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ORIGINAL PAPER

Observed changes in extreme precipitation in Poland: 1991–2015 versus 1961–1990

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Abstract

Several episodes of extreme precipitation excess and extreme precipitation deficit, with considerable economic and social impacts, have occurred in Europe and in Poland in the last decades. However, the changes of related indices exhibit complex variability. This paper analyses changes in indices related to observed abundance and deficit of precipitated water in Poland. Among studied indices are maximum seasonal 24-h precipitation for the winter half-year (Oct.–March) and the summer half-year (Apr.–Sept.), maximum 5-day precipitation, maximum monthly precipitation and number of days with intense or very intense precipitation (respectively, in excess of 10 mm or 20 mm per day). Also, the warm-seasonal maximum number of consecutive dry days (longest period with daily precipitation below 1 mm) was examined. Analysis of precipitation extremes showed that daily maximum precipitation for the summer half-year increased for many stations, and increases during the summer half-year are more numerous than those in the winter half-year. Also, analysis of 5-day and monthly precipitation sums show increases for many stations. Number of days with intense precipitation increases especially in the north-western part of Poland. The number of consecutive dry days is getting higher for many stations in the summer half-year. Comparison of these two periods: colder 1961–1990 and warmer 1991–2015, revealed that during last 25 years most of statistical indices, such as 25th and 75th percentiles, median, mean and maximum are higher. However, many changes discussed in this paper are weak and statistically insignificant. The findings reported in this paper challenge results based on earlier data that do not include 2007–2015.

1 Introduction

According to the Clausius-Clapeyron law, there is more room for water vapour in the warming atmosphere; hence, potential for intense precipitation grows. The 5th Assessment Report of the IPCC (2014) states that it is very likely that global near-surface and tropospheric air humidity has increased since the 1970s. Also, frequency and intensity of heavy precipitation events has likely increased in North America and Europe, as a result of anthropogenic forcing, which leads to an intensification of the water cycle. Existing analyses of trends in hydrometeorological data cover large scales, that is the global scale: e.g. Groisman et al. 2005; Alexander et al. 2006; Donat et al. 2013; the European scale: e.g. Zolina et al. 2010; Zolina 2012; van den Besselaar et al. 2013, Fleig et al. 2015 as well as regional or national scales (e.g. Lorenc and Olecka 2006; Bartholy and Pongrácz 2007; Kysely 2009; Ustrnul and Czekierda 2009; Łupikasza 2010; Łupikasza et al. 2011; Hattermann et al. 2012; Karagiannidis et al. 2012; Arnone et al. 2013; Piccarreta et al. 2013; Niedźwiedź et al. 2015; Scherrer et al. 2016; Martinkova and Hanel 2016; Degirmendžić and Kożuchowski 2017).

However, the so-far change-detection exercises do not show a ubiquitous and consistent signal in extremely high precipitation at the continental (European), regional or national levels. Nevertheless, updating change-detection efforts in order to interpret the climate-change signal is of considerable importance and interest. According to climate projections, future extreme precipitation will likely increase. Globally, heavy precipitation indices (maximum 1-day precipitation total and maximum 5-day precipitation total) are projected to increase in all regional domains (Hay et al. 2016), while a strong increase in dry-day frequencies is projected over land regions, which are now experienced by problems with scarcity of water, e.g. in the Mediterranean region (Polade et al. 2014). Therefore, investigation of observed changes is an important

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task to enable better interpretation of possible future trends. Increase of the extreme abundance of water has potential impacts, including floods, erosion, flash floods and inundation. Deficits of water may affect water resources, agriculture and ecosystems.

Several episodes of extreme precipitation excess and extreme precipitation deficit, leading to dramatic floods and droughts, with considerable economic and social impacts, have occurred in Europe in the last decades. Major floods occurred in the decade of the 1990s, such as in 1993 and 1995 (the basins of the River Rhine and its tributaries), in 1994 (the Mediterranean region) and in 1997 (Central Europe). In the twenty-first century, serious floods occurred in 2000 in Western Europe (UK, Italy, France and Switzerland), in 2005, 2007 and 2010. The most severe floods with the absolute record of annual flood loss in Europe, exceeding €20 billion (nominal value, unadjusted for inflation) were observed in August 2002 (Kundzewicz et al. 2013). One year after these great floods, in the summer of 2003, many parts of Europe experienced severe droughts and heat waves. The summer of 2010, exceptionally warm and dry in Eastern Europe and large parts of Russia, was more severe than the hottest summer of 2003 because of higher amplitude and spatial extent. During that time, extensive fires across western Russia occurred. According to projections, these anomalously warm and dry episodes are recognised as summers which are likely to occur more frequently in the later decades of the twenty-first century (Beniston 2004, Barriopedro et al. 2011).

In Poland, destructive floods as a result of abundant rainfall with high material damage and tens of fatalities occurred in 1970, 1997, 2001 and 2010. The most severe floods of 1997 and 2010 were preceded by very intense and long-lasting precipitation over large areas, so in consequence, large parts of Poland were flooded (Kundzewicz et al. 2012). Noticeable is an increasing number of local floods in urban areas (flash floods) caused by intensive rainfall. In 2017, several cities in Poland were affected by abundant rainfall, e.g. the town of Elbląg, after precipitation of 81.2 mm in 24 h (http://floodlist.com/europe/poland-floods-elblag-september-2017).

Changes in extreme deficit of precipitation may affect risk of droughts. Particularly, precipitation deficit accompanied with high air temperatures (e.g. heat waves) is critical, as observed in Poland over the last three decades (1992, 1994, 2003, 2006, 2008 and 2015). These extensive droughts caused considerable crop yield loss. Extremely hot and dry summer of 2015 (particularly August and September) occurred across the whole country. An extended period without precipitation led to the lowest values of the stages (and discharges) on record (typically records go back to the 1950s) at many rivers. The Vistula River reached the lowest stage since the eighteenth century, when records began (Somorowska 2016).

However, intense precipitation as well as precipitation deficit have exhibited complex variability over the last decades. This paper analyses changes in observed precipitation extremes, related to abundance and deficit of precipitated water, and it attempts to detect the climate-change signal in precipitation. The regional earlier studies did not cover more recent years, such as 2010, 2011 and 2014, with occurrence of extreme precipitation, and 2015, with deficit of precipitation. Comparison of findings of this paper with results of earlier studies reported in references improves our knowledge and gives a better understanding and interpretation of the changes.

2 Data and methods

Precipitation datasets used in this study were provided by the Institute of Meteorology and Water Management-State Research Institute (IMGW-PIB). Datasets were complete, without missing data, but metadata for most of stations were unavailable. In order to examine homogeneity of data, three tests were used: Mann-Whitney-Pettitt test, Penalised maximal *t* test and the standard normal homogeneity test (SNHT) for single series. They were applied with the AnClim software (Štěpánek 2008). Verification of data homogeneity was conducted on monthly totals, calculated from daily data. According to results of three tests for each series, data were classified as "useful", if the number of tests rejecting the null hypothesis about homogeneity at the 5% level is not greater than one and as "suspect", where two or three tests reject the null hypothesis. Data from 44 out of 46 were classified as "useful" and two (Racibórz and Śnieżka) as "suspect". Data from Racibórz were tested additionally by SNHT for two series with respect to a neighbouring, sufficiently correlated homogeneous station. This applied test did not reject the null hypothesis. This method is considered to be more powerful than tests, which use only the single series (Wijngaard et al. 2003). Śnieżka is one of the two mountainous stations, included by WMO to Global Atmosphere Watch – stations, so despite the test results, data were used. However, it is impossible to exclude some inhomogeneity because of strong natural variability of precipitation, especially extreme precipitation.

Figure 1 illustrates the spatial coverage of stations with precipitation data for Poland used in this paper.

