

Observed Changes in Air Temperature and Precipitation and Relationship between them, in the Upper Vistula Basin

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Abstract The chapter presents changes in air temperature and precipitation in the Upper Vistula Basin. Data from 18 meteorological stations covering the 1951–2015 period was used to investigate variability and trends in air temperature, precipitation and linkages between them. Air temperature in the Upper Vistula Basin was significantly rising during the research period. Distinct warming on annual scale started in the first half of the eighties. Spring and summer air temperatures have been significantly increasing; winter air temperature trends were much weaker while no significant changes were found in autumn. Upward trends in air temperature within the Upper Vistula Basin were also reflected in the frequency of thermally characteristic days which was significantly changing during the research period. Strong downward trends were found in the frequency of winter days ($T_{avg} \leq 0 \text{ }^\circ\text{C}$) while trends in warm characteristic days were positive. Most observed changes in precipitation were not statistically significant at the level of 0.05. This indicates that significant increase in air temperature is not currently accompanied by significant increase in precipitation thus changes in precipitation are not directly related to changes in air temperature and they possibly vary in time. Relations between

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precipitation and air temperature are not straightforward. The results indicate that strong increase in air temperature is rather accompanied by decrease in precipitation frequency and amount. However, this applies only to overall precipitation totals and not to extreme events which are random and can occur unexpectedly. Flood precipitation can also occur during drier periods, as in the last decade of the research period. It however must be mentioned that for nearly all stations mean precipitation totals from the warmer period of 1991–2013 (1991–2011) were higher than in previous period 1961–1990. Moreover the study revealed that increasing, statistically significant, trend (from 0.15 to 0.24 °C/decade) in mean annual air temperature likely impacted changes in heavy precipitation. The links between air temperature ranges (0–10, 10–20 °C and above 20 °C) and precipitation ranges (0–10 mm, 10–20 mm, etc. to above 50 mm) for two periods examined at nine stations in the Upper Vistula Basin revealed that when air temperature exceeded 20 °C more intense precipitation was observed in the second warmer period 1991–2013.

Keywords Air temperature · Precipitation · Trends · Climate change · The Upper Vistula Basin

1 Introduction

The Upper Vistula River Basin (about 51,000 km²) is located in the southern and south-eastern part of Poland (Fig. 1). It is the most differentiated part of the country with regard to natural environment, with elevation varying between 140 m in Sandomierz Basin up to 2499 m in the Polish part of the Tatra Mountains and to 2655 m in Slovakia (Gerlach). This is the highest range of the whole Carpathian Mountains.

Four climatic zones were distinguished within the Upper Vistula Basin on the basis of annual course of air temperature and precipitation (Niedźwiedz and Obrębska-Starkłowa 1991; Fig. 1). The mountain climate region (A) encompasses the highest part of the Carpathian Mountains above 900 m, with mean annual temperature lower than 7 °C and precipitation above 900 mm. Hess (1965) counted this region among the fifth vertical climatic belt categorized on the base of vertical profile of mean annual air temperature. The moderately cool climate with annual temperature below 4 °C extends to 1150 m. The cool belt (temperature between 4 and 2 °C) reaches the upper tree line (1520 m). The very cool subalpine belt with mean annual air temperature between 2 and 0 °C is located between 1520 and 1850 m. The moderately cold alpine belt stretches to the climatic snow line (2200 m) which is marked by location of the isotherm of –2 °C. Above this line the cold belt reaching the highest summits of the Tatra Mountains is located. The lowest part of the Carpathians (250–900 m) is encompassed by the temperate-warm climatic region (B) with the mean annual temperature between 7 and 8 °C and precipitation between 700 and 900 mm. The warmest and moderately dry climate (region C) embraces the Oświęcim-Sandomierz Basin. The upland climatic region (D) is cooler and more humid comparing to region C. In the Holy-Cross Mountains (611 m) near Kielce mean annual temperature drops to about

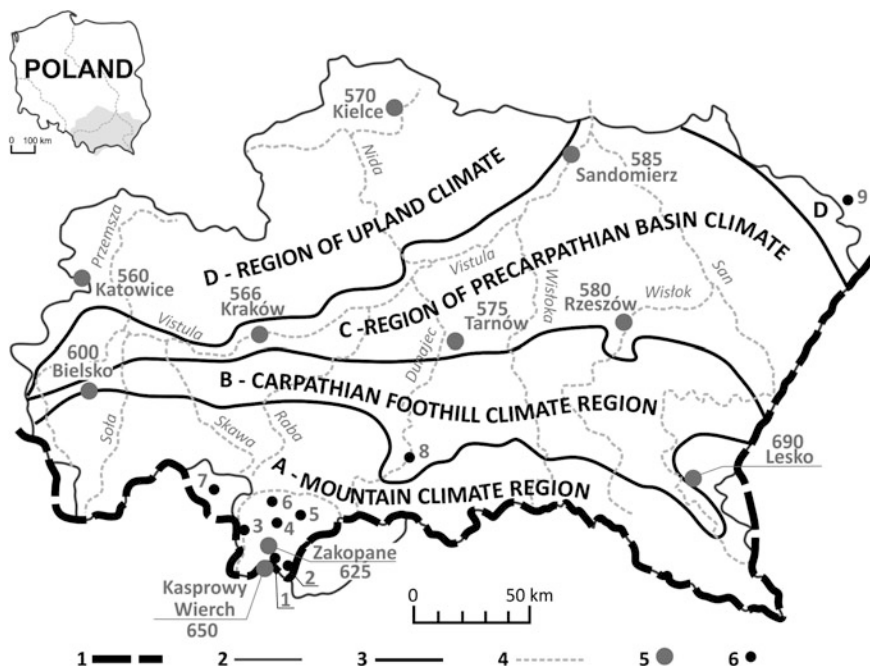


Fig. 1 Location of the studied area in Poland and location of the meteorological stations in the area of the Upper Vistula Basin. Climatic regions after Niedźwiedź and Obrębska-Starkłowa (1991). Borders: 1—cross-country borders, 2—the Upper Vistula Basin, 3—climatic regions; 4—rivers, 5—main meteorological stations with WMO numbers, 6—other meteorological stations (1—Hala Gąsienicowa, 2—Morskie Oko, 3—Witów, 4—Poronin, 5—Białka Tatrzańska, 6—Szaflary, 7—Jabłonka, 8—Nowy Sącz, 9—Tomaszów Lubelski)

6 °C and precipitation increases to 900 mm. Climatological characteristics of air temperature and precipitation in the research period for selected 18 stations in the Upper Vistula Basin are gathered in Table 1. In the research period mean annual air temperature at majority of stations varied between c.a. 7.5 and 8.5 °C with an exception of Zakopane and Kasprowy Wierch where air temperature was much lower as a result of vertical decrease (Table 1).

Despite clear vertical decrease in air temperature the Tatra Mountains climate is characterized by abundant precipitation. Annual precipitation totals exceed 1500–1750 mm above the altitude of 1400 m a.s.l. In the research period maximum 10-day precipitation totals were higher than 100 mm at many stations and exceeded the threshold of 200 mm at three stations. The country-wide peak of daily precipitation total amounting to 300 mm was recorded on 30 June 1973 at Hala Gąsienicowa station (1520 m a.s.l.) (Niedźwiedź 2003). Precipitation extremes typically occur during warm part of the year, from May to September, with maximum in July. Several-day high rainfalls have not only caused severe flash floods and landslides in small catchments, but also catastrophic large-scale floods in the

Table 1 The list of stations with their altitudes (Hs), the research periods and mean value of indices for available periods

Station	Altitude Hs (m a.s.l.)	Available period	Mean annual precipitation totals (mm)	Mean maximum 10-day precipitation totals (mm)	Mean maximum monthly precipitation totals (mm)	Annual mean temperature (°C)
Kasprowy Wierch	1991	1951–2013	1752	213	307	-0.6
		1951–2015	1750			-0.5
Hala Gąsienicowa	1520	1951–2011	1696	242	349	–
Morskie Oko	1408	1954–2011	1583	205	301	–
Zakopane	857	1951–2013	1126	160	236	5.4
		1951–2015	1129			5.5
Witów	835	1954–2011	1033	145	212	–
Poronin	773	1954–2011	992	151	214	–
Białka Tatrzańska	700	1951–2011	846	114	166	–
Szaflary	655	1951–2011	857	116	170	–
Jablönka	615	1955–2011	746	94	243	–
Bielisko-Biała Aleksandrowice	398	1951–2013	990	144	166	8.1
		1951–2015	987			8.2
Lesko	386	1954–2013	806	107	162	7.5
		1954–2015	811			7.6
Katowice	317	1951–2013	719	89	134	8.2
		1951–2015	715			8.3
Nowy Sącz	292	1954–2013	733	109	349	8.3
Tomaszów Lubelski	273	1951–2013	634	84	124	–
Kielce-Suków	268	1951–2013	630	88	129	7.5
		1951–2015	630			7.6
Kraków-Balice	237	1951–2015	670			8.2
Sandomierz	217	1951–2013	567	84	121	8.0
		1951–2015	566			8.1
Tamów	209	1951–2013	710	106	148	8.6
		1951–2015	712			8.7
Rzeszów-Jasionka	200	1952–2013	636			–
		1951–2015	631	86	127	8.1

Upper Vistula Basin, and further downstream. The most severe floods occurred in July 1903, 1934, 1960, 1970, 1997, 2001, and 2010. The flood in July 1934 was one of the most pronounced deluges in the 20th century in the Vistula Basin, causing death of 55 people, while the flood in May and June 2010 caused economic losses up to 3.2 billion US dollars (Chorynski et al. 2012).

According to the Clausius–Clapeyron law, higher temperatures are associated with higher saturated water vapour pressure in the atmosphere. Hence, warming can lead to occurrence of more intense precipitation as well as to extend the periods of precipitation occurrence. Although studies (Niedzwiedz et al. 2015) on intense precipitation at two stations located on the northern foothills of the Tatra Mountains (Kasprowy Wierch and Zakopane) indicated no statistically significant trends, upward trends in maximum daily, maximum five-day and warm half-year precipitation totals as well as in the frequency of days with precipitation ≥ 50 mm were found at both stations.

Since flood risk is likely to depend on current climate change manifesting itself in significant climate warming, this chapter discusses changes in selected characteristic of air temperature and precipitation in the Upper Vistula Basin. The first part of the chapter concerns changes in air temperature including monthly seasonal and annual means. Moreover, we also investigated variability in the frequency of selected thermally characteristic days which were recognized as direct indicators of current climate change. Regional air temperature changes are discussed on the background of global changes. Next we explored changes in monthly, seasonal and annual precipitation including extremes. We paid special attention to warm half-year and summer season which are the most flood parts of the year in the Upper Vistula Basin. Further part of the chapter compares precipitation climatology in the Tatra Mountains and Podhale Basin with the remaining part of the Upper Vistula Basin and seeks relations between precipitation and air temperature. We used different sets of the stations, depending on analysis. Majority of analyses use 10 stations located in the Upper Vistula Basin. These stations represent different parts of the research area including the highest altitudes (Kasprowy Wierch, Zakopane) and the foothills of the Carpathian Mountains (Bielsko, Lesko). The remaining six stations represent the areas of the Upper Vistula Basin located further to the north (Tarnów, Kraków, Rzeszów, Katowice, Sandomierz, Kielce) as shown in Fig. 1. The data from these stations cover the period 1951–2015. The further nine stations used in the chapter are listed in Table 1. Summing up we used the data from 19 stations covering various periods to explore changes in air temperature and precipitation.

2 Changes in Air Temperature of the Upper Vistula Basin in the Light of Global Temperature Trends

The enhanced violence of extreme weather events is currently being attributed to contemporary climate change, manifesting itself in significant air temperature increase on both regional and global scales (Trepínska 1983, 1997; Limanówka

1997; Trepńska et al. 1997; Fortuniak et al. 2001; Kożuchowski and Żmudzka 2001; Wibig and Głowicki 2002; Cebulak and Limanówka 2007; Bielec-Bakowska and Lupikasza 2009; Bielec-Bakowska and Piotrowicz 2013). A recent report on global climate state (NOAA 2016) announced that three warmest years of the last 136 years (1880–2015) were recorded at the end of this period. In 2015, the average global air temperature across land and ocean was warmer by $+0.90\text{ }^{\circ}\text{C}$ comparing to the 1910–2000 average. The annual air temperature in the previous year, 2014, exceeded the long-term average by $+0.74\text{ }^{\circ}\text{C}$ and was the second warmest in the series. The mean air temperature increase in Poland was up to $+0.8\text{ }^{\circ}\text{C}$ in the second half of the 20th century (cf. Fortuniak et al. 2001; Kożuchowski and Żmudzka 2001; Degirmendzić et al. 2004).

This chapter uses average, maximum and minimum air temperature from 10 stations, location of which is shown in Fig. 1. Long-term course of air temperature in the Upper Vistula Basin exhibits a lot of natural, inter-annual and intra-annual variability but general trend relates to global changes. This is illustrated in Fig. 2 showing standardized global annual air temperature and analogous temperature in the Upper Vistula Basin in the 1951–2015 period. Fluctuations and no clear tendency dominated before 1975. Since the middle of the 1970s evident increase was recognized. Average annual air temperature for 1988–2015 was higher by $+0.9\text{ }^{\circ}\text{C}$ than for previous long-term period (1951–1987). The increase was restrained at the turn of the centuries but the distinctive maximum of the annual air temperature which occurred in 2014 and 2015 ($+8.8\text{ }^{\circ}\text{C}$ which is higher by $2.5\text{ }^{\circ}\text{C}$ than the average from 1951–1975) may suggest renewal of the warming rate both within the research area and globally. Finally two periods can be distinguished on the basis of long-term course of annual air temperature—the cooler temperatures covered the 1951–1987 period and a distinct increase of annual temperature encompassed the 1988–2015 period.

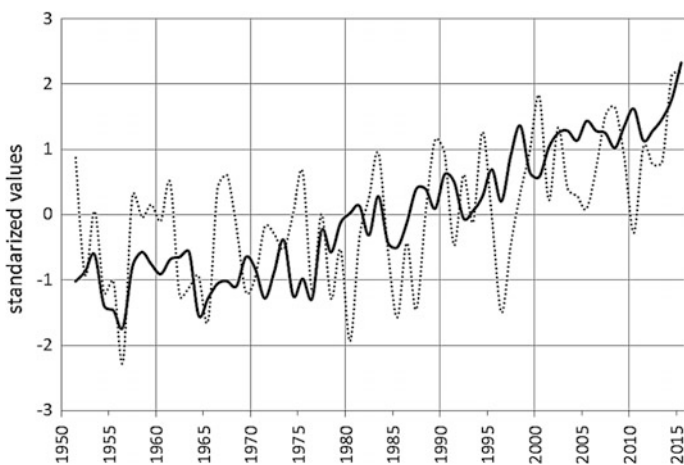


Fig. 2 Standardized values of annual air temperature for the Upper Vistula Basin (*spot line*) and global air temperature (*solid line*) in the 1951–2015 period

3 Annual, Seasonal and Monthly Air Temperature

Spatial and seasonal distribution of air temperature in the Upper Vistula Basin is influenced by various factors of which topography is the most crucial local one. Climatological characteristics of air temperature in the research period are presented in Table 2. The annual range of monthly air temperature within the Upper Vistula Basin reached almost 27 °C. The extreme monthly values varied from -8.3 °C in February at Kasprowy Wierch station to 18.6 °C in July at Tarnów and Sandomierz located in the lowest altitudinal belt. Although the lowest average monthly temperature fell in February (see Kasprowy Wierch in Table 2), it is January which is the coolest month at majority of stations. In that month air temperature changed in the vertical profile from -1.7 °C in Lesko to -8.0 at Kasprowy Wierch (Table 2). At most stations monthly temperatures exceeded 10 °C from May to September with maximum in July varying between 14.9 and 18.6 °C, depending on the station. The period between May and September is the most flood-prone season in the Upper Vistula Basin. At the Kasprowy Wierch high mountain station, the annual range of temperature spread between -8.3 °C (February) and 7.7 °C (August).

The absolute range of air temperature at particular stations within the Upper Vistula Basin ranged from more than 53 °C at Kasprowy Wierch to more than 70 °C in Rzeszów and Kielce (Table 3). The highest ever daily temperature occurred on 8 August 2013 in Tarnów while the lowest one was recorded on 28 February 1963 in Rzeszów located on the borderline between Sandomierz Basin and the Carpathian Foothills. The occurrence of the lowest daily temperature minimums at hollows and basins of the Carpathian Mountains is due to the slide down of cold heavy air along the slopes and its stagnation in a concave topographic form.

The long-term course of mean seasonal temperature averaged for the region indicates various seasonal patterns with clear increase in spring and summer temperatures since the beginning of the 1980s. Similar tendency was also seen in the long-term course of autumn temperature but since the beginning of the 1990s. Winter air temperature was dominated by vivid fluctuations with no clear tendency (Fig. 3). In all seasons, the highest air temperatures were recorded in the last decade of the 20th century or in the 21st century (9.0 °C in spring 2007, 18.4 °C in summer 2015, 9.7 °C in autumn 2006 and 1.4 °C in winter 2006/2007). These features can clearly be seen in Fig. 3 showing standardized seasonal air temperatures calculated as arithmetical averages from ten stations. Only in spring there was a continuous increase in air temperature throughout the entire period as shown by fitted 5th order polynomial. However, in the last years, the most rapid increase was found in summer temperature. For example eight of ten highest summer temperatures were recorded in the 21st century. On the other hand, vividly cooler summers occurred in the WMO normal period of 1961–1990. All the lowest seasonal temperatures fell before 1980: 3.8 °C in spring 1955, 13.9 °C in summer 1978, 5.6 °C in autumn 1956, -8.4 °C in winter 1962/1963.

Long-term course of air temperature discussed above is well reflected in the results of trend analysis showing distinct, statistically significant changes between

Table 2 Average monthly, seasonal and annual air temperature in the Upper Vistula Basin in the period 1951–2014

Season	12 650 Kasprowy Wierch	12 625 Zakopane	12 600 Bielsko-Biała	12 690 Lesko	12 566 Kraków Balice	12 575 Tarnów	12 580 Rzeszów	12 585 Sandomierz	12 560 Katowice	12 570 Kielce
Jan	-8.0	-4.2	-1.7	-2.7	-2.6	-2.0	-2.9	-3.1	-2.1	-3.1
Feb	-8.3	-3.4	-0.9	-1.7	-1.4	-0.9	-1.9	-1.9	-1.0	-2.2
Mar	-6.3	-0.1	2.8	2.1	2.6	3.1	2.3	2.2	2.8	1.6
Apr	-2.4	5.1	8.0	7.6	8.3	8.8	8.2	8.4	8.3	7.5
May	2.4	10.1	12.7	12.5	13.4	13.7	13.4	13.7	13.2	12.9
Jun	5.7	13.2	15.8	15.5	16.6	16.9	16.7	16.9	16.4	16.2
Jul	7.6	14.9	17.6	17.2	18.3	18.6	18.4	18.6	18.1	17.8
Aug	7.7	14.4	17.2	16.6	17.7	18.0	17.7	18.0	17.5	17.2
Sep	4.3	10.5	13.4	12.7	13.4	13.8	13.4	13.5	13.3	12.8
Oct	1.1	6.2	9.1	8.4	8.5	9.2	8.5	8.3	8.7	7.9
Nov	-3.3	1.4	4.1	3.5	3.4	4.3	3.5	3.1	3.7	2.9
Dec	-6.5	-2.6	0.1	-0.9	-0.7	0.0	-0.8	-1.1	-0.4	-1.1
MAM	-2.1	5.0	7.8	7.4	8.1	8.5	7.9	8.1	8.1	7.4
JJA	7.0	14.2	16.9	16.4	17.5	17.9	17.6	17.8	17.3	17.1
SON	0.7	6.0	8.9	8.2	8.4	9.1	8.5	8.3	8.6	7.8
DJF	-7.6	-3.4	-0.8	-1.8	-1.6	-0.9	-1.9	-2.0	-1.1	-2.2
Year	-0.5	5.5	8.2	7.6	8.2	8.7	8.1	8.1	8.3	7.6

Table 3 Absolute extremes of daily air temperature at selected stations in the Upper Vistula Basin (1951–2015)

WMO No	Station name	Hs (m a.s.l.)	Tmax (°C)	Date	Tmin (°C)	Date	Temperature (range K)
12 650	Kasprowy Wierch	1991	23.0	5 July 1957	-30.2	17 January 1963	53.2
12 625	Zakopane	857	32.8	8 August 2013	-34.1	1 February 1956	66.9
12 600	Bielsko-Biała	398	36.4	8 August 2013	-29.6	9 February 1956	66.0
12 690	Lesko	420	33.8	7 August 1956	-32.5	28 February 1963	66.3
12 566	Kraków-Balice	237	37.3	8 August 2013	-29.9	13 January 1987	67.2
12 575	Tarnów	209	37.9	8 August 2013	-30.3	20 January 1963	68.2
12 580	Rzeszów	200	36.5	15 August 1952	-35.8	28 February 1963	72.3
12 585	Sandomierz	217	37.1	15 August 1952	-28.6	9 February 1956	65.7
12 560	Katowice	284	37.2	8 August 2013	-30.0	9 February 1956	67.2
12 570	Kielce	260	36.4	9 August 2013	-33.9	8 January 1987	70.3

Bolded values are the highest and the lowest air temperatures

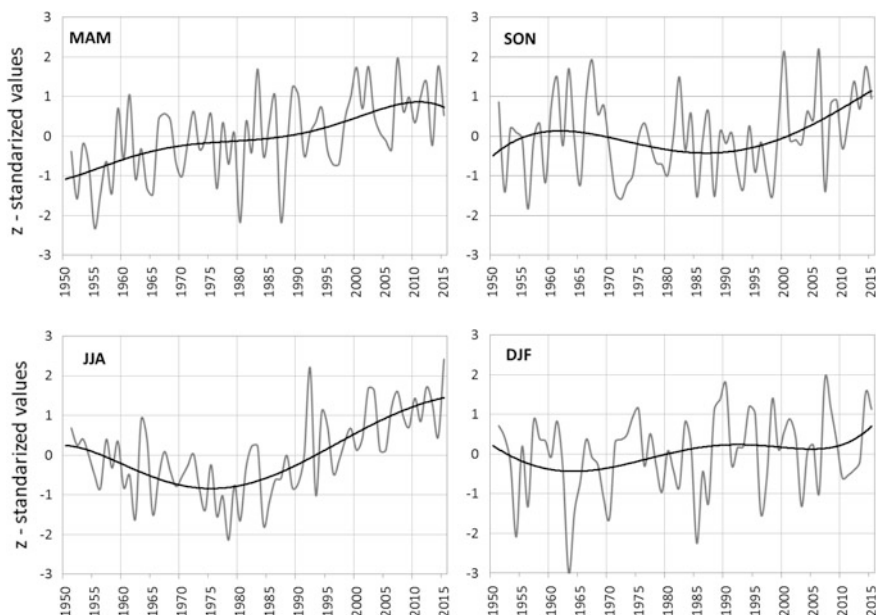


Fig. 3 Standardized values of seasonal air temperature for the Tatra Mountains in the 1951–2015 period (*grey line*—observed temperature, *black line*—fitted 5th order polynomial)

March and August (Table 4). Significant increase in annual air temperature of the rate of $+0.13\text{ }^{\circ}\text{C}$ per 10 years to $+0.29\text{ }^{\circ}\text{C}$ per 10 years, depending on station, was found within the entire research area. On a seasonal scale, the most significant was increase in summer and spring air temperature, particularly in August and July. No significant changes were found in autumn and winter months, however majority of air temperature trends were positive despite those for October and December at Lesko station. It is also worth to notice that magnitudes of insignificant trends in January and February air temperatures were much higher comparing to the monthly trends in air temperature from September to December. If the rate and pattern of current climate change continues to the future, trends in January and February air temperature will likely become statistically significant.

Significant increase in air temperature is also well reflected in the frequency of thermally characteristic days which are considered as direct indicators of current climate change. We analysed five characteristic days selected on the basis of average, maximum and minimum air temperature for eight stations representing topographically different parts of the Upper Vistula region. Winter and summer days were defined as days with average daily mean air temperature ≤ 0 and $\geq 15\text{ }^{\circ}\text{C}$, respectively. Daily maximum air temperature was used to select ice days ($T_{\text{max}} \leq 0\text{ }^{\circ}\text{C}$), hot days ($T_{\text{max}} \geq 25\text{ }^{\circ}\text{C}$) and very hot days ($T_{\text{max}} \geq 30\text{ }^{\circ}\text{C}$). Long-term course of thermally characteristic days frequency at particular stations is presented in Figs. 4, 5, 6, 7 and Fig. 8. For the most part of the Upper Vistula Basin

Table 4 Trends (change per 10 years) in monthly, seasonal and annual mean air temperature in the Upper Vistula Basin in the 1951–2015 period

Season	12 650	12 625	12 600	12 690	12 566	12 575	12 580	12 585	12 560	12 570
	Kasprowy Wierch	Zakopane	Bielsko-Biala	Lesko	Kraków Balice	Tarnów	Rzeszów	Sandomierz	Katowice	Kielce
Jan	+0.30	+0.42*	+0.34	+0.30	+0.36	+0.38	+0.44*	+0.38	+0.36	+0.33
Feb	+0.20	+0.35	+0.37	+0.24	+0.38	+0.40	+0.47	+0.41	+0.40	+0.38
Mar	+0.13	+0.34*	+0.37*	+0.28	+0.39*	+0.44**	+0.51**	+0.48**	+0.41*	+0.40*
Apr	+0.24*	+0.34**	+0.36**	+0.26*	+0.31**	+0.34**	+0.35***	+0.32**	+0.38***	+0.28**
May	+0.35**	+0.34**	+0.37***	+0.23*	+0.33***	+0.38***	+0.35***	+0.28**	+0.35***	+0.26*
Jun	+0.16	+0.20*	+0.22**	+0.08	+0.16*	+0.18*	+0.18*	+0.06	+0.16*	+0.02
Jul	+0.33**	+0.32***	+0.38***	+0.29**	+0.34***	+0.36***	+0.36***	+0.30**	+0.35***	+0.26*
Aug	+0.33***	+0.34***	+0.36***	+0.31***	+0.33***	+0.31***	+0.36***	+0.27**	+0.33***	+0.26**
Sep	+0.03	+0.11	+0.06	+0.04	+0.11	+0.04	+0.14	+0.08	+0.10	+0.06
Oct	+0.03	+0.12	+0.07	-0.01	+0.09	+0.04	+0.07	+0.03	+0.07	+0.00
Nov	+0.20	+0.21	+0.21	+0.14	+0.10	+0.14	+0.23	+0.16	+0.18	+0.09
Dec	+0.11	+0.10	+0.08	-0.03	+0.03	+0.04	+0.08	+0.09	+0.09	+0.03
MAM	+0.24**	+0.34***	+0.37***	+0.26**	+0.34***	+0.38***	+0.40***	+0.36***	+0.38***	+0.31***
JJA	+0.28***	+0.29***	+0.32***	+0.23***	+0.28***	+0.28***	+0.30***	+0.21**	+0.28***	+0.18**
SON	+0.09	+0.14	+0.11	+0.06	+0.10	+0.07	+0.15*	+0.09	+0.12	+0.05
DJF	+0.21*	+0.31*	+0.27	+0.15	+0.26	+0.29	+0.33*	+0.30*	+0.29*	+0.25
Year	+0.20***	+0.27***	+0.27***	+0.13*	+0.24***	+0.25***	+0.29***	+0.24***	+0.26***	+0.20***

Trends calculated with linear regression of least squares method, statistical significance tested with t-test, significance levels: * $\alpha \leq 0.05$, ** $\alpha \leq 0.01$, *** $\alpha \leq 0.001$

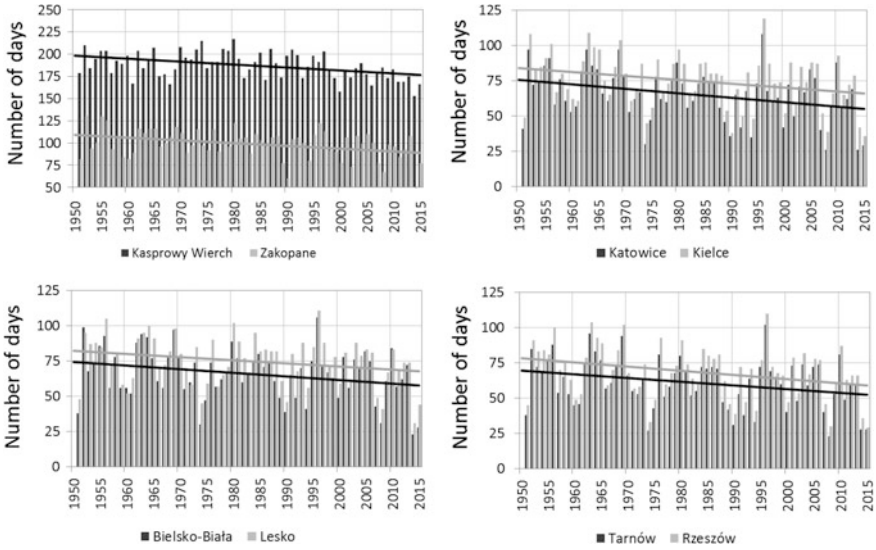


Fig. 4 Annual number of winter days ($T_{mean} \leq 0\text{ }^{\circ}\text{C}$) at selected stations in the Upper Vistula Basin in the 1951–2015 period (*bars*—observed number of days, *lines*—fitted linear trend)

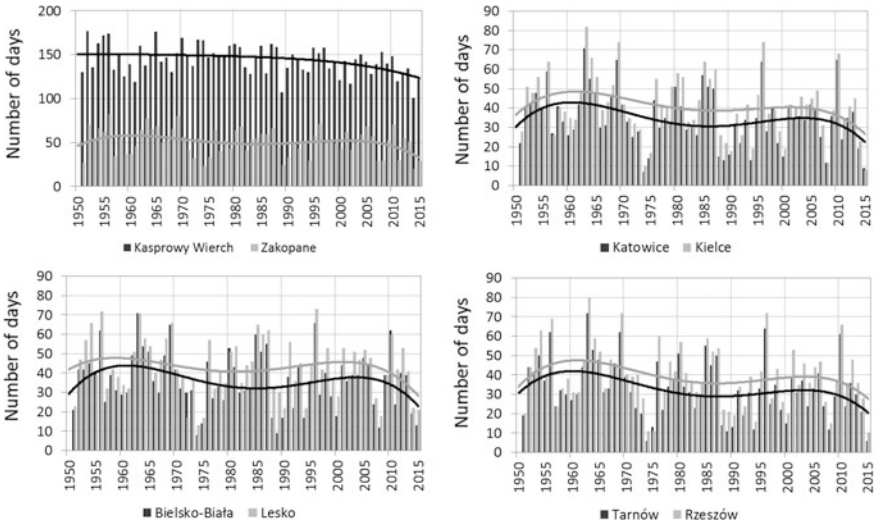


Fig. 5 Annual number of ice days ($T_{max} \leq 0\text{ }^{\circ}\text{C}$) at selected stations in the Upper Vistula Basin in the 1951–2015 period (*bars*—observed number of days, *lines*—fitted 4th order polynomial)

winter days occurred during 18–21 % of days a year (102–119 days). At more elevated Zakopane and Kasprowy Wierch stations such days constituted 27 and 51 % of days a year, respectively. The 1996 year was the most exceptional over the

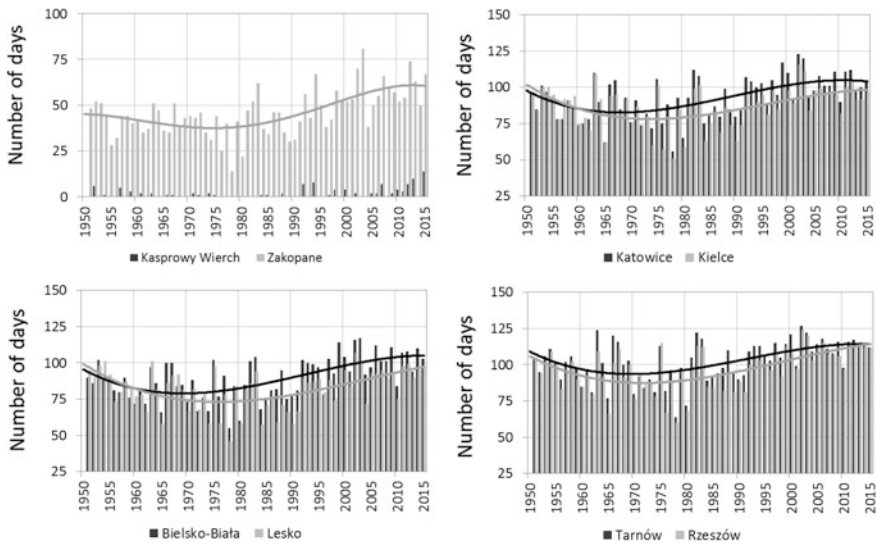


Fig. 6 Annual number of summer days ($T_{\text{mean}} \geq 15 \text{ }^\circ\text{C}$) at selected stations in the Upper Vistula Basin in the 1951–2015 period (*bars*—observed number of days, *lines*—fitted 3rd [Zakopane] and 4th order polynomial)

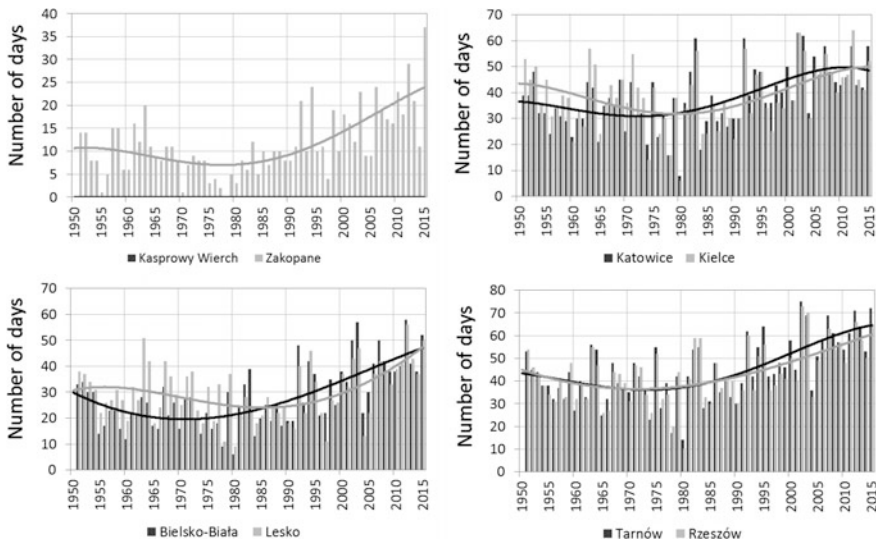


Fig. 7 Annual number of hot days ($T_{\text{max}} \geq 25 \text{ }^\circ\text{C}$) at selected stations in the Upper Vistula Basin in the 1951–2015 period (*bars*—observed number of days, *lines*—fitted 3rd [Zakopane] and 4th order polynomial)

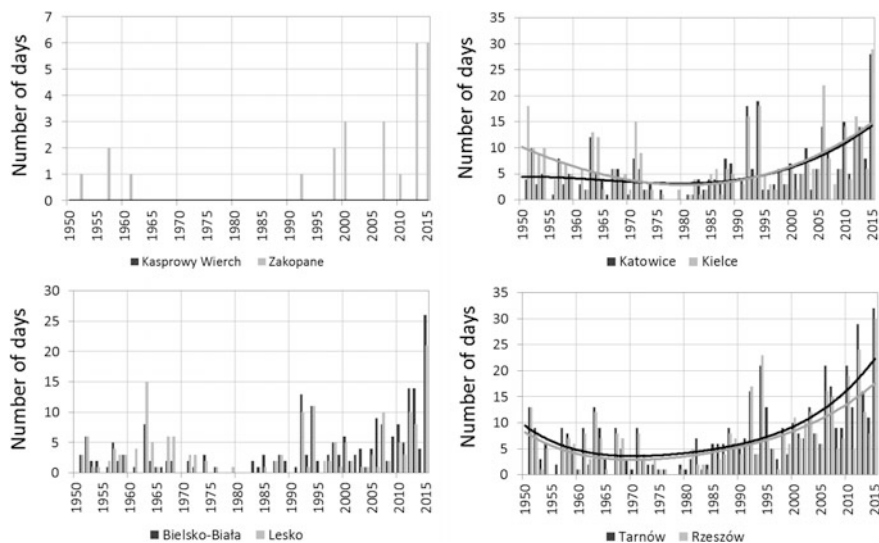


Fig. 8 Annual number of very hot days ($T_{max} \geq 30\text{ }^{\circ}\text{C}$) at selected stations in the Upper Vistula Basin in the 1951–2015 period (hot days were not noted at the Kasprowy Wierch station in the research period) (*bars*—observed number of days, *lines*—fitted 4th order polynomial)

entire research period due to the highest number of winter days at majority of meteorological stations. At the Kasprowy Wierch station the frequency of winter days reached its maximum in 1980 when more than 59 % of days (217 days) had mean temperature below freezing point. The frequency of winter days was significantly decreasing over the research period at majority of stations with a rate of about -3 days per 10 years. We found the most significant downward trend at the high mountain Kasprowy Wierch station ($\alpha \leq 0.001$). In the last two years of the research period (2014, 2015) the number of winter days was very low.

In the Upper Vistula Basin, ice days (Fig. 5) constituted about 10 % of days a year; their frequency was distinctly higher at Kasprowy Wierch station (40 % of days). At majority of stations, the highest number of ice days was found in 1963, except for Zakopane and Kasprowy Wierch where the maximum occurred in the 1950s (82 days in 1956 and 117 days in 1952, respectively). At majority of stations ice days were very rare in the first part of the 1970s but the index reached its minimum value in 2015. The fraction of ice days was diminishing in the Upper Vistula Basin over the research period, however the trends were weaker than those for winter days, being significant at only two of eight stations (Tarnów: -2 days per 10 years and Kasprowy Wierch: -3 days per 10 years). In the recent years clear decrease in the number of ice days can be seen since the first pentad of the 21st century with the only exception of the 2010 flood year.

Summer days with average temperature $\geq 15\text{ }^{\circ}\text{C}$ (Fig. 6) constituted on average 22–35 % of days per year including the Zakopane station. At the Kasprowy peak, their frequency dropped to only 4 % of days a year. The year with the highest

percentage of summer days was 2002 and, at some stations, 2003 (Zakopane, Bielsko-Biała). Hot days (Fig. 7) did not occur at all at Kasprowy Wierch station in the research period while at other stations they constituted from 15 % (Lesko) to 21 % (Tarnów) of days in a year. In the Tatra Mountains, the upper limit of the hot days occurrence is placed at the level of about 1800 m a.s.l. The record-breaking frequency of hot days occurred in 2002 (Tarnów, Rzeszów and Katowice) or in 2012 (Bielsko-Biała, Lesko, Kielce). Zakopane experienced the highest number of hot days in 2015.

In the Upper Vistula Basin, very hot days were rather rare constituting on average from 2 % (Zakopane) to 9 % (Tarnów) of days a year. Such days did not occur at all at Kasprowy Wierch (Fig. 8) because their occurrence is limited to the altitude of about 1200 m. In the research period it was possible to point out several years with clearly high frequency of very hot days including 1963, 1992, 1994, 2003, 2006, 2007, 2010, 2012, 2013. However, their record breaking frequency was noted in 2015 when daily maximum temperature exceeded the threshold of 30 °C during 21 days (Lesko) to 32 days (Tarnów), depending on station. Even in Zakopane where average frequency of very hot days equalled 0.4 day, 6 such days were noted in 2015. The long-term courses of warm temperature indices were less spatially variable over the research period compared with cold temperature indices. Actually, at every station two periods with opposite trend direction can be distinguished. Decrease in all warm temperature indices covered the first three decades of the research period (1951–1980). The minimum values of warm day indices fell at the turn of the 1970s and 1980s and then there was their gradual increase. Linear trends calculated over the entire research period were statistically significant at majority of station excluding Lesko and Tarnów. Magnitude of statistically significant trends (at least $\alpha \leq 0.5$) varied from 0.5 days (Kasprowy Wierch) to 3.8 days (Bielsko-Biała) per 10 years for summer days, from 1.9 days (Zakopane) to 3.9 days (Tarnów) per 10 years for hot days and from 1.1 day (Bielsko-Biała) to 1.9 day (Tarnów) per 10 years for very hot days. Trends in both air temperature and thermally characteristic days indicate statistically significant (often at $\alpha < 0.001$) increase in air temperature which in future is likely to manifest itself as increase in the frequency of extreme weather events.

4 Changes in Precipitation of the Upper Vistula Basin

The occurrence of precipitation and its amount strongly depend on altitude and atmospheric circulation which is also triggering temporal precipitation variability. In the Upper Vistula Basin, linkage between precipitation amount and altitude is clearly seen both in annual, seasonal and monthly precipitation totals which at Kasprowy Wierch station (1750.4 mm) are twice or even more as high as at other stations (Table 5). In summer, the region received about 40 % (from 35 % at Kasprowy Wierch to 43 % in Zakopane) while in winter about 16 % of annual total (from 13 % in Zakopane to 20 % at Kasprowy Wierch). Spring and autumn

precipitation totals were almost equal. Such an annual course of precipitation is typical in moderate continental climate. Monthly extremes fell in July (maximum) and February (minimum) (Table 5).

The most recent flood year (2010) had the highest ever annual precipitation total at nine stations in the large region (1646 mm in Zakopane, 1562 mm in Poronin, 1518 mm in Witów, 1215 mm in Tarnów, 1154 mm in Nowy Sącz, 1150 mm in Szaflary, 1104 mm in Lesko, 1029 mm in Tomaszów Lubelski, 964 mm in Jabłonka). At other nine stations precipitation in 2010 was counted between the highest values in the series: 2nd highest record in Hala Gąsienicowa: 2359 mm (in 2001: 2626 mm), 2nd in Bielsko-Biała: 1478 mm (in 1966: 1505), 2nd in Rzeszów: 966 mm (in 1966: 1009 mm), 3rd in Morskie Oko: 2256 mm (in 1974: 2290 mm; in 2001: 2271 mm), 3rd in Katowice: 965 mm (in 1974: 1011 mm; in 1977: 973 mm), 6th in Sandomierz 720 mm (in 1966: 860 mm), 7th in Białka Tatrzańska: 1015 mm (in 1970: 1128 mm; in 2001 1062 mm), 10th in Kasprowy Wierch: 2117 mm (in 2001: 2600 mm), and 11th in Kielce: 744 mm (in 1966: 1000 mm; 2001: 918 mm).

The highest daily precipitation totals recorded in the Upper Vistula Basin were, in some cases, only slightly lower than mean monthly totals (Cebulak 1992, 1997; Ustrnul and Czekerda 2009). Daily precipitation exceeded 100 mm at least once at six out of 10 stations. The highest daily total at Kasprowy Wierch reached 232.0 mm but it did not beat the record of 300 mm measured on 30 June 1973 at Hala Gąsienicowa. Daily maximum precipitation totals for each month and each station are presented in Table 6. Flood precipitation in the Tatra Mountains is usually noted at days with air advection from north-east under an influence of low pressure system. Such a situation is usually linked to stationary low with its centre located over Ukraine. Additionally, resulting long-lasting precipitation is enhanced by orographic effect. Sometimes extreme precipitation totals are a result of torrential rainfall of a short duration and local extent as it happened in Sandomierz (140.5 mm) at night 25/26 of July 2011 and had damaging effect. This flood-causing rainfall was linked to the convective cell which flew from the south-eastern sector and stopped to give exceptional 3-h shower of an unexpected intensity. Variability of flood conditions in the Southern Poland and the Tatra Mountains was presented in several latest publications (cf. Kundzewicz et al. 2012; Niedźwiedz et al. 2015; Ruiz-Villanueva et al. 2016).

Changes in precipitation within the Upper Vistula Basin were earlier discussed in a few general publications (Cebulak 1997; Degirmendzić et al. 2004; Łupikasza 2010) including those based on the longest time series for Cracow (Trepieńska 1969, 1983, 1997; Twardosz 1999, Niedźwiedz et al. 2009). In order to assess long-term variability in precipitation characteristics during the last 65 years (1951–2015), we investigated its annual, summer and warm half-year totals as well as maximum daily precipitation in these seasons. We also analysed the frequencies of days with high precipitation (≥ 30 and ≥ 50 mm) which can be used as indirect index of flood-prone conditions. Since we did not identify any monotonic increases in the chronological series of precipitation indices we decided to fit a polynomial of the 5th order to the data in order to identify the periods of precipitation abundance and

Table 5 Mean monthly, annual and seasonal precipitation totals (in mm) for selected stations in the Upper Vistula Basin (1951–2015)

Season	12 650 Kasprowy Wierch	12 625 Zakopane	12 600 Bielsko-Biala	12 690 Lesko	12 566 Kraków Balice	12 575 Tarnów	12 580 Rzeszów	12 585 Sandomierz	12 560 Katowice	12 570 Kielce
Jan	118.9	47.7	46.2	36.3	36.4	36.5	31.8	27.7	41.2	40.3
Feb	106.6	46.3	45.4	34.7	30.7	31.8	27.9	24.2	36.3	32.9
Mar	118.3	58.6	54.0	41.6	36.1	37.7	33.5	29.6	42.9	37.7
Apr	132.0	79.6	70.4	55.9	47.1	50.3	44.6	39.4	47.8	39.8
May	174.6	130.0	117.3	91.8	78.1	81.5	74.9	63.6	77.4	63.0
Jun	218.1	169.2	141.9	106.1	90.9	101.6	83.2	74.9	86.5	75.1
Jul	218.5	179.4	142.3	121.9	90.6	108.0	90.8	90.0	102.0	92.4
Aug	180.1	136.6	110.3	91.7	79.7	78.3	69.0	62.9	78.8	71.0
Sep	132.2	97.9	89.0	78.9	56.3	61.2	56.7	50.1	60.9	51.2
Oct	107.2	70.7	60.1	55.3	44.4	44.6	43.8	39.5	46.6	39.5
Nov	120.9	61.2	59.9	46.7	42.6	41.5	38.6	34.1	48.7	44.0
Dec	123.1	51.3	50.2	47.3	37.1	38.3	36.6	30.6	45.6	43.3
MAM	424.9	268.2	241.7	189.3	161.2	169.6	153.0	132.6	168.1	140.5
JJA	616.7	485.2	394.5	319.6	261.2	288.0	243.0	227.7	267.2	238.6
SON	360.3	229.8	209.0	180.9	143.3	147.3	139.2	123.7	156.3	134.7
DJF	348.5	145.3	141.8	118.3	104.2	106.6	96.2	82.5	123.1	116.5
Year	1750.4	1128.6	987.0	811.0	669.8	711.6	631.4	566.5	714.7	630.2

Table 6 Maximum daily precipitation totals (in mm) for selected stations in the Upper Vistula Basin (1951–2015)

Season	12 650	12 625	12 600	12 690	12 566	12 575	12 580	12 585	12 560	12 570
	Kasprowy Wierch	Zakopane	Bielsko-Biała	Lesko	Kraków Balice	Tarnów	Rzeszów	Sandomierz	Katowice	Kielce
Jan	65.3	31.4	31.6	31.0	20.0	22.7	23.8	45.6	24.5	28.1
Feb	76.4	44.3	26.4	26.0	17.4	28.4	28.1	27.6	21.2	17.4
Mar	53.2	59.8	37.6	37.0	24.0	30.2	24.5	20.9	28.2	21.5
Apr	70.5	56.7	53.3	45.4	44.8	53.8	41.2	36.0	81.6	42.1
May	130.1	104.2	162.7	71.4	87.4	81.0	62.2	47.2	62.1	59.0
Jun	232.0	138.7	88.2	53.6	71.9	71.9	65.2	49.5	74.1	76.5
Jul	166.1	138.7	132.1	68.0	74.4	110.8	59.2	140.5	58.4	155.2
Aug	118.7	90.4	147.4	66.4	62.4	65.2	61.8	59.5	61.6	66.3
Sep	100.5	77.6	91.5	80.7	64.0	83.6	45.7	51.2	47.2	44.5
Oct	63.7	73.1	46.4	41.5	51.4	32.8	55.7	37.4	40.6	28.2
Nov	66.4	48.4	54.1	48.1	33.9	33.8	25.0	24.9	27.4	26.8
Dec	59.4	33.1	36.6	32.0	29.8	34.2	24.3	22.9	28.6	26.7
MAM	130.1	104.2	162.7	71.4	87.4	81.0	62.2	47.2	81.6	59.0
JJA	232.0	138.7	147.4	68.0	74.4	110.8	65.2	140.5	74.1	155.2
SON	100.5	77.6	91.5	80.7	64.0	83.6	55.7	51.2	47.2	44.5
DJF	76.4	44.3	36.6	32.0	29.8	34.2	28.1	45.6	28.6	28.1
Year	232.0	138.7	162.7	80.7	87.4	110.8	65.2	140.5	81.6	155.2

deficit. The patterns of long-term precipitation variability, shown in Figs. 9, 10, 11, 12, 13 and 14, allow identification of wetter and drier periods which in case of all indices were quite synchronic. The most individual features were found in the

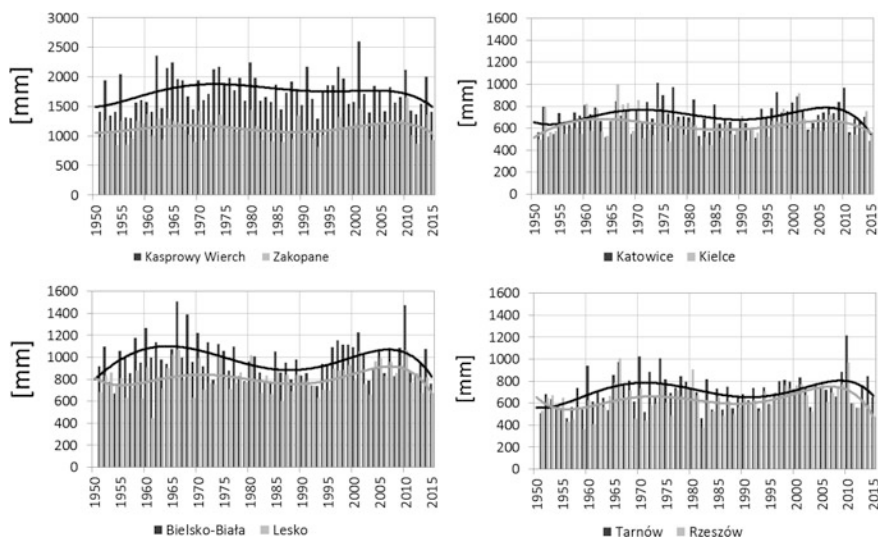


Fig. 9 Annual precipitation totals at selected stations in the Upper Vistula Basin in the period 1951–2015 (*bars*—observed number of days, *lines*—fitted 5th order polynomial)

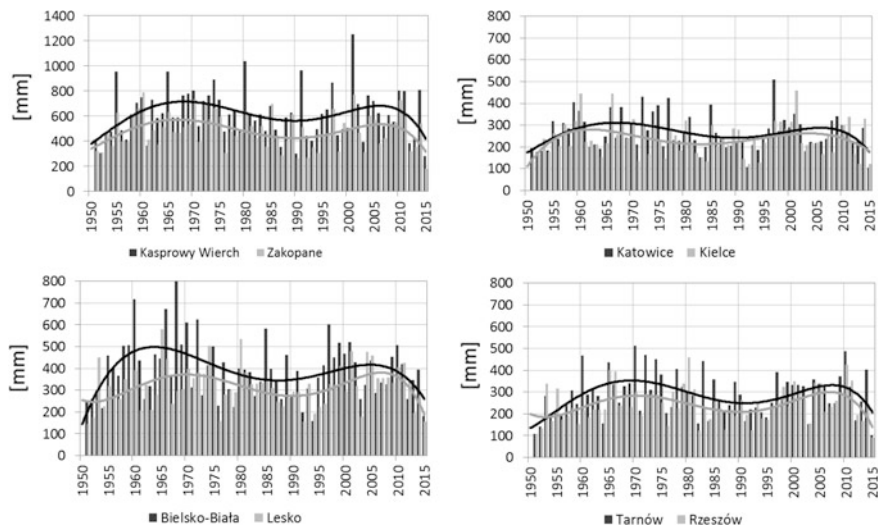


Fig. 10 Summer precipitation totals at selected stations in the Upper Vistula Basin in the period 1951–2015 (*bars*—observed number of days, *lines*—fitted 5th order polynomial)

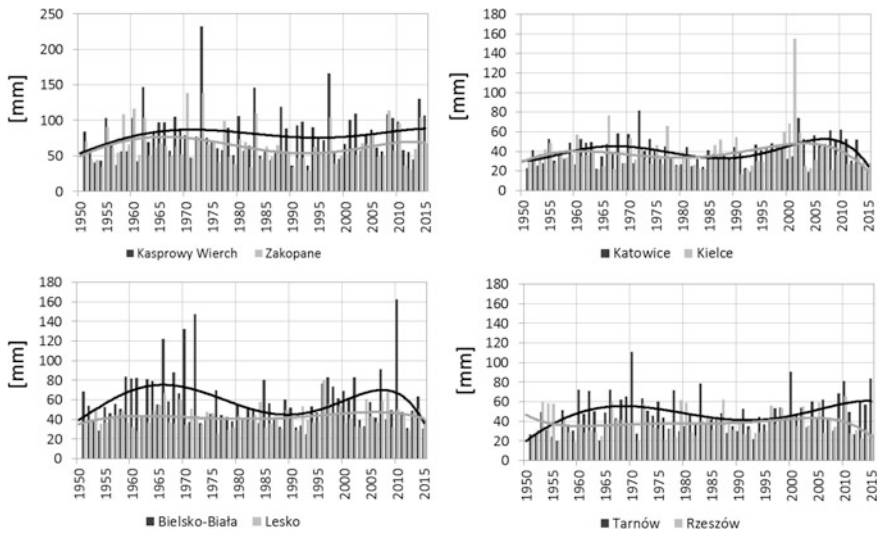


Fig. 11 Maximum daily summer precipitation totals at selected stations in the Upper Vistula Basin in the period 1951–2015 (*bars*—observed number of days, *lines*—fitted 5th order polynomial)

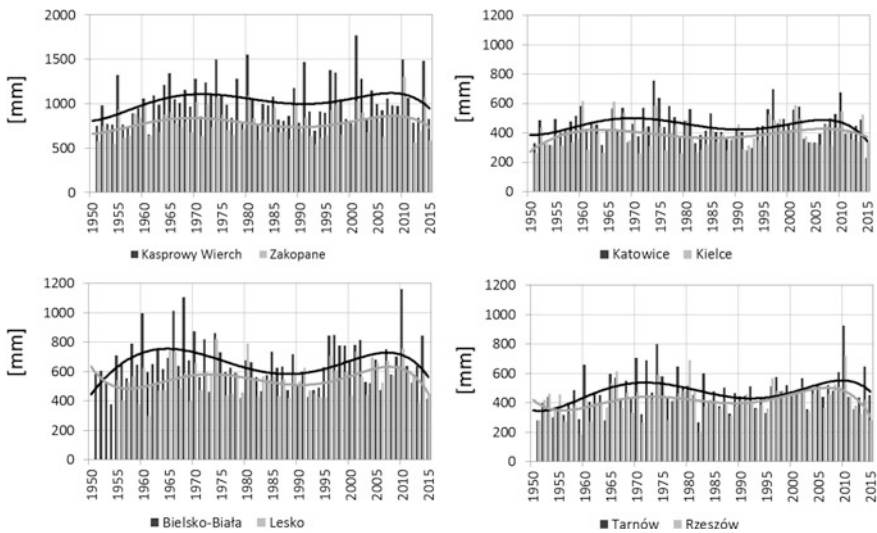


Fig. 12 Warm half-year precipitation totals at selected stations in the Upper Vistula Basin in the period 1951–2015 (*bars*—observed number of days, *lines*—fitted 5th order polynomial)

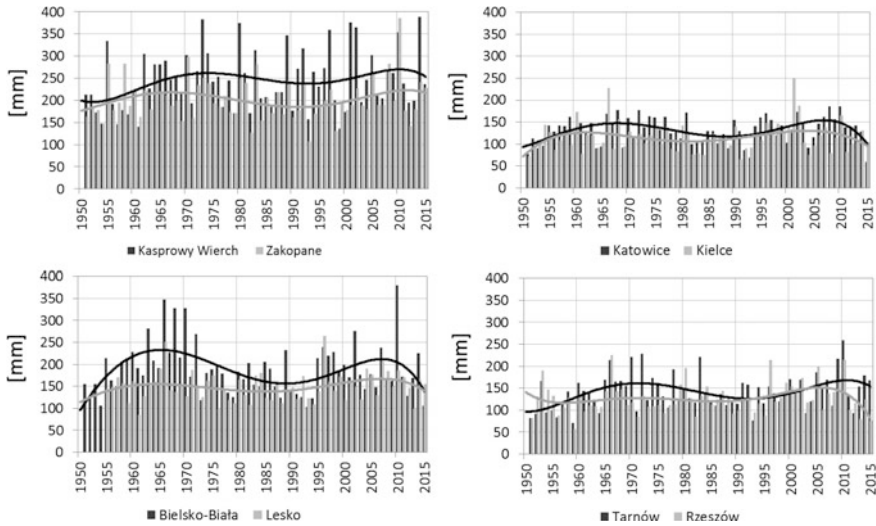


Fig. 13 Maximum daily summer half-year precipitation totals in the Upper Vistula Basin in the 1951–2015 period (*bars*—observed number of days, *lines*—fitted 5th order polynomial)

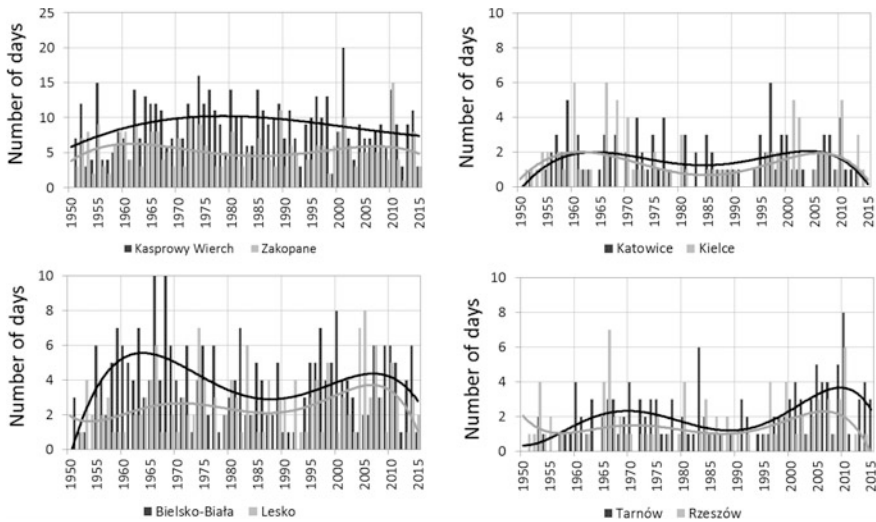


Fig. 14 Annual number of days with precipitation ≥ 30 mm at selected stations in the Upper Vistula Basin in the period 1951–2015 (*bars*—observed number of days, *lines*—fitted 5th order polynomial)

pattern for Kasprowy Wierch. Annual precipitation totals which ranged between 566.5 mm (Sandomierz) to 1750.4 mm (Kasprowy Wierch) were lower than average in the first decade of the research period covering the 1950s and between

1980 and 1995. The wettest years were identified to occur in 1960s and at the turn of the centuries. The third pentad of the 21st century, just after the exceptionally floody year 2010, exhibits clear decrease in annual precipitation totals (Fig. 9). The year 2015 was recognized as one of the driest in the series. Relatively dry 1950s and 1980s and relatively wet 1960s and the turn of the centuries were also identified, however with small shifts, in the long-term course of other indices.

In summer the Upper Vistula Basin received on average 334 mm (from 616.7 mm at Kasprowy Wierch to 227.7 mm in Sandomierz). Average summer precipitation totals from wet decades were by about 20 % higher than averages from dry period. In fact, this disproportion was not very distinct but noticeable (Fig. 10). Summer might be expected as the season of the highest maximum daily precipitation totals. Indeed, at six of ten meteorological stations, daily precipitation records were recorded in summer, but at other stations absolute maximums were noted at other seasons. At all stations, summer precipitation totals have been decreasing since 2010. Such a tendency was also spotted in the long-term course of summer daily maximums but not at every station. For example at Kasprowy Wierch there was an increase in the variability of daily maximums from year to year which finally resulted in weak increasing tendency since the beginning of the 21th century (Fig. 12). In the Upper Vistula Basin, significant increase in summer air temperature was not accompanied by any clear tendency in precipitation.

Long-term course of warm half-year precipitation totals and daily maximums did not differ from general pattern identified (Figs. 12 and 13). It could be mentioned, however, that this half-year received from 59 % (1030.7 mm) to 69 % (783.8 mm) of the annual precipitation total. In the wettest years warm half-year precipitation constituted from 149 % (Lesko) to 195 % (Tarnów) of the average value for 1951–2015. In contrast, precipitation totals in the driest year were as low as 43 % (Rzeszów) to 69 % (Zakopane) of the average value for 1951–2015. Changes in precipitation totals seem not to be directly related to changes in air temperature and do strongly vary in time. However, in some periods, for example in the first and the last decade of the research period, an increasing tendency in air temperature was accompanied by a decreasing tendency in precipitation. This suggests that the periods with lower temperature are typically wetter than the periods of high temperature. This applies only to overall aggregated precipitation totals and not to short intervals and extreme events. This is indicated by high maximum daily precipitation totals which were registered in the summers and warm half-years of the last decade of the research period (Figs. 11 and 13).

There is strong spatial and temporal variability in precipitation, so that trends are usually insignificant and can change in a short time. Trends in monthly, seasonal and annual precipitation totals in the Upper Vistula region are shown in Table 7. These trends were calculated with linear regression of least squares method and its significance was tested with nonparametric Mann-Kendall test. Most trends were not statistically significant. Noticeable changes were identified in a few cases only. Furthermore trend directions also varied depending on the season and the station. Even trends in annual totals were of various signs. March and September were the only months with increases noted at every station while in August opposite,

Table 7 Trends (mm/10 years) in monthly, seasonal and annual precipitation totals in the Upper Vistula Basin in the 1951–2015 period

Season	12 650	12 625	12 600	12 690	12 566	12 575	12 580	12 585	12 560	12 570
	Kasprowy Wierch	Zakopane	Bielsko-Biala	Lesko	Kraków Balice	Tamów	Rzeszów	Sandomierz	Katowice	Kielce
Jan	-0.4	+0.5	+0.7	+1.7	+2.2	+1.1	+1.8	-0.6	+2.7	-0.8
Feb	-5.5	+0.7	-1.6	+0.3	-0.9	+0.4	+0.7	-2.5**	0.0	-2.0
Mar	+0.6	+2.9	+1.7	+2.2	+1.7	+1.8	+2.9*	+0.1	+2.7	+1.1
Apr	-3.2	-1.9	-2.9	+1.1	-0.6	+0.8	+1.1	-0.3	-1.4	-1.6
May	+5.0	+8.5	+3.1	+5.7	+1.6	+4.5	+3.3	+1.9	-0.1	+3.3*
Jun	-5.0	-6.4	-2.0	-2.6	-0.9	+2.3	+1.1	-3.8	-1.3	-2.5
Jul	+8.0	+4.7	-2.0	+4.6	-0.4	+3.5	+4.2	+1.7	-1.4	+1.7
Aug	-2.9	-4.5	-5.7	-1.0	-2.2	-2.3	-1.3	-2.2	-0.4	-0.2
Sep	+9.7	+5.6	+5.2	+5.0	+3.4	+6.0*	+4.2	+2.4	+2.0	+1.6
Oct	+3.1	+1.9	-0.1	+1.2	+0.5	+0.1	+1.0	+1.2	+0.9	+0.5
Nov	-1.1	-1.2	-1.3	-0.7	+0.1	-1.3	-0.8	-2.1	+1.1	-0.5
Dec	-6.5	-3.5*	-2.3	-3.7*	-1.1	-1.9	-1.6	-2.9*	+0.1	-3.1
MAM	+2.3	+9.4	+1.9	+9.0*	+2.6	+7.1	+7.3**	+1.7	+1.2	+2.9
JJA	+0.1	-6.3	-9.7	+1.0	-3.5	+3.5	+4.0	-4.3	-3.0	-1.0
SON	+11.6*	+6.2	+3.8	+5.6	+4.0	+4.8	+4.4	+1.4	+4.0	+1.5
DJF	-9.6	-1.2	-2.1	-1.4	+1.1	+0.5	+1.7	-5.2*	+3.9	-5.0
Year	+1.7	+7.1	-7.2	+11.1	+3.3	+14.9	+16.5*	-7.2	+4.9	-2.4

Statistical significance: * $\alpha \leq 0.05$, ** $\alpha \leq 0.01$, *** $\alpha \leq 0.001$

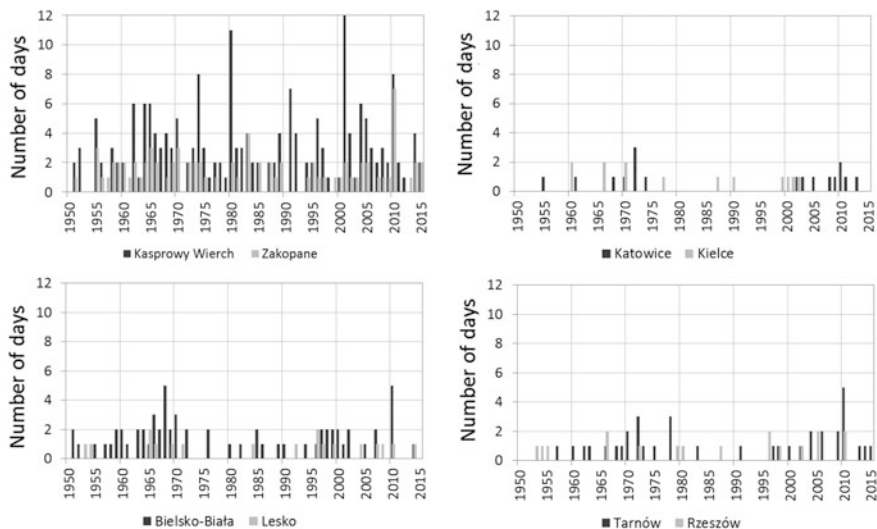


Fig. 15 Annual number of days with precipitation ≥ 50 mm at selected stations in the Upper Vistula Basin in the period 1951–2015

negative trends were found at every station (Table 7). Seasonal precipitation totals experienced more uniform changes. Spatially coherent increase was identified in spring and autumn precipitation. However, significant trends were only detected in Rzeszów (+7.5 mm per 10 years in spring).

In the Upper Vistula Basin, precipitation ≥ 30 mm occurred, on average, several times a year with maximum at Kasprowy Wierch (9 days) and minimum in Sandomierz (1.3 days). The record-high frequencies of days with heavy precipitation fell in different years, depending on the station. However, they accumulated during previously recognized wet periods, namely in 1960s and in particular years of the 1995–2015 period. Tarnów was the only station with statistically significant increase in the frequency of days with precipitation ≥ 30 mm. This tendency was particularly visible between 1995 and 2010 (Fig. 14).

Days with precipitation ≥ 50 mm are very rare in the Upper Vistula Basin (Fig. 15). Even at the most rainy station, Kasprowy Wierch, they occurred on average only 3 times a year. At other stations the frequency of such days varied between 1.2 days (Zakopane) and 0.2 days (Sandomierz, Kielce). In the long-term course, daily precipitation ≥ 50 mm showed tendency to cluster in the second half of the 1960s or between 1965 and 1975 and in the last three pentads of the research period.

We performed detailed analysis of precipitation characteristics using daily data taken from 18 meteorological stations (Table 1; Fig. 1) located within the Tara Mountains and Podhale Basin. The meteorological series that we used end in different periods depending on station (Table 1). We investigated maximum 10-day precipitation total and maximum monthly precipitation total by calculating average

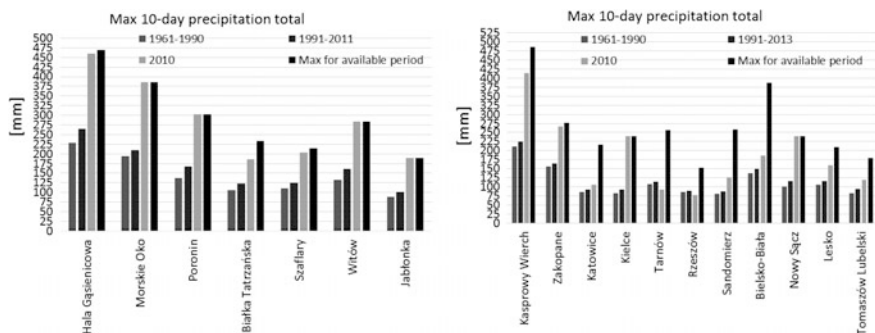


Fig. 16 Comparison of mean 10-day maximum precipitation total for period 1961–1990 with the mean value for the period 1991–2011 (*left*) or 1991–2013 (*right*); the value for 2010 year and the maximum value for all research period

indices for the WMO climatological standard period 1961–1990 and for the 1991–2011 (or 1991–2013 depending on the data availability). These values were compared with the values of indices in the flood year of 2010, as well as with maximum value for the studied period.

Trend detections (Radziejewski and Kundzewicz 2004) for maximum 10-day precipitation totals showed a statistically significant increase at $\alpha < 0.05$ for Tomaszów Lubelski and Lesko. We also found weak ($\alpha < 0.25$) upward trends at four further stations including Hala Gąsienicowa, Poronin, Rzeszów and Tarnów. The comparison of average maximum 10-day precipitation totals for 1961–1990 with 1991–2013 (or 1991–2011) showed that in case of every station the index for the latest period was higher than that for the base period 1961–1990 (Fig. 16). The biggest difference was noted in Poronin (29 mm; 21.5 % of the average 1961–1990) while at other eight stations the increase reached about 10 % with minimum in Rzeszów: 4.2 %. At six stations the highest maximum 10-day precipitation total, just like annual totals, occurred in 2010 while at other five stations the index for 2010 was rated among the highest values.

Maximum monthly precipitation totals significantly increased at the level of 0.05 at stations: Lesko, Tarnów and Tomaszów Lubelski. Similar trends but significant at $\alpha < 0.1$ were also found at Hala Gąsienicowa and Rzeszów. On the other hand at three stations (Białka Tatrzańska, Szaflary and Witów) increases, however very weak, were also identified. At every station, average monthly precipitation for 1991–2013 (or 2011) was higher than that for the WMO base period 1961–1990. The biggest difference was recognised in Poronin (42 mm; 21.8 %). For other nine stations the differences were usually higher than 10 % but the smallest one—3.3 %—was noted at Kasprowy Wierch.

Figure 17 presents mean maximum monthly precipitation total for the normal period 1961–1990 and for the latest period 1991–2013. Also, the values of monthly precipitation total for the flood year 2001 and the maximum value from the entire

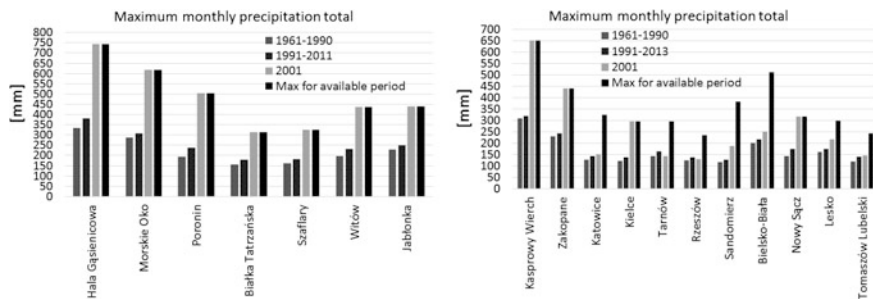


Fig. 17 Comparison between mean monthly maximum precipitation total for the period 1961–1990 and the mean value from period 1991–2011 (*left*) or 1991–2013 (*right*); the value for flood 2001 year and the maximum value for all research period

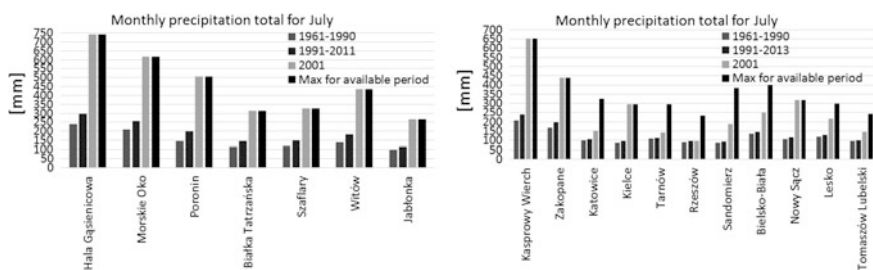


Fig. 18 Comparison between mean monthly precipitation total for July in the period 1961–1990 with the mean value from period 1991–2011 (*left*) or 1991–2013 (*right*); the value for July during flood 2001 year and the maximum value for all research period

period are shown. At every station located on the northern foothills of the Tatra Mountains, maximum monthly precipitation total was registered in the flood year 2001. However, we found no significant changes in monthly precipitation in July, when the totals are the highest of all monthly values. The mean July precipitation totals from the period 1991–2013 (or 2011) were higher than these from the WMO normal period. This increase was fairly evident at 10 stations, where the difference in precipitation totals was higher than 20 %. The highest increase was calculated for Poronin (54 mm; 37.9 %); for another six stations precipitation was recently higher by 10 % than in previous period. The lowest increase was detected in Tarnów (2.6 %).

Figure 18 depicts average monthly precipitation totals for July and extreme values for 2001 and the maximum for the entire research period. Beside July, May is the second month of large flood occurrence in the studied period. May precipitation has slightly increased in Tomaszów Lubelski and at stations: Lesko, Nowy Sącz, Rzeszów, Poronin and Zakopane. The flood during May and June 2010 was one of the most destructive floods in Poland. Precipitation in May 2010 was the

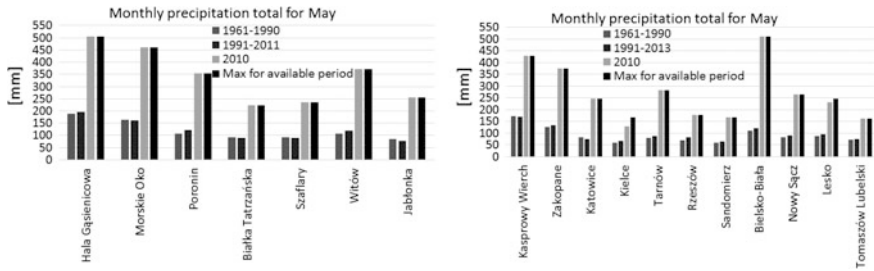


Fig. 19 Comparison between mean monthly precipitation total during May for period 1961–1990 with the mean value from period 1991–2011 (*left*) or 1991–2013 (*right*); the value for May during the flood 2010 year and the maximum value for all research period

highest of the whole available period at 16 stations. Furthermore, average May precipitation for the period 1991–2013 (or 2011) was higher than for the WMO base period at 12 stations, with the highest increase in Rzeszów: 15.9 % i.e. 11.2 mm (Fig. 19).

5 Links Between Temperature and Precipitation

Although there are several non-climatic factors influencing flood hazard, climate change is considered to be one of the principal drivers of the flood frequency. Climate models indicate that severe precipitation and rain-caused floods are likely to become more frequent due to climate warming at various spatial scales (from global via continental, national to regional and local) (IPCC 2013). However relations between precipitation and air temperature are not straightforward. Undebatable increase in air temperature is not currently accompanied by significant increase in precipitation. This is supported by correlation analysis that we performed between precipitation characteristics and summer air temperature (Fig. 20). The only significant ($\alpha < 0.01$) inverse correlation ($r = -0.33$) was found between temperature mentioned and the number of days with precipitation ≥ 30 mm. Decrease in precipitation characteristic in the periods of relatively high temperature in summer was also possible to notice in the long-term course of temperature and precipitation indices discussed previously in this chapter. Decrease in precipitation as a reaction on temperature increase is also proved by differences of temperature and precipitation indices calculated between the 1951–1987 and 1988–2015 periods presented in Table 8. Significant increase in air temperature and insignificant decrease in summer precipitation at majority of stations was found in summer. Trends in the frequency of days with precipitation ≥ 30 mm were insignificant and had different directions.

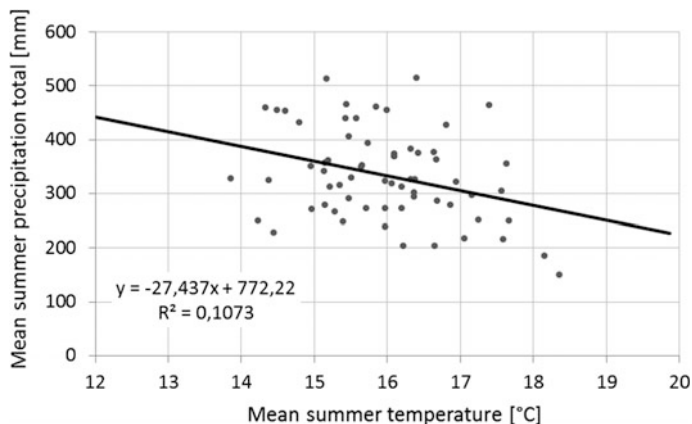


Fig. 20 Regression between mean summer precipitation totals and mean summer air temperature in the Upper Vistula Basin in the period 1951–2015. Mean is the arithmetical average from 10 stations

Figure 21 presents mean precipitation at nine stations, divided into daily precipitation intensity ranges (0–10, 20–20, ... 40–50 mm, and above 50 mm) for two periods: 1961–1990 (WMO climatological standard normal) and more recent, warmer interval 1991–2013. Mean precipitation for the warmer interval 1991–2013 was slightly lower in the range of 40–50 mm, but much higher in the range above 50 mm. This illustrates the increase in precipitation intensity.

Figure 22 presents the mean annual number of days with precipitation in particular ranges for two periods, 1961–1990 and 1991–2013. Only for precipitation range 30–40 mm mean number of days is lower for warmer period 1991–2013. In all other cases mean annual number of days with precipitation was higher than in the base WMO period.

Figure 23 illustrates the time series of mean temperature and precipitation total in the warm half-year, from April to September. A broken-line trend can be spotted, consisting of two linear trends for sub-intervals, 1955–1984 and 1985–2013. In the former sub-interval, slight decrease in temperature and precipitation can be spotted, while in the latter sub-interval both variables are on the rise. However, looking at individual warm half-years, one can see that both time series are in counter-phase, i.e. a local minimum of one coincides with a local maximum of the other. Wet warm half-years 2001 and 2010 coincided with local temperature minima, while a dry half-year 2012 coincided with local temperature maximum.

Table 8 Comparison of selected climatic elements during the cool period (A 1951–1987) and warm period (B 1988–2015) identified on the basis of long-term course of air temperature in the Upper Vistula Basin

Element	Period	12 650	12 625	12 600	12 690	12 566	12 575	12 580	12 585	12 560	12 570	Average from 10 stations
		Kasprowy Wierch	Zakopane	Bielsko-Biala	Lesko	Kraków Balice	Tarnów	Rzeszów	Sandomierz	Katowice	Kielce	
Mean annual T (°C)	A	-0.8	5.1	7.8	7.3	7.7	8.2	7.6	7.7	7.8	7.2	6.6
	B	0.0	6.1	8.8	8.0	8.8	9.2	8.7	8.7	8.9	8.0	7.5
	B-A	+0.8***	+1.0***	+1.0***	+0.7***	+1.0***	+1.0***	+1.1***	+1.0***	+1.0***	+1.0***	+0.9***
Mean summer T (°C)	A	6.5	13.6	16.3	16.0	17.0	17.3	17.1	17.4	16.8	16.7	15.5
	B	7.7	14.9	17.6	17.0	18.3	18.6	18.3	18.4	18.0	17.6	16.6
	B-A	+1.2***	+1.2***	+1.3***	+1.0***	+1.3***	+1.2***	+1.2***	+1.0***	+1.2***	+0.9***	+1.2***
Mean annual P (mm)	A	1757.7	1122.2	996.9	796.6	669.3	702.1	610.2	578.1	715.1	629.0	857.7
	B	1740.9	1137.1	974.0	826.1	670.6	724.1	660.2	551.2	714.2	631.9	863.0
	B-A	-16.8	+14.9	-22.9	+29.5	+1.3	+21.9	+50.1	-27.0	-0.9	+2.9	+5.3
Mean summer P (mm)	A	622.7	501.9	413.4	323.5	269.4	291.7	241.5	236.7	277.2	238.4	341.6
	B	608.8	463.1	369.5	310.1	250.3	283.1	245.0	215.8	254.0	238.8	323.8
	B-A	-13.9	-38.7	-43.9	-13.4	-19.1	-8.6	+3.4	-21.0	-23.2	+0.4	-17.8
NoD	A	9.2	5.3	4.1	2.3	1.5	1.7	1.3	1.5	1.5	1.4	3.0
	B	8.6	5.4	3.6	2.8	1.8	2.4	1.5	1.1	1.5	1.4	3.0
P ≥ 30 mm	A	-0.6	0.0	-0.5	+0.5	+0.3	+0.7	+0.2	-0.4	0.0	0.0	0.0
	B-A											

T—air temperature, P—precipitation, NoD—number of days, A 1951–1987, B 1988–2015, (statistical difference between mean air temperature tested with t-test and between mean precipitation with Mann-Whitney test), statistical significance: * $\alpha \leq 0.05$, ** $\alpha \leq 0.01$, *** $\alpha \leq 0.001$

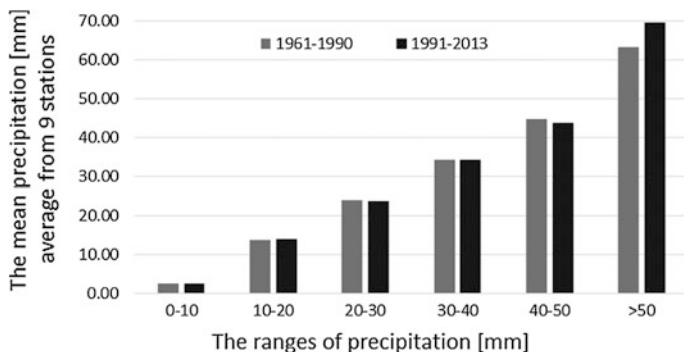


Fig. 21 Mean precipitation at nine stations, divided in daily precipitation intensity ranges (0–10, 20–20, ... 40–50 mm, and above 50 mm) for two periods: 1961–1990 (WMO climatological standard normal) and more recent, warmer interval 1991–2013

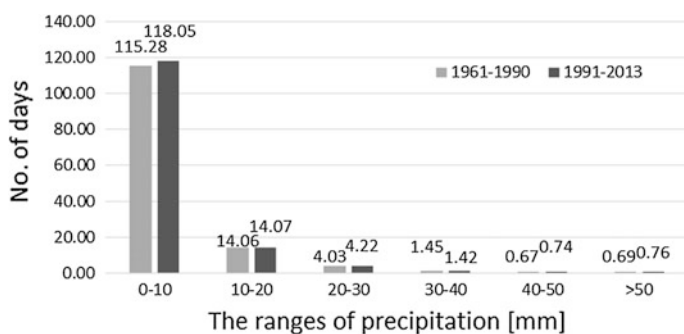


Fig. 22 Mean annual number of days with precipitation (mean from nine stations) for two periods: 1961–1990 and 1991–2013

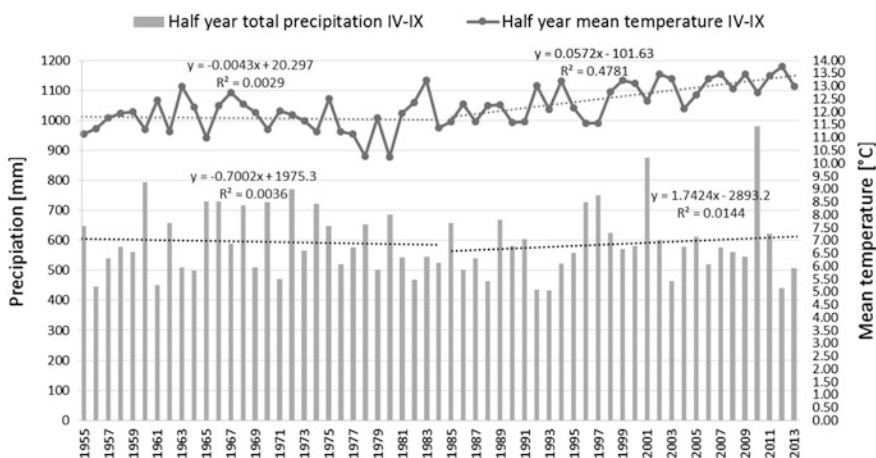


Fig. 23 Time series of mean temperature and precipitation total in the warm half-year, from April to September

6 Conclusions

The Upper Vistula Basin with the Tatra Mountains located in the south-eastern part of Poland are very specific in the scale of the country due to its natural environment which results from variegated altitude. In addition the Tatra Mountains play crucial role in flood precipitation generation being an orographic barrier for air masses flowing into the region from the north-eastern sector. The climatic condition and its changes in the Tatra Mountains can lead to changes in flood condition thus. Using data from 18 meteorological stations covering the period 1951–2015 this chapter discusses changes in air temperature and precipitation characteristics within the Upper Vistula Basin.

Air temperature in the Upper Vistula Basin, likewise on global scale, was significantly rising during the research period. Distinct warming on annual scale started in the first half of the eighties. Different pattern of long-term variability were found for particular seasons. Spring and summer air temperature has been significantly increasing, particularly since the beginning of the eighties, with the rate of 0.21 to 0.40 K per 10 years depending on season and station. Winter air temperature trends were much weaker, however significant at some stations while no significant changes were found in autumn. Upward trends in air temperature within the Upper Vistula Basin were also reflected in the frequency of thermally characteristic days which were significantly changing during the research period. Strong downward trends were found in the frequency of winter days ($T_{avg} \leq 0 \text{ }^\circ\text{C}$) while trends in warm temperature characteristics (hot and very hot days) were positive.

Although there was significant warming in the flood seasons, no significant trends were found in the precipitation indices in the period 1951–2015 in spite of single stations. Moreover these insignificant trends were of various directions depending on station and season. March, September and August were the only months with coherent trends within the entire research area. On seasonal scale quite coherent increases were identified in spring and autumn. On the other hand trend analysis performed for shorter periods (to 2011 or 2013) revealed more coherent increases, but also insignificant. Additionally, the highest values of many precipitation indices occurred in flood years of 2001 and 2010. Important is that in the long-term course of daily precipitation $\geq 50 \text{ mm}$ there was a tendency to their clustering in the second half of the sixties or between 1965 and 1975 and in the last three pentads of the research period.

Trend analysis for 18 stations revealed precipitation increases, but in most cases they were not statistically significant due to precipitation strong irregular natural variability. Every increase in precipitation, especially an increase in long lasting precipitation, i.e. in 10-day precipitation total and monthly precipitation total for the stations located in the area of the Upper Vistula basin can contribute in the future to more severe flash floods and landslides in small catchments of the mountainous tributaries of the Vistula (such as the River Dunajec) and it can generate flood events on lower area of Poland.

Significant increase in air temperature is not currently accompanied by significant increase in precipitation thus changes in precipitation are not directly related to changes in air temperature and they possibly vary in time. Relations between precipitation and air temperature are not straightforward. The results indicate that strong increase in air temperature is rather accompanied by decrease in precipitation frequency and amount. However, this applies only to overall precipitation totals and not to extreme events which are random and can occur unexpectedly. Flood precipitation can also occur during drier periods, as in the last decade of the research period.

Acknowledgments This study was carried out within the FLORIST project (Flood risk on the northern foothills of the Tatra Mountains), supported by a grant from the Swiss Government through the Swiss Contribution to the enlarged European Union (PSPB No. 153/2010). Temperature and precipitation data were made available by Institute of Meteorology and Water Management, National Research Institute (IMGW, PIB). Part of data for the period 2000–2015 was taken from synoptic data-base OGMET.

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