extremes in the Eastern Mediterranean," *Meteorology and Atmospheric Physics*, 89, pp. 69–85. Available at: https://doi.org/10.1007/s00703-005-0122-2.

Kożuchowski, K. (1985) "Zmienność opadów atmosferycznych w Polsce w stuleciu 1881–1980 [Variation in precipitation in Poland in the years 1881–1980]," *Acta Geographica Lodziensia*, 48. Wrocław: Zakład Narodowy Imienia Ossolińskich, Warszawa: Wydaw. PAN.

Kożuchowski, K. (2004) "Zmienność opadów atmosferycznych w Polsce w XX i XXI wieku [The variability of precipitation totals in Poland in twentieth and twentieth-first century]," in K. Kożuchowski (ed.) *Skala, uwarunkowania i perspektywy współczesnych zmian klimatycznych w Polsce [Scale, conditions and prospects of contemporary climate change in Poland]*. Łódź: Wydawnictwo "Biblioteka", pp. 47–58.

Kumar, S. *et al.* (2014) "Less reliable water availability in the 21st century climate projections," *Earth's Future*, 2(3), pp. 152–160. Available at: https://doi.org/10.1002/2013EF000159.

Moberg, A. and Jones, P.D. (2005) "Trends in indices for extremes in daily temperature and precipitation in central and western Europe, 1901–99," *International Journal of Climatology: A Journal of the Royal Meteorological Society*, 25(9), pp. 1149–1171. Available at: https://doi.org/10.1002/joc.1163.

Osuch, M. *et al.* (2016) "Trends in projections of standardized precipitation indices in a future climate in Poland," *Hydrology and Earth System Sciences*, 20(5), pp. 1947–1969. Available at: https://doi.org/10.5194/hess-20-1947-2016.

Polade, S.D. *et al.* (2014) "The key role of dry days in changing regional climate and precipitation regimes," *Scientific Reports*, 4(1), 4364. Available at: https://doi.org/10.1038/srep04364.

Schewe, J. *et al.* (2014) "Multimodel assessment of water scarcity under climate change," *Proceedings of the National Academy of Sciences*, 111(9), pp. 3245–3250. Available at: https://doi.org/10.1073/pnas.1222460110.

Şen, Z. (2020) "Up-to-date statistical essentials in climate change and hydrology: A review," *International Journal of Global Warming*, 22(4), pp. 392–431. Available at: https://doi.org/10.1504/IJGW.2020.111515.

Sillmann, J. *et al.* (2013) "Climate extremes indices in the CMIP5 multimodel ensemble: Part 2. Future climate projections," *Journal of Geophysical Research: Atmospheres*, 118(6), pp. 2473–2493. Available at: https://doi.org/10.1002/jgrd.50188.

Skowera, B., Kopcińska, J. and Kopeć, B. (2014) "Changes in thermal and precipitation conditions in Poland in 1971–2010" *Annals of Warsaw University of Life Sciences-SGGW. Land Reclamation*, 46(2), pp. 153–162. Available at: https://doi.org/10.2478/sggw-2014-0013.

Szwed, M. (2019) "Variability of precipitation in Poland under climate change," *Theoretical and Applied Climatology*, 135(3–4), pp. 1003–1015. Available at: https://doi.org/10.1007/s00704-018-2408-6.

Szyga-Pluta, K. (2018) "Zmienność czasowa i przestrzenna opadów atmosferycznych w Wielkopolsce w latach 1981–2014 [Temporal and spatial variability of atmospheric precipitation in Wielkopolska in the 1981–2014 period]," *Przegląd Geograficzny*, 90(3), pp. 495–516. Available at: https://doi.org/10.7163/PrzG.2018.3.5.

Tomczyk, A. and Bednorz, E. (eds.) (2022) *Atlas klimatu Polski (1991–2020) [Atlas of the climate of Poland (1991–2020)]*. Poznań: Bogucki Wydawnictwo Naukowe.

Tongal, H. (2019) "Spatiotemporal analysis of precipitation and extreme indices in the Antalya Basin, Turkey," *Theoretical and Applied Climatology*, 138(3–4), pp. 1735–1754. Available at: https://doi.org/10.1007/s00704-019-02927-4.

Wibig, J. (2009) "The variability of daily precipitation totals in Poland (1951–2000)," *Geographia Polonica*, 82(1), pp. 21–32.

Zhou, W. *et al.* (2023) "Identification and frequency analysis of drought-flood abrupt alternation events using a daily-scale standardized weighted average of the precipitation index," *Frontiers in Environmental Science*, 11, 1142259. Available at: https://doi.org/10.3389/fenvs.2023.1142259.

Ziernicka-Wojtaszek, A. and Kopcińska, J. (2020) "Variation in atmospheric precipitation in Poland in the years 2001–2018," *Atmosphere*, 11(8), 794. Available at: https://doi.org/10.3390/atmos11080794.

Żmudzka, E. (2002) "O zmienności opadów atmosferycznych na obszarze Polski nizinnej w drugiej połowie XX wieku [Variation in atmospheric precipitation in lowland Poland in the second half of the 20th century]," *Wiadomości Instytutu Meteorologii i Gospodarki Wodnej*, 25(4), pp. 23–38.