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Spatio-temporal changes in atmospheric precipitation over south-western Poland between the periods 1891–1930 and 1981–2010

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Abstract

In this paper, we quantify the changes in precipitation distribution in south-western Poland between the periods 1891–1930 and 1981–2010. The average monthly precipitation totals available for 368 and 245 stations, respectively, are spatially interpolated and processed to calculate maps of differences and pluvial continentality indices for both periods. The maps are analysed against changes in atmospheric circulation and take into account the potential role of the mountain barrier of the Sudetes. The main findings are (1) winter totals generally increased in conjunction with a higher frequency of zonal circulation; it is more pronounced in the upper parts of the Sudetes due to orographic effects; (2) a decreased frequency of zonal circulation together with an increased frequency of southern flows has likely led to the reduction of precipitation in spring and autumn. These changes have led to a significant modification of the region's pluvial regime, mostly by decreasing continentality features (especially in the Sudetes and the western lowlands). In addition, the strong sheltering influence of the mountain barrier is observed, driving the preservation or even the enhancement of the continental pluvial characteristics in the north-eastern to eastern foregrounds of the Sudetes. This leads to the conclusion that in areas where long-term observed trends or future projections of precipitation are ambiguous, there may occur significant modifications in regional characteristics, especially as a result of changes in atmospheric circulation modified by local orography.

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1 Introduction

Atmospheric precipitation is one of the key elements of the hydrological cycle. It plays a vital role in all natural ecosystems and many human-environment sectors including agriculture, forestry, energy production, water supply and many others. The surplus or deficit in precipitation results in such environmental hazards as, for example, floods, droughts or landslides. Precipitation is also subject to past and future climate changes (IPCC 2014). For the period 1901–2008, globally averaged precipitation exhibits a significant increasing trend. The northern hemisphere mid-latitudes (30–60° N) show an overall rise in precipitation, which is statistically significant for the entire 1901–2008 period, but not significant for 1951–2008 (IPCC 2014). Mean annual precipitation trends since the 1950s show an increase by up to 70 mm per decade in North-eastern and North-western Europe and a decrease by up to 70 mm in some parts of Southern Europe. Seasonal trends show an increase in winter precipitation in Northern Europe and a decrease in Southern Europe, but with large interannual variations (EEA 2012). Similar tendencies

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are projected to continue in the future, with less clear trends in annual totals in Central Europe, an increase in Northern and a decrease in Southern Europe. Climate projections also show a precipitation decrease for the summer months and an increase in winter (Schmidli et al. 2007).

In the area of Central Europe and Poland, the long-term changes of mean precipitation are ambiguous. Measurements show increasing but statistically not significant trends of totals for selected months in the period 1951–2000. Only for March, trend is positive and statistically significant. Despite the lack of statistical significance for the remaining months, a distinct change in seasonal precipitation has taken place. The contribution of summer to annual totals has decreased from 39 to 36% over the last 50 years, and this is attributed to the weakening of continental features of climate (Degirmendžić et al. 2004).

The results of the regional scale project NEYMO (NEYMO 2016) have shown that even in a relatively small area of transboundary region of Poland, Germany and Czech Republic, the trends in mean and extreme precipitation vary seasonally in spatial terms, in relation to both the magnitude and direction. These local variations suggest that a strong role is played by local factors, including orography, which influence regional changes (Uvo 2003; Jaagus et al. 2010). However, the changes in atmospheric circulation are considered one of the main factors modifying pluvial characteristics (Ustrnul and Czekierda 2001). In recent years, much attention has been devoted to the links between atmospheric circulation and precipitation in Central Europe. The research has focused both on the assessment of the synoptic situation, favourable to high daily and extreme rainfalls (Ustrnul and Czekierda 2009; Plavcová et al. 2014; Twardosz et al. 2016), as well as on changes of precipitation totals in time (Degirmendžić et al. 2004; Santos et al. 2016) and space (Hoy et al. 2014).

The main aim of this article is to quantify spatio-temporal changes in monthly and seasonal precipitation totals that have taken place over south-western Poland between XIX/XX c. and XX/XXI c. Such changes are considered to be largely caused by the alteration of the atmospheric circulation together with the impact of the mountain barrier of the Sudetes. These changes are of great importance for the environment and economy in the region analysed.