Based on the data, the following indices related to extreme precipitation were calculated:

- Maximum seasonal 24-h precipitation for the winter half-year (Oct.–March) and the summer half-year (Apr.–Sept.)
- Maximum 5-day precipitation
- Maximum monthly precipitation
- Number of days with intense precipitation ≥ 10 mm per day
- Number of days with very intense precipitation ≥ 20 mm per day

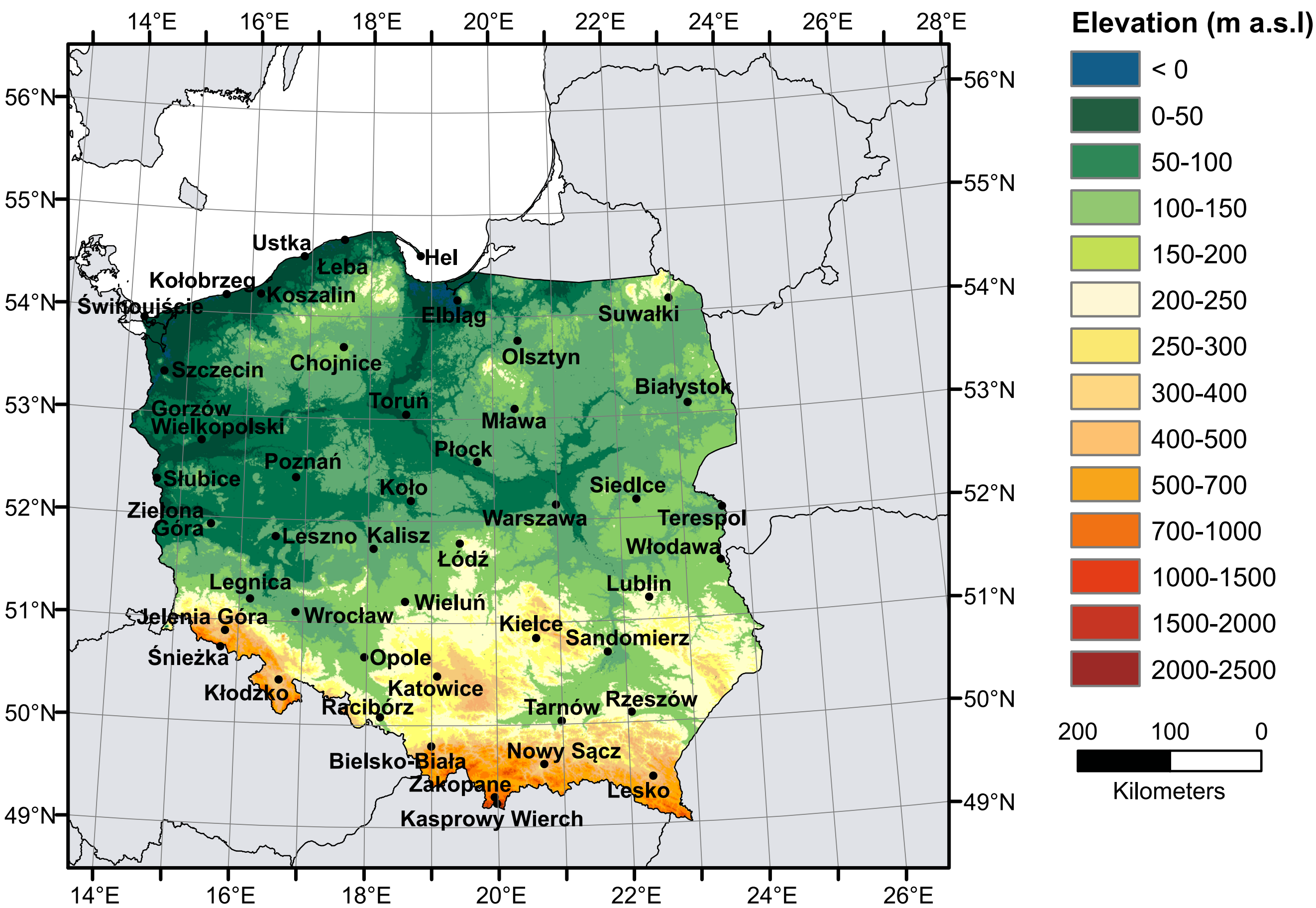


Fig. 1 Location of stations with precipitation data used in this study

– Seasonal (Apr.–Sept.) maximum number of consecutive dry days CDD (longest period with daily precipitation below 1 mm)

First, the absolute maximum values of three analysed extreme indices for the whole available period were indicated. In most of cases, this was for the period 1951–2015, only for few stations the initial year was different: 1952 for Rzeszów, 1954 for Nowy Sącz and Tarnów, 1955 for Terespol and Lesko, 1958 for Leszno and 1961 for Mława. The time series of data for Elbląg terminated on 31.03.2013 because after this date, the station was relocated to another place, about 10 km apart (https://meteomodel.pl/BLOG/stacje-meteo-elblag-milejewo/). The maximum 24-h, maximum 5-day and maximum monthly precipitation totals and their dates of observation were identified. Such an overview gives a preliminary evidence whether date of maximum values has moved in the studying period from earlier, cooler, decades to later, warmer, decades. Additionally, this information indicated how "extreme" precipitation can be on particular meteorological stations (Ustrnul and Czekierda 2009).

To examine changes in extreme precipitation in Poland, data from all meteorological stations were examined in a common time interval, from 1961 to 2015. In this research, percentage changes for stations are presented for the last 25 years: 1991–2015 in comparison to the climate standard normal period 1961–1990. Additionally, the annual mean percentage changes for all stations of extreme indices were calculated and these aggregated data have been examined in order to detect changes. For two studied intervals: 1961–1990 and 1991–2015, statistical values were calculated and presented as box plots.

Statistical significance level has been examined by non-parametric Mann-Kendall test with the help of the Hydrospect software 2.0 (Radziejewski and Kundzewicz 2000). This test, particularly useful for detection of a trend in time series, is based on the *tau* statistic introduced by Kendall (Kendall 1938), which was adapted by Mann to time series analysis (Salas 1992; WCAP-3 1998). This method makes no assumptions about the distribution of the variable, so it is better suited for such climate indices. The raw data have been pre-processed and ranks were calculated. The level, labelled as significant, has been set as equal to or less than 0.1.

Table 1 shows a list of 46 stations for Poland and mean value of examined indices for 1961–1990 time interval. The mean values of maximum 24-h precipitation totals for winter half-year ranged from 15.3 mm (Mława) to 46.4 mm (high mountain station—Kasprowy Wierch), while most values did

Table 1 List of meteorological stations in Poland with precipitation data used and mean characteristics of extreme indices for 1961–1990. The absolutely highest values are marked in bold and the lowest in italic

Station	Elevation H (m a.s.l.)	Mean 1961–1990						
		Max 24-h P for Oct.–March (mm)	Max 24-h P for Apr.–Sept. (mm)	Max 5-day P (mm)	Monthly Max P (mm)	No. of days with $P \geq 10$ mm	No. of days with $P \geq 20$ mm	CDD for Apr.–Sept. (days)
Białystok	148	17.1	36.4	60.7	117.9	13.1	2.7	17.5
Bielsko-Biała	398	24.7	62.2	111.3	199.7	28.8	9.6	13.0
Chojnice	172	17.8	35.1	56.4	108.6	12.0	2.6	17.8
Elbląg	38	18.8	38.3	66.7	126.5	16.3	3.7	17.0
Gorzów Wielkopolski	72	18.9	36.2	58.4	105.2	11.6	2.6	18.1
Hel	1	18.0	36.0	57.8	111.6	13.3	2.9	19.1
Jelenia Góra	342	20.1	43.0	79.5	144.3	17.1	5.1	14.7
Kalisz	140	17.0	32.6	53.6	102.8	11.3	2.6	18.1
Kasprowy Wierch	1991	**46.4**	**81.5**	**169.4**	**308.9**	**58.1**	**22.8**	*10.2*
Katowice	317	17.8	39.9	68.3	126.8	19.4	5.0	15.2
Kielce-Suków	268	16.7	36.9	64.9	121.1	14.5	3.3	16.4
Kłodzko	316	17.8	42.4	71.0	132.7	14.8	4.9	16.3
Koło	116	17.0	34.1	56.7	107.2	11.3	3.0	17.6
Kołobrzeg	3	18.8	34.8	61.5	118.1	15.7	3.6	19.0
Koszalin	33	21.5	44.0	71.8	134.7	17.1	4.4	17.6
Legnica	122	17.8	39.7	69.1	121.1	12.7	4.0	17.6
Lesko	386	23.1	41.7	79.4	160.1	23.0	6.5	13.8
Leszno	91	17.6	37.9	60.5	109.8	11.8	3.4	17.7
Lublin	238	16.2	36.3	61.3	106.6	12.9	3.5	16.5
Łeba	2	20.8	37.3	66.3	127.7	14.7	3.2	18.8
Łódź	187	16.8	35.3	59.1	117.3	13.3	3.4	15.8
Mława	147	*15.3*	33.5	52.8	104.9	12.6	3.0	17.5
Nowy Sącz	292	19.9	44.4	80.9	143.8	19.8	5.9	15.2
Olsztyn	133	18.4	35.9	58.2	117.0	15.1	3.5	16.7
Opole	176	17.6	38.1	64.8	123.4	15.6	4.1	16.5
Płock	106	17.2	35.8	56.6	109.0	12.1	2.7	17.7
Poznań	86	16.7	30.6	54.1	101.3	*11.2*	2.3	18.4
Racibórz	190	15.9	33.2	64.7	123.6	17.8	4.9	15.6
Rzeszów	200	17.7	37.9	67.7	124.7	15.8	4.2	15.3
Sandomierz	217	16.9	37.5	64.5	115.6	13.6	3.9	17.2
Siedlce	146	16.3	36.6	59.8	104.2	12.3	3.3	17.6
Słubice	21	17.5	39.1	62.7	100.2	11.5	2.8	19.1
Suwałki	184	16.5	32.3	54.7	116.5	13.9	3.0	17.4
Szczecin-Dąbie	1	19.8	*27.1*	*48.0*	94.6	11.9	*1.5*	**19.6**
Śnieżka	1603	32.2	66.3	122.2	217.4	35.0	10.8	11.9
Świnoujście	6	17.6	30.8	53.6	*94.5*	11.6	1.8	17.7
Tarnów	209	19.0	49.4	86.2	143.1	19.0	5.6	13.9
Terespol	133	15.7	35.3	56.7	101.5	12.0	2.5	17.2
Toruń	69	15.9	36.9	59.7	107.8	11.4	3.2	17.3
Ustka	6	22.8	34.9	64.6	137.9	17.4	3.8	18.1
Warszawa	106	16.0	32.7	58.3	106.8	12.3	3.0	18.0
Wieluń	195	18.1	35.5	60.9	113.4	14.7	3.3	16.5
Włodawa	175	16.8	34.3	57.7	101.5	12.7	2.7	16.7

Table 1 (continued)

Station	Elevation H (m a.s.l.)	Mean 1961–1990						
		Max 24-h P for Oct.–March (mm)	Max 24-h P for Apr.–Sept. (mm)	Max 5-day P (mm)	Monthly Max P (mm)	No. of days with $P \geq 10$ mm	No. of days with $P \geq 20$ mm	CDD for Apr.–Sept. (days)
Wrocław	120	18.5	39.2	68.1	127.1	15.1	4.1	16.6
Zakopane	857	28.8	65.5	126.2	229.5	33.6	11.3	11.1
Zielona Góra	180	18.5	36.3	64.5	113.5	13.2	3.0	18.2

not exceed 20 mm. Values of maximum 24-h precipitation for summer half-year were between 27.1 mm (Szczecin-Dąbie) and 81.5 mm (Kasprowy Wierch), and most values did not exceed 40 mm. Similarly, values of maximum 5-day precipitation were the lowest in Szczecin-Dąbie (48 mm) and the highest at Kasprowy Wierch (169.4 mm) and most values were below 80 mm.

Monthly maximum precipitation ranged from 94.5 mm (Świnoujście) to 308.9 mm (Kasprowy Wierch), and only eight values were above 140 mm. The lowest numbers of days with intense (≥ 10 mm/day) and very intense precipitation (≥ 20 mm/day) were recorded in Poznań and in Szczecin-Dąbie (respectively: 11.2 and 1.5 days) while the highest numbers were observed at Kasprowy Wierch (58.1 and 22.8 days). At most stations, the numbers of days with intense precipitation were less than 20 and the numbers of days with very intense precipitation—less than five. The mean longest drought period occurred in Szczecin-Dąbie (19.6 days) and the shortest at Kasprowy Wierch (10.2 days). Most values exceeded 15 days.

3 Results

3.1 Observed maximum extreme precipitation

Table 2 presents maximum values of extreme indices related to the precipitation totals over intervals of 24 h, 5 days and 1 month for the whole research period and their dates of occurrence. Most maximum daily precipitation records occurred in 2011 (five records), then in 2001 (four records) and in 2010 (three records). In 2001 and 2010, major floods were recorded in Poland. Comparison of two intervals: 1961–1990 and 1991–2015, shows that records at 20 stations occurred before 1991 (colder period) and at 27 stations after 1990 (warmer period, what was noted globally—cf. IPCC 2013 and nationally—cf. Kożuchowski and Żmudzka 2001; Graczyk et al. 2017; bold in Table 2). The highest value in this dataset occurred at a mountainous station, Kasprowy Wierch (232 mm on 30 June 1973), while at a lower located station—162.7 mm in Bielsko-Biała (16 May 2010). However, the highest maximum daily precipitation record in Poland, 300 mm, was observed at Hala Gąsienicowa (1520 m a.s.l.) in the Tatra Mts. on 30 June 1973. Even higher 24-h precipitation totals were observed in neighbour countries, near to Polish border during large floods: 312 mm from 12 August 2002, 6 a.m. to 13 August 2002, 6 a.m. in Zinnwald-Georgenfeld (Saxony, Germany), but this record observed from 12 August 2002, 3 a.m. to 13 August 2002, 3 a.m. reached 352.7 mm. A little less, 345.1 mm, was recorded on 30 July 1897 at the Nová Louka station (780 m a.s.l.) in the Jizerské Mts., Czech Republic, while also at Śnieżka, 24-h precipitation

Table 2 Values of maximum 24-h, maximum 5-day and maximum monthly precipitation totals for the whole available research period with their date of occurrence

Stations	Available period	Extremes for whole available period					
		Max 24-h P (mm)	Date of max 24-h P	Max 5-day P (mm)	Date of max 5-day P (last day)	Monthly max P (mm)	Date of monthly max P
Białystok	1951–2015	90.6	1985-06-26	144.7	1972-08-04	234.3	Aug '72
Bielsko-Biała	1951–2015	162.7	**2010-05-16**	346.6	**2010-05-18**	511.5	**May '10**
Chojnice	1951–2015	84.6	1974-07-19	108.3	1980-07-12	198.4	Jul '80
Elbląg	1951–31.03.2014	83.8	**1992-09-06**	129.6	1960-07-28	252.9	Jul '60
Gorzów Wielkopolski	1951–2015	77.4	1977-08-08	111.3	1977-08-11	194.7	Jul '57
Hel	1951–2015	77.1	**2010-09-27**	129.4	**1995-09-02**	176.1	Aug '78
Jelenia Góra	1951–2015	119.3	**2001-07-20**	186.7	1981-07-21	409.6	**Jul '97**
Kalisz	1951–2015	86.8	1985-08-08	176.8	1985-08-10	227.8	Aug '85
Kasprowy Wierch	1951–2015	232.0	1973-06-30	388.7	1980-07-26	651.4	**Jul '01**
Katowice	1951–2015	81.6	1972-04-22	163.6	**1997-07-08**	323.4	**Jul '97**
Kielce	1951–2015	155.2	**2001-07-24**	211.4	**2001-07-24**	294.2	**Jul '01**
Kłodzko	1951–2015	101.2	**2009-06-26**	151.6	**2009-06-26**	246.8	**Jul '97**
Koło	1951–2015	79.1	1956-08-23	124.7	1985-08-10	207.9	**Aug '06**
Kołobrzeg	1951–2015	85.2	**1996-07-09**	146.5	**1996-07-09**	208.5	**Aug '06**
Koszalin	1951–2015	101.3	**1991-08-18**	136.3	**1996-07-09**	236.1	**Jun '91**
Legnica	1951–2015	85.9	**2001-07-20**	158.5	1964-08-13	263.1	**Jul '01**
Lesko	1955–2015	80.7	**1996-09-06**	160.7	**2004-07-30**	298.3	Jul '80
Leszno	1958–2015	79.2	**1997-08-29**	117.8	1965-07-17	202.6	Jul '81
Lublin	1951–2015	90.0	**2007-09-06**	132.6	**2007-09-08**	239.9	**May '14**
Łeba	1951–2015	141.0	1988-07-24	145.0	1988-07-26	224.4	Jul '88
Łódź	1951–2015	99.8	1980-06-15	165.2	**1997-07-08**	258.1	Jul '57
Mława	1961–2015	78.5	**1995-08-31**	118.0	**1999-06-12**	176.0	**Jun '99**
Nowy Sącz	1954–2015	107.2	1958-06-29	211.5	**2001-07-27**	317.0	**Jul '01**
Olsztyn	1951–2015	98.9	**1992-09-06**	127.0	**1992-09-09**	222.2	**Jul '11**
Opole	1951–2015	99.0	**1998-07-27**	166.2	**1997-07-08**	270.3	**Jul '97**
Płock	1951–2015	83.8	1962-05-14	129.2	1960-07-27	216.3	Jul '60
Poznań	1951–2015	85.7	**1996-07-08**	126.8	**1996-07-12**	200.7	Jul '57
Racibórz	1951–2015	92.9	**1997-07-07**	244.3	**1997-07-08**	352.3	**Jul '97**
Rzeszów	1952–2015	65.2	**2010-06-03**	136.5	**2004-07-30**	233.8	**Jul '11**
Sandomierz	1951–2015	140.5	**2011-07-26**	176.8	**2011-07-30**	382.9	**Jul '11**
Siedlce	1951–2015	81.0	**2006-08-11**	120.5	**2010-09-03**	255.5	**Aug '06**
Słubice	1951–2015	132.5	1978-08-08	155.0	1978-08-10	249.7	**Aug '10**
Suwałki	1951–2015	66.8	**2011-08-07**	113.2	**2007-07-07**	203.2	**Jul '07**
Szczecin-Dąbie	1951–2015	76.6	**2011-07-28**	121.8	**2011-07-31**	255.2	**Jul '11**
Śnieżka	1951–2015	149.7	1977-07-31	350.0	1977-08-04	430.6	Aug '77
Świnoujście	1951–2015	74.3	1978-08-08	105.8	**1996-07-09**	184.6	**Jul '11**
Tarnów	1954–2015	110.8	1970-07-18	230.1	1970-07-19	294.4	Jul '70
Terespol	1955–2015	81.9	1975-05-19	107.8	**2006-08-14**	249.1	**Aug '06**
Toruń	1951–2015	101.6	1980-06-15	162.9	1980-06-18	298.6	Jun '80
Ustka	1951–2015	94.2	1988-07-24	137.6	1954-07-14	283.1	Oct '74
Warszawa	1951–2015	75.8	**2011-07-31**	118.8	**2002-08-06**	295.0	**Jul '11**
Wieluń	1951–2015	78.7	**1997-07-06**	153.9	**1997-07-07**	336.6	**Jul '97**
Włodawa	1951–2015	91.3	**2009-06-25**	122.0	**2006-08-14**	273.8	**Aug '06**
Wrocław	1951–2015	74.4	**2001-07-20**	164.9	**2006-08-08**	250.8	Jul '80
Zakopane	1951–2015	138.7	1970-07-18; 1973-06-30	235.9	1972-08-22	439.2	**Jul '01**
Zielona Góra	1951–2015	89.0	**2011-07-21**	147.3	1964-08-13	219.3	Jul '81

total was very high—239 mm (Cebulak 1992; Munzar and Ondraček 2010; Kundzewicz 2011).

Maximum 5-day precipitation total in the studied period was observed most often in July 1997 (five records), then in July 1996 (four records) and three cases during June and July 1980 and during August 2006. The highest precipitation totals were at two high mountain stations: Kasprowy Wierch (388.7 mm on 22–26 July 1980) and Śnieżka (350 mm on 31 July–4 August 1977). There were 19 maximum 5-day precipitation totals recorded before 1991 and 27 after 1990 (bold).

Maximum monthly precipitation sums in the studied interval occurred most often in July 1997 (month with a dramatic flood) and July 2011 (six records each), and then five records in July 2001 (flood month) and in August 2006 (very wet August after very dry July). The highest value of maximum monthly precipitation sum in this dataset was observed in the flood month—July 2001 at Kasprowy Wierch (654.1 mm)

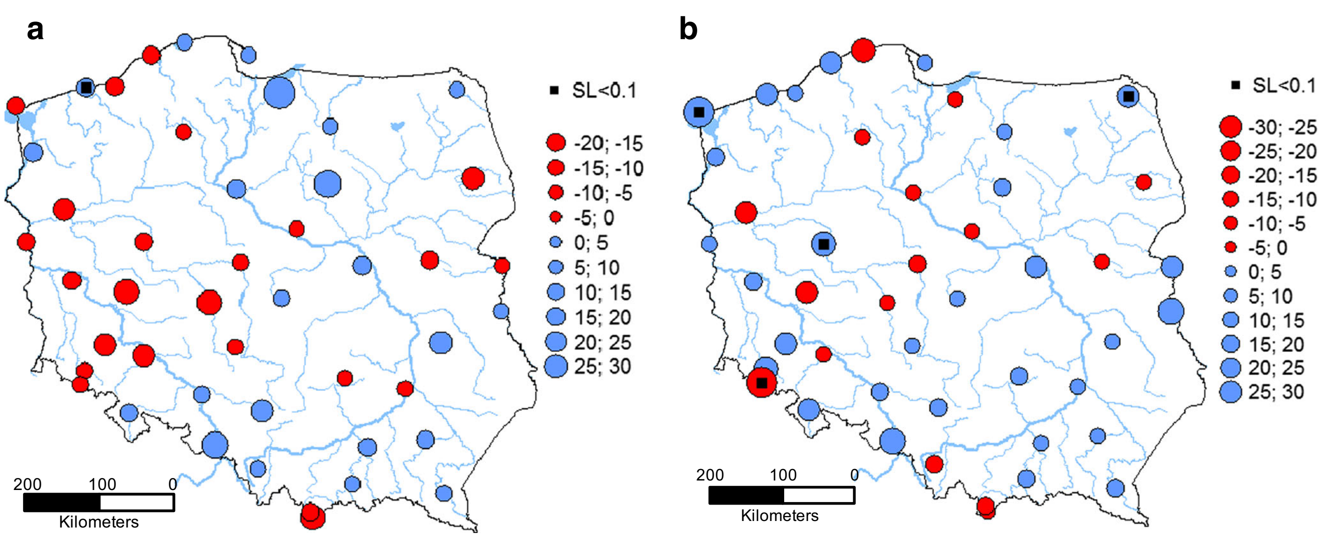


Fig. 2 Percentage change of daily maximum precipitation for the winter half-year (**a**) and the summer half-year (**b**). Mean for the 1991–2015 interval is related to the mean for 1961–1990. Black squares show statistically significant change at the level of 0.1

and 511.5 mm at a lower-situated station Bielsko-Biała (in May 2010; also flood month). Also, there were less record values of maximum monthly precipitation total before 1991 (18) and more after 1990 (28; bold).

3.2 Spatial changes in extreme precipitation

Figure 2a presents percentage change of daily maximum precipitation for the winter half-year and the summer half-year for the interval 1991–2015, related to 1961–1990. Maximum daily precipitation for winter half-year decreases in the west of Poland and increases in the south (except for Kasprowy Wierch and Zakopane, with negative changes) and north, with highest increases, above + 25%, in Elbląg. However, only increase in Kołobrzeg is statistically significant.

Decreases of the seasonal 24-h precipitation for the warm period, presented in Fig. 2b, are lower than for the cold period (the largest decrease is for Śnieżka − 28%, and this change is statistically significant). Daily maximum precipitation increases in the east-southern part of Poland and on the coast; the most for the stations: Świnoujście (+ 28%, statistically significant change), Racibórz (+ 23%), Włodawa (+ 22%), Poznań (+ 19%, also statistically significant) and Jelenia Góra (+ 17%).

Figure 3 shows changes of precipitation total for a longer period, that is maximum 5-day and monthly precipitation total. The maximum 5-day precipitation totals increase (see Fig. 3a) for 35 stations out of 46, the most for Włodawa, Nowy Sącz, Świnoujście, Poznań and Mława (all changes above + 15%), what is visible especially in

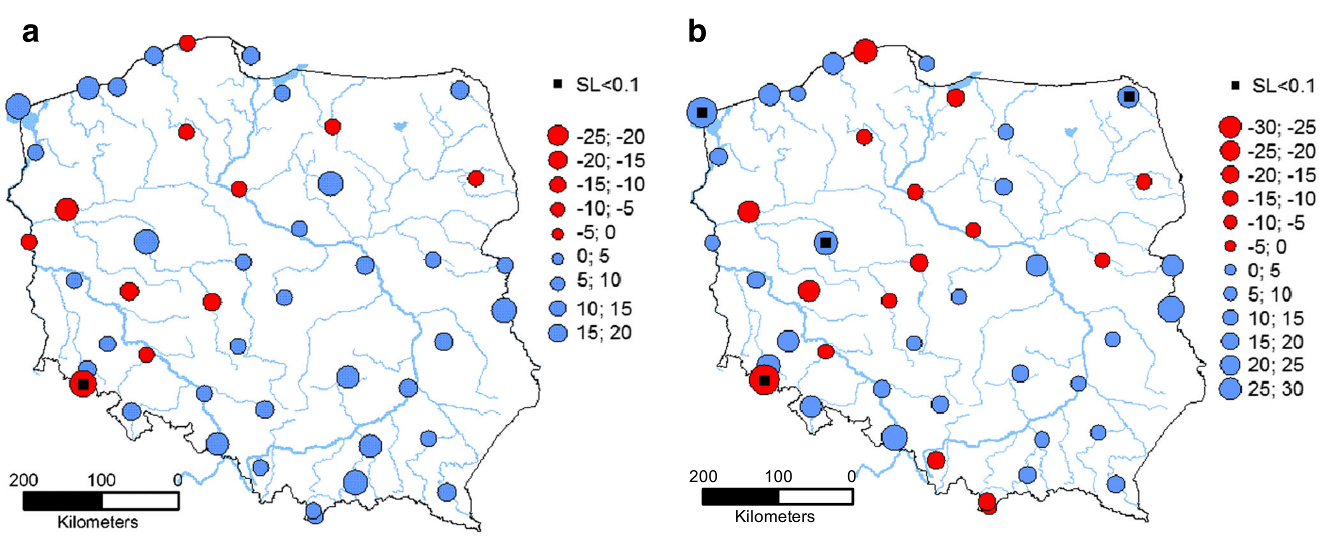


Fig. 3 Percentage change of maximum 5-day precipitation total (**a**) and maximum monthly precipitation total (**b**). Mean for the 1991–2015 interval is related to the mean for 1961–1990. Black squares show statistically significant change at the level of 0.1

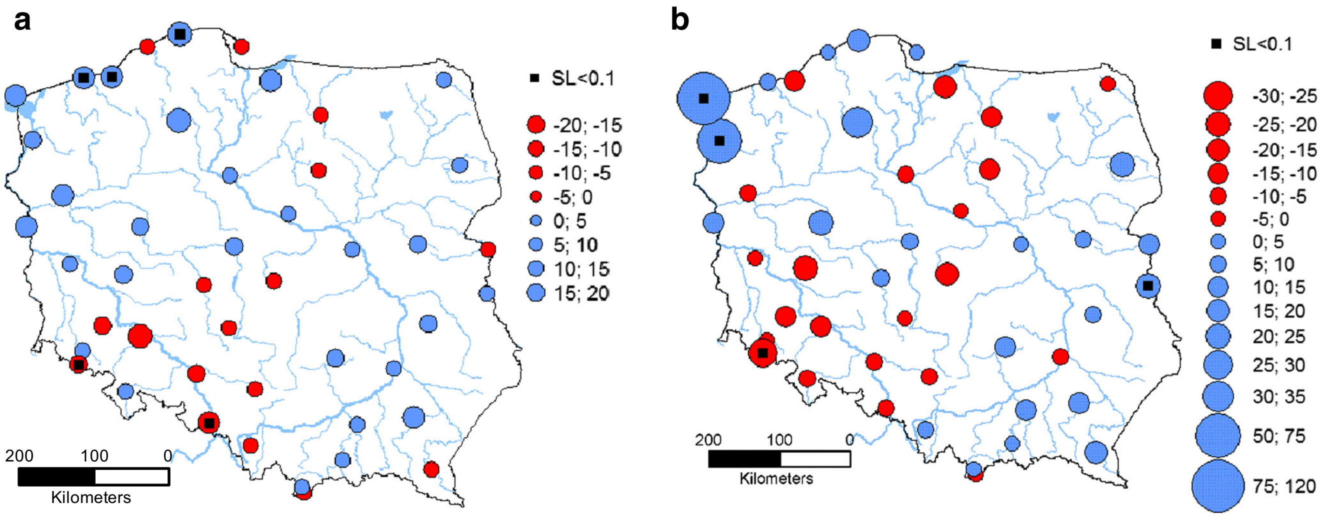


Fig. 4 Percentage change of the number of days with intense precipitation (equal to or greater than 10 mm) (**a**) and with very intense precipitation (equal to or greater than 20 mm) (**b**). Mean for the 1991–2015 interval is related to the mean for 1961–1990. Black squares show statistically significant change at the level of 0.1

southern and eastern parts of Poland and on the coast. The highest decrease, statistically significant, has been noted at Śnieżka (− 21%).

Maximum monthly precipitation sum exhibits similar spatial patterns of changes as maximum 5-day precipitation total (Fig. 3b), but there are more statistically significant changes. This index decreases only for 10 stations, and these changes are small, with the largest one, statistically significant, for Śnieżka (− 9%). For other stations, one can observe increases over a large area of Poland, with the highest ones in Włodawa (+ 23%; statistically significant), Słubice (+ 22%; statistically significant), Lublin (+ 21%; statistically significant), as well as in Świnoujście, Tarnów, Szczecin and Siedlce (in all four cases, increases are statistically significant) and Lesko (all changes above + 15%).

Changes in the number of days with intense precipitation (equal to or greater than 10 mm) and in the number of days with very intense precipitation (equal to or greater than 20 mm) are presented in Fig. 4. Number of days with daily precipitation equal to or greater than 10 mm (Fig. 4a) increases especially in the north-western part of Poland with three statistically significant changes (Kołobrzeg, Koszalin, Łeba), then a bit less in the central and south-eastern parts of the country. Less days with intense precipitation have been noted on south-western part of the country with two statistically significant decreases for Śnieżka and Racibórz.

Changes in the number of days with very intense precipitation (equal to or greater than 20 mm; Fig. 4b) have a similar spatial distribution, but are greater. Increases are especially visible for Świnoujście (+ 116%, statistically significant), Szczecin (+ 70%, statistically significant), Chojnice (+ 34%), Białystok (+ 24%) and Włodawa (+ 24%, also statistically significant) (Fig. 4b). Decreases have been observed especially on the south-western part of Poland with a statistically significant change at Śnieżka, and then in the north-central part of the country.

One drought index—maximum dry period with daily precipitation below 1 mm during the summer half-year, from April to September—is getting longer (Fig. 5). Increases (statistically significant in three cases) are visible for 36 stations out of 46, the most for Lublin (+ 19%, statistically significant), Chojnice (+ 18%) and Łeba (+ 17%). For Kłodzko, consecutive dry days, CDD, decreased strongest − 11%.

Table 3 presents synthesis of results for particular indices of extreme precipitation in Poland. For nearly all indices, maximum increase is higher than maximum decrease, except for

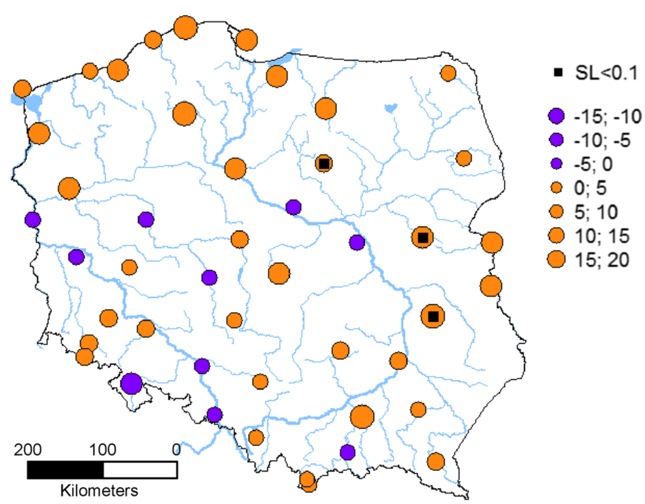


Fig. 5 Percentage change of number of consecutive dry days, CDD, (the longest dry period with daily precipitation below 1 mm) during the summer half-year, from April to September. Mean for the 1991–2015 interval is related to the mean for 1961–1990. Black squares show statistically significant change at the level of 0.1

Table 3 Maximum and mean relative changes (%) for indices and the number of statistically significant changes (bold in brackets)

Index	Max decreasing change (%)	Mean change (%)	Max increasing change (%)
Max 24-h P for Oct.–March	− 19.2 (**0**)	− 0.2	26.4 (**1**)
Max 24-h P for Apr.–Sept.	− 28.5 (**1**)	3.3	28.8 (**3**)
Max 5-day P	− 21.9 (**1**)	4.0	18.6 (**0**)
Monthly max P	− 8.7 (**1**)	7.1	23.1 (**8**)
No. of days with $P \geq 10$ mm	− 16.1 (**2**)	2.6	16.2 (**3**)
No. of days with $P \geq 20$ mm	− 28.0 (**1**)	4.9	116.5 (**3**)
CDD for Apr.–Sept.	− 11.2 (**0**)	6.2	19.0 (**3**)

maximum 5-day precipitation total. Similarly, for nearly all indices, the mean change is positive with except of maximum 24-h precipitation for winter half-year. The highest mean increase was observed for maximum monthly precipitation total, and maximum increase was the largest for number of days with very intense precipitation (≥ 20 mm/day). Statistically significant increases are much more common (21; the highest number for monthly maximum precipitation total, 8) than decreases (6).

3.3 Changes in extreme precipitation for aggregated data from all 46 stations

Figure 6 presents long-term variability of mean percentage changes of extreme indices for all analysed 46 stations for 1961–2015, relative to the reference interval 1961–1990 (left column) and box plots for two studied intervals: colder 1961–1990 and warmer 1991–2015 statistical values: min–max, 25–75% and median (right column). Trends for all these indices are statistically insignificant. For five of them, trends are increasing; for one (maximum 24-h precipitation total for winter half-year), the trend is decreasing, and the number of days with intense precipitation (equal to or greater than 10 mm/day) does not show any changes.

The highest increase of maximum 24-h precipitation total for the summer half-year (Fig. 6b1) has been noted in 2010 (increase by nearly 40% relative to the mean 1961–1990) and then in 1997 (increase by nearly 30%). Box plots presented in Fig. 6b2 show minimum, median, 75 percentile and maximum of this index higher for the last 25 years in comparison with period 1961–1990.

Mean change of maximum 5-day precipitation total relative to the mean for the reference interval, 1961–1990, (Fig. 6c1) was the highest in 1997 (increase by nearly 50%), the second one occurred in 2010 (increase by above 40%). Values of 25 percentile, median, 75 percentile and also maximum (Fig. 6c2) were higher for the second, warmer period 1991–2015.

The highest percentage changes for these extreme indices occurred in 2 years with large floods, i.e. in 1997 and 2010, except for the maximum 24-h precipitation total for winter half-year. For this index, the highest value was recorded in 1975 (Fig. 6a1), where increase was by 70% relative to the mean for 1961–1990, as a result of a very wet October 1974 with a high sum of daily precipitation at many stations. For Ustka, monthly precipitation total for October 1974 was the highest (283.1 mm) for all available data from 1951 to 2015 (see Table 2). Comparison of two periods: 1961–1990 and 1991–2015 (Fig. 6a2), revealed that during warmer period minimum, 25 percentile and median were higher than for colder period, while 75 percentile and maximum were lower.

Figure 6d1 shows mean change of maximum monthly precipitation total. In 1997, the change was the highest (increase by 60%), also, another high value was recorded in 2011 (increase by nearly 50%) and a bit smaller in 2010. During the second warmer interval 1991–2015, all statistics presented in Fig. 6d2 were higher than for the first, colder period 1961–1990.

Number of days with precipitation equal to or greater than 10 mm was the highest in 2010 (increase by nearly 50%), and the second greatest value, smaller by 10%, was noted in 1970 (Fig. 6e1). Values of minimum, 25th percentile, median and maximum were higher for 1991–2015 (Fig. 6e2).

For the number of days with very intense precipitation (equal to or greater than 20 mm), mean percentage change was the highest out of all indices (Fig. 6f1). Increase in 2010 reached nearly 90%, relative to the mean for 1961–1990. Second highest record was noted in 1966 and was much smaller—increase by above 40%. Box plots in Fig. 6f2 show that the median and maximum values of this index are higher for the last 25 years than for the earlier period, 1961–1990.

Figure 6g1 presents mean percentage change of the drought index, CDD. The longest period with precipitation less than 1 mm occurred in 2009 (increase by above 40%), as a result of dry September. The second longest period has been noted in 2000, when dry days occurred at the turn of April and May (increase by nearly 40%). Also, very high temperatures were observed in April 2000. All statistics, (Fig. 6g2), except minimum, were higher in the recent period, 1991–2015, than in the earlier period.

4 Discussion

Since the topical area of observed changes in intense precipitation in Europe is of much general interest, there has been a plethora of related publications. Zolina (2012) noted that typically (but not ubiquitously), intense precipitation has increased in Europe and has become more extreme during the last decades. Moreover, precipitation structure has changed in the sense that short and isolated rain events have been regrouped into prolonged wet spells. At the same time, the duration of dry spells has also increased over the continent, showing that this effect is not modulated by the changing number of wet days but rather associated with the regrouping of rainy events.

Van den Besselaar et al. (2013) studied maximum 24-h and 5-day precipitation totals with return period of 5, 10 and 20 years in Europe (without the area of Poland). Analysing the relative changes between 1951–1970 and 1991–2010, they found that all return periods decreased especially in Northern Europe in spring and winter and changes for the 20-year return period were larger than those for the 5-year, that is rare events are getting more common.

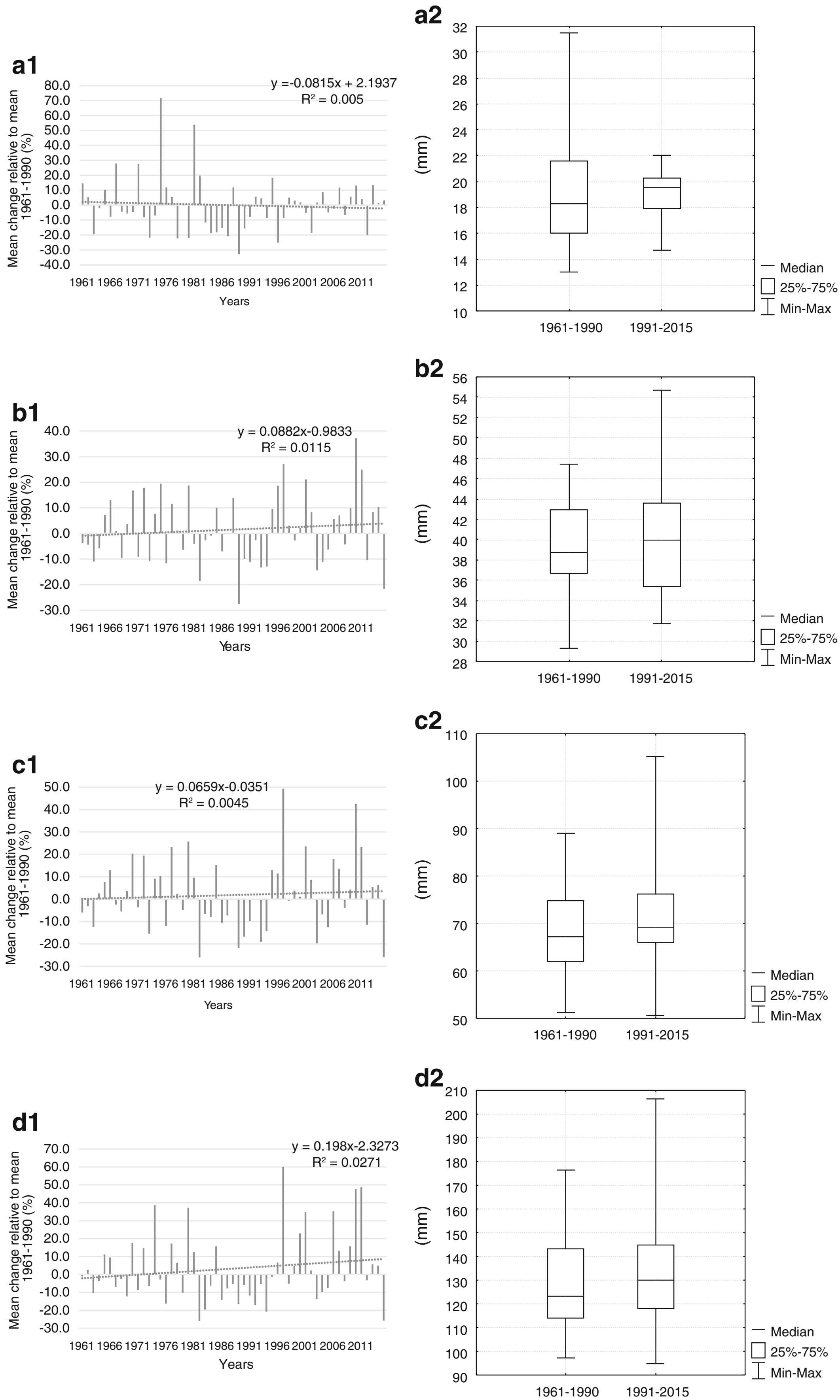
There have been many recent publications showing that some regions in Europe and the Mediterranean show irregular trends in extreme precipitations. According to Hartmann et al. (2013), there are increases in extreme precipitation in more regions of Europe than decreases, but an assessment of changes is hampered by regional and seasonal variations.

Regional studies show that changes in extreme precipitation in Europe vary, depending on the regions, datasets used and calculated indices. Karagiannidis et al. (2012) examined trends in extreme precipitation for 1958–2000, excluding summer time. They found decreasing trends in Southern Europe (Iberian Peninsula and Greece), no significant trend on the southern side of the Alps (northern Italy) and a statistically significant positive trend in Switzerland (on the northern side of Alps). Piccarreta et al. (2013) studied trends of the annual and seasonal greatest 3- and 5-day precipitation totals for the Basilicata region (Southern Italy) and revealed decreasing trends over the 1951–2010, but strong increases in the last 30-year period, 1981–2010. As well as intensity of precipitation shows a general positive trend, mainly due to the upward trend for spring and decrease of precipitation total during autumn and winter. Also, our findings agree with the results that for last the 25 years, 1991–2015, there was an increase in maximum 5-day precipitation total. Arnone et al. (2013) examined extreme annual daily and sub-daily events for Sicily. The analysis showed an increasing trend for precipitation total with shorter durations, especially for 1-h duration and, in contrast, a decreased trend for 24-h precipitation total. In turn, annual precipitation total decreased significantly, mainly due to lower precipitation during the winter season. Scherrer et al. (2016) studied intensity and frequency of heavy precipitation in Switzerland for a long period 1901–2014/2015. The analysis showed that, for a large number of meteorological stations, extreme precipitation is getting more frequent and more intense. On average, the maximum 24-h precipitation total increased by 10.4% per 100 years; the increase in the number of days exceeding the 99th percentile was even higher—on average by + 26.5% per 100 years. Kysely (2009) identified increasing trends of heavy precipitation in the western part of Czech Republic for 1961–2005 in winter, trends prevailed also in summer, but they were insignificant. Martinkova and Hanel (2016) also revealed increasing trends in extreme precipitation for 1966–2006 in the western region of Czech Republic. They also found that changes in extreme precipitation in the western region are greater than in the eastern region of the Czech Republic. Hattermann et al. (2012) examined changes of intense precipitation in Germany (a neighbour country of Poland), using many indicators, such as percentiles of 24-h precipitation, maximum 24-h and 5-day precipitation totals, contribution of heavy precipitation events to the total precipitation, as well as the number of days in a year, with precipitation above pre-defined thresholds. They considered annual values, as well as seasonal (summer half-year and winter half-year, also winter and summer) values. They found that in winters, the signal was strong and increasing trends prevailed. These findings partly support our results. In Poland, our study revealed a not so clear signal for 24-h precipitation total: there was a decreasing trend for winter half-year and a weak increasing trend for summer half-year.

Bartholy and Pongrácz (2007) examined extreme precipitation indices in the Carpathian Basin for two periods: 1946–2001 and 1976–2001. Most indices showed positive trends, mainly in the last 26 years, especially for the number of very intense precipitation days (≥ 20 mm/day), and this is in agreement with our findings.

Yet, the general picture of changes is complex. Lorenc and Olecka (2006) showed an increasing trend in the number of days with intense precipitation (≥ 10 mm/day) on a large area of Poland for the period of 1971–2002. Also, the number of days with very intense precipitation (≥ 20 mm/day) increased, like in our study. In turn, Łupikasza et al. (2011) showed dominating increasing trends in extreme precipitation in central-eastern Germany and mostly decreasing trends in southern Poland. Also, studies with larger number of stations in Poland for 1951–2006 revealed decreasing trends in extreme precipitation indices, which dominated in both the warm

Fig. 6 Mean percentage change of extreme indices for all 46 analysed stations relative to the 1961–1990 mean: long-term variability (left column: **a1**–**g1**) and box plots with statistics (right column: **a2**–**g2**) of indices: daily maximum precipitation total for the winter half-year (a), daily maximum precipitation total for the summer half-year (b), maximum 5-day precipitation total (c), maximum monthly precipitation total (d), number of days with intense precipitation (equal to or greater than 10 mm) (e), number of days with very intense precipitation (equal to or greater than 20 mm) (f) and CDD for the summer half-year (g)


a1
y =-0.0815x + 2.1937
R² = 0.005
Mean change relative to mean 1961-1990 (%)
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
-10.0
-20.0
-30.0
-40.0
1961 1966 1971 1976 1981 1986 1991 1996 2001 2006 2011
Years
a2
(mm)
32
30
28
26
24
22
20
18
16
14
12
10
1961-1990
1991-2015
Median
25%-75%
Min-Max
b1
y = 0.0882x-0.9833
R² = 0.0115
Mean change relative to mean 1961-1990 (%)
40.0
30.0
20.0
10.0
0.0
-10.0
-20.0
-30.0
1961 1966 1971 1976 1981 1986 1991 1996 2001 2006 2011
Years
b2
(mm)
56
54
52
50
48
46
44
42
40
38
36
34
32
30
28
1961-1990
1991-2015
Median
25%-75%
Min-Max
c1
y = 0.0659x-0.0351
R² = 0.0045
Mean change relative to mean 1961-1990 (%)
50.0
40.0
30.0
20.0
10.0
0.0
-10.0
-20.0
-30.0
1961 1966 1971 1976 1981 1986 1991 1996 2001 2006 2011
Years
c2
(mm)
110
100
90
80
70
60
50
1961-1990
1991-2015
Median
25%-75%
Min-Max
d1
y = 0.198x-2.3273
R² = 0.0271
Mean change relative to mean 1961-1990 (%)
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
-10.0
-20.0
-30.0
1961 1966 1971 1976 1981 1986 1991 1996 2001 2006 2011
Years
d2
(mm)
210
200
190
180
170
160
150
140
130
120
110
100
90
1961-1990
1991-2015
Median
25%-75%
Min-Max

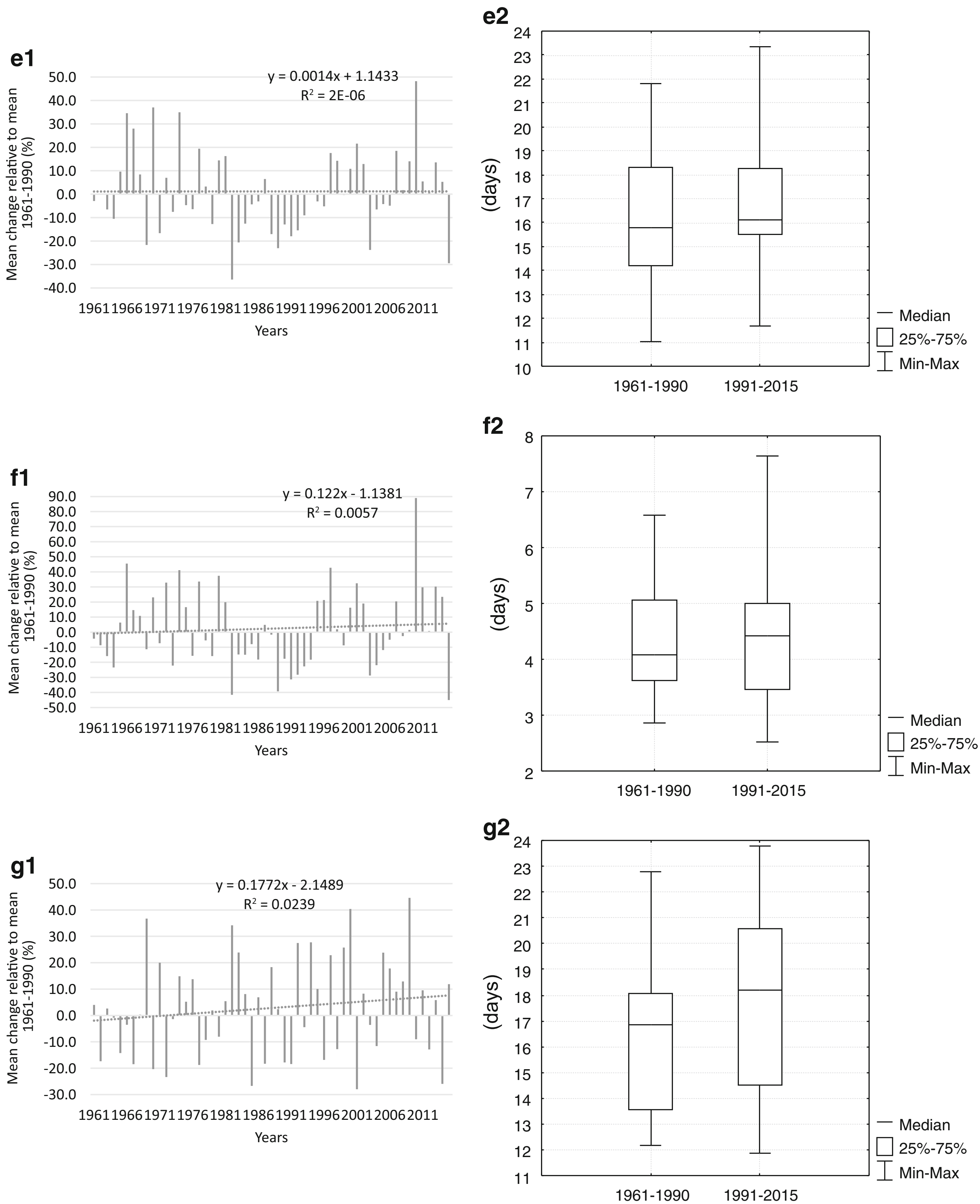


Fig. 6 (continued)

and cold half-year and during the seasons (Łupikasza 2010). Results of this study, based on long time series of records (1961–2015) differ from other works that did not use recent data (records up to 2006). However, in this present study, extending to 2015, the mean highest values of indices in Poland have occurred during the last 20 years, especially during two large floods: 1997 and 2010, and their values were much higher than the others. Also, Piccarreta et al. (2013) pointed out that although the wet periods decreased in 1951–2010, a strong increase has been observed in the last 10 years.

Observed climate warming has a potential impact on increase of intense precipitation. Hattermann et al. (2012) showed that the distribution of intensity of daily precipitation depends on temperature (mean daily temperature on the day of precipitation). The percentage of low-intensity precipitation for the lower temperature range was found to be higher than for higher temperature range, while, in contrast, percentage of high-intensity precipitation increases with temperature. The warmer it gets, the more precipitation comes in heavy rainfall events and the smaller the proportion of the precipitation total provided by low-intensity showers. Scherrer et al. (2016) found that the intensity of maximum 24-h precipitation total increases on average by + 7.7%/K of Swiss annual mean temperature, verifying the Clausius-Clapeyron law.

According to IPCC (2014), increase in surface and tropospheric air humidity has been very likely. Wibig and Siedlecki (2007) studied values of precipitable water in the atmosphere over Europe and the northern Atlantic for 1958–2005. Increasing trends were observed for the whole year in the eastern part of the continent and over the British Isles, while decreasing trends occurred mainly in the south of Europe (except for the autumn, when they increased) and also during winter and spring in Western Europe and over the Scandinavian Peninsula. For shorter interval, 1973–2005, increasing trend of precipitable water was especially higher during spring in central Europe and over the British Isles and during summer in the north and east of Europe. However, Degirmendžić and Kożuchowski (2017) studied the relationship between the Mediterranean cyclones, precipitable water and precipitation in Poland for the period 1958–2008 and found that the number of cyclones from the Mediterranean Sea basin, which have an impact on precipitation in Poland, decreased. Also, the mean precipitable water content in the atmosphere over Poland has decreased. Despite of the decrease in precipitation totals associated with Mediterranean cyclones, the intensity of daily precipitation of the Mediterranean origin in lowland Poland insignificantly increased for nearly all seasons without autumn and during summer for the mountains. Niedźwiedź et al. (2015) and Niedźwiedź and Łupikasza (2016) conducted studies on a long period of circulation types (1874–2015) and long precipitation records (1951–2015) for mountainous station Kasprowy Wierch and Zakopane, located on northern foothills of the Tatra Mountains that have a great impact on flood generation. They revealed statistically insignificant increasing trends in maximum daily, maximum 5-day and summer half-year precipitation totals and also in the frequency of days with very high precipitation (≥ 50 mm/day). Additionally, they identified three cyclonic circulation types responsible for the triggering of the most extreme precipitation and showed the long-term increase in the frequency of these circulation types.

Another issue related to climate warming and its impact on rainfall are the changes in winter precipitation. According to Zolina (2014), strong structural changes in winter precipitation over Germany may contribute in the future to flood risk during winter. Observed warming has an impact on the form of precipitation during winter, i.e. decrease of solid precipitation (snow) and increase of liquid precipitation (rainfall).

5 Conclusions

There have been several episodes of extreme precipitation excess, as well as of extreme precipitation deficit, with considerable economic and social impacts, in Europe and in Poland in the last decades. Increasing intensity of precipitation may result in inundations and, in particular, flash and urban floods. Examination of precipitation extremes in Poland, carried out in this paper, demonstrated that, typically, most indices showed increasing trends. Comparison of two periods: colder 1961–1990 and warmer 1991–2015, revealed that, during the last 25 years, most statistical indices, such as 25th and 75th percentiles, median, mean and maximum were higher. This particularly holds for the maximum 5-day and maximum monthly precipitation total. Weak, decreasing trends were observed for maximum 24-h precipitation total for winter half-year. On the other hand, periods without precipitation extend, leading to increase in consecutive dry days, what may be additionally magnified by the occurrence of high air temperatures (and heat waves). The number of consecutive dry days is getting higher for many stations in the summer half-year.

However, trends presented in this study, for analysed indices and stations, are statistically significant only in few cases. This may indicate that the detection of changes in extreme precipitation is a complex task and that the results are not robust. Differences in results can be attributed to the selection of a region and a period for examination, as well as the selection of indices. The findings reported in this paper challenge results reported in literature, based on earlier data that do not include the recent interval from 2007 to 2015.

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