2 Data and methods

2.1 Study area

The area of interest (AOI), delineated along the boundaries of physical geographical mesoregions (Kondracki 2011), is presented in Fig. 1. The region consists partly of mountain areas (the Sudetes) and foothills in the south, lowlands in the north-west (Silesian-Lusatian Lowlands), north and centre (Silesian Lowland) and highlands in the east (Silesian Highlands). The altitude changes from less than 50 m a.s.l. in the north-west to 1602 m a.s.l. on top of Mt. Śnieżka—the highest peak of the Sudetes. The region is characterised by a transitional climate, with dominating continental features and maritime influences decreasing from west to east. The annual regime of precipitation is typical for a continental climate with summer maxima and winter minima. Mean annual totals reach 1500 mm in the mountains and about 500 mm in the lowlands (Sobik et al. 2014).

2.2 Precipitation datasets

Human activity, including the emission of greenhouse gases, is believed to be a key driver in the recent changes in climate (IPCC 2014). Some studies suggest a potential role of increased concentrations of carbon dioxide and atmospheric aerosols on precipitation (Palmer and Räisänen 2002; Wang et al. 2016). To achieve the main goal of this study, we use two long-term datasets which consist of a sufficient number of rainfall stations for spatial interpolation purposes. The first dataset (historical period (HP)) represents the measurements for the period of relatively low CO_2 concentrations (1891–1930). The second represents the more recent conditions of years 1981–2010 (contemporary period (CP)). The monthly mean precipitation totals for HP were compiled by the German *Reichsamt für Wetterdienst*, and published in *Klimakunde des Deutschen Reiches* (1939). Data for HP were prepared as geodatabase (Latocha et al. 2016) and consists of 368 stations. The CP geodatabase includes measurements provided by the Institute of Meteorology and Water Management in Poland and consists of 245 stations (Fig. 1). The measurements in the two networks, historical German and contemporary Polish, were conducted using the same type of pluviometer—the Hellmann gauge.

For CP, we decided to use the data from the shorter, 30-year 1981–2010 period (in comparison to 40-year-long HP), because of the significant difference in the number of stations with available measurement data. In 1971–2010, there were only 175 stations operating continuously in the region and the closest surroundings. The number of data points is crucial for the quality of spatial interpolation, mainly for the stochastic part of the regression-kriging model used for spatialisation in this study. Reducing the input dataset by 40 stations, while extending the study period to 1971–2010, would be disadvantageous, concerning further reduction of the interpolation set of data necessary to evaluate the quality of interpolation and the reliability of precipitation maps (see Sect. 2.3). The choice of shorter period was supported by testing for statistically significant ($p < 0.05$) differences in monthly means between 1971–2010 and 1981–2010 periods, using the same set of 175 station data. The t test with H0: m1 = m2 (m1 and m2 are means for two periods) revealed that the mean sums differ
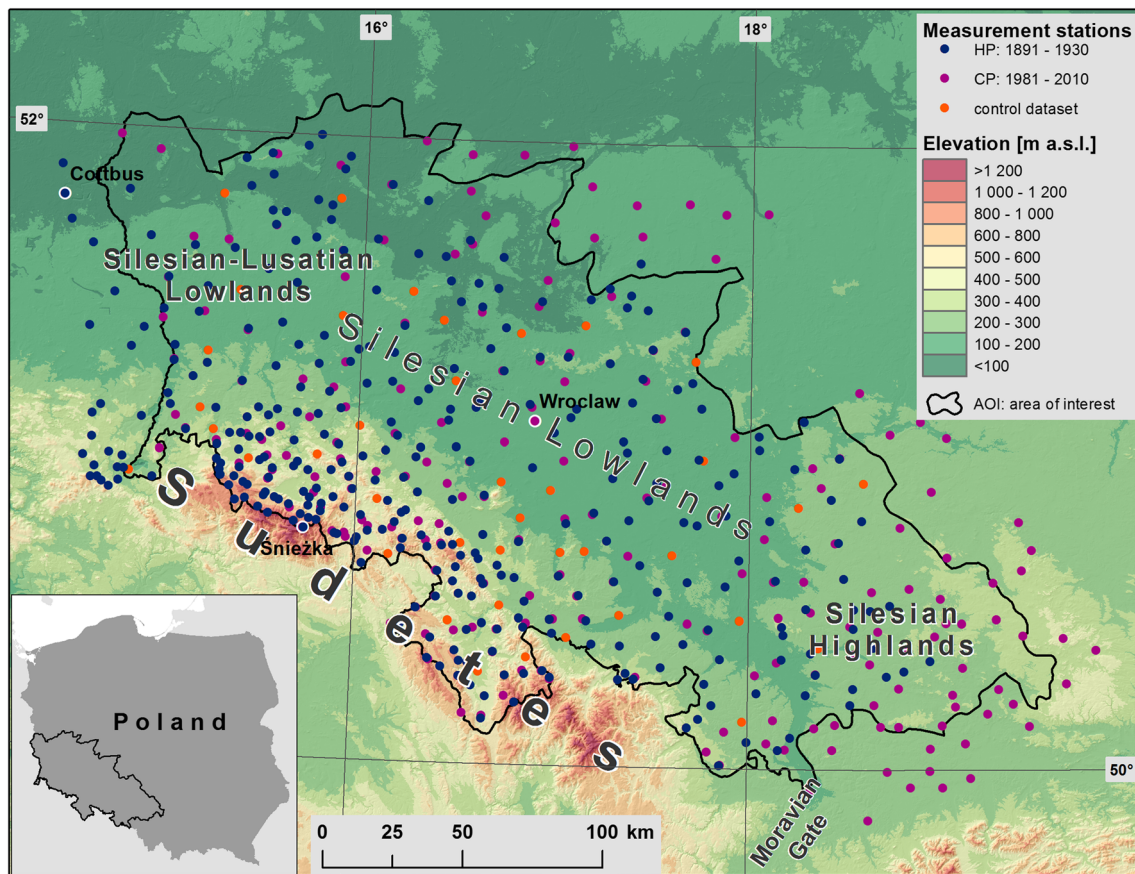
Fig. 1 Study area and distribution of measurement stations in the periods 1891–1930 and 1981–2010

significantly only for March (greater means in 1981–2010 than in 1971–2010), and April and October (smaller means in 1981–2010 than in 1971–2010). Complementing Levene's test with H0: var1 = var2 (var1 and var2 are variances for two periods analysed) showed no statistical differences in variances between monthly datasets for two periods. It should be also stressed that HP could not had been shorten to 30 years, because only mean totals for the whole 1891–1930 period, not for particular months, were published (Klimakunde des Deutschen Reiches 1939).

Time series (1891–2010) analysis were performed based on reconstructed and tested for homogeneity monthly precipitation sums for Wrocław (Bryś and Bryś 2010), located in the central part of AOI, as well as for Cottbus (CDC 2016), located in the western part (Fig. 1), because these were the only stations in AOI with the measurements for the entire period 1891–2010. Statistical significance of trends for all months/seasons was tested with the use of Mann-Kendall test.

2.3 Spatial interpolation

Maps of mean monthly precipitation totals were prepared separately for HP and CP using a spatial interpolation technique. Firstly, the control dataset was established by

the random extraction of 40 stations, common to both datasets. Next, the Śnieżka station, where a significant underestimation of precipitation had been detected (Sobik et al. 2014), was excluded from both datasets. Finally, the interpolation was performed using data from 327 and 204 stations for HP and CP, respectively (Fig. 1). As the interpolated climatological variables are environmentally correlated and the spatial process is likely to be non-stationary, the method of geographically weighted regression-kriging (GWRK) was applied. A combined, deterministic-stochastic GWRK algorithm was developed for the spatial interpolation of climate data in Poland (Szymanowski and Kryza 2011, 2017; Szymanowski et al. 2013). The maps were prepared with a 100 m × 100 m spatial resolution. Each model was validated against the measurements by using the control dataset (Online Resource 1). The annual and seasonal maps were calculated as sums of monthly maps. Areal statistics and statistical tests for differences between HP and CP areal means (Z test with H0: m1 = m2, where m1 and m2 were areal means for HP and CP, respectively) were performed basing on all, over four million grids in AOI. The final step was to calculate the maps of absolute and relative differences between the CP and HP periods and their quotients.

2.4 Continentality indices

Five pluvial continentality indices were selected for comprehensive analysis in this study (Kożuchowski and Wibig 1988). In the continental climate, winter precipitation sums (R_{Win}) are usually smaller than in summer (R_{Sum}), and winter and autumn (R_{Aut}) sums are smaller than for spring (R_{Spr}). Accordingly, three continentality indices are calculated as R_{Win}/R_{Sum}, R_{Win}/R_{Spr} and R_{Aut}/R_{Spr} using the gridded monthly and seasonal totals. All the indices are interpreted similarly—the lower the index value, the stronger the continental signal. The next two indices are Vemic (Szreffel 1961)—k and Wilgat (1949)—v. The Vemic index represents the share of March to September sums in annual total precipitation (R_Y):

$$k = \frac{R_{Mar} + R_{Apr} + \ldots + R_{Sep}}{R_Y}\ 100\ [\%]$$

The second index, also called the index of periodicity, expresses the share of absolute differences between monthly precipitation totals (R_m) and the mean monthly total in the full annual amount:

$$v = \frac{\sum_{m=1}^{12}\left|R_m - \frac{1}{12}R_Y\right|}{R_Y}$$

In both cases (k and v indices), the larger the value of the index, the stronger the continental signal.

The changes in continentality indices between the CP and HP were calculated for each grid cell and presented in maps. Spatial analysis, performed with gridded precipitation, was completed by the analysis of the annual cycle at each station. To eliminate the influence of number of days in months on calculated precipitation sums, the mean daily amounts of precipitation instead of mean monthly sums were used for the analysis. Then, to make annual mean courses of precipitations between station comparable independently of the absolute precipitation amounts, the annual course from each station was standardised. Next, HP and CP datasets were merged to perform a common cluster analysis. The latter was done using the k-means algorithm, and the number of clusters was determined based on the optimisation of the SSB (sum of squares (between)) statistics.

2.5 Atmospheric circulation analysis

For the cause-and-effect analysis, the Grosswetterlagen (GWL) classification and catalogue (Werner and Gerstengarbe 2010; DWD 2016) was used as the frequently applied system for Central Europe and the only dataset covering both HP and CP. GWL takes into account, besides the surface pattern, the synoptic situation in the middle troposphere, which is especially important for the formation of precipitation (Ustrnul and Czekierda 2001). The frequencies of all 30 subtypes were calculated and then merged into 10 circulation types and 3 forms: zonal, half-meridional and meridional. The subtypes were also grouped into cyclonal/anticyclonal forms, continental highs and Atlantic lows and the so-called winter and summer monsoons (Online Resource 2). Differences in proportions of the analysed types/forms between HP and CP were tested using Z test with H0: p1 = p2, where p1 and p2 were proportions in HP and CP, respectively. Additional analysis was performed based on the mean values of the Hurrell station-based monthly NAO index (NAO 2016), calculated separately for HP and CP.

3 Results

3.1 Differences in precipitation totals

The precipitation data covering the whole period 1891–2010 were analysed for Wrocław and Cottbus (Fig. 1). Mean annual sums are very similar in both stations: 576.8 mm in Wrocław and 577.2 mm in Cottbus, and no significant trend in annual totals has been observed in each station (Table 1). However, the lack of clear tendency in annual sums does not mean the lack of significant changes occurring in some months or seasons. Furthermore, the observed tendencies can be opposed in Wrocław and Cottbus. For example, in Wrocław, the statistically significant decreasing trends have been noticed in winter (Jan.) and spring (Apr.) and increasing in summer (Jun.). On the contrary, in Cottbus, the decreasing trend has been observed in summer (Jul.) and increasing in winter (Dec.) and autumn (Nov.). Such a distribution of trends can be interpreted as the intensification of oceanic impact in the west and continental impact in the centre of the study area. This is, however, only partially confirmed by the analysis of trends in continentality indices. The increase of oceanic features in the west (Cottbus) is not statistically significant in period 1891–2010, but there are significant trends in three of five indices in Wrocław: decreasing of R_{Win}/R_{Sum} and increasing of k and v, all supporting the thesis of increasing pluvial continentality in the region of Wrocław (Table 1).

Comparing two analysed periods, the HP was relatively more abundant in rainfall than CP if taking into account annual totals. However, only in autumn the same direction of change (decreasing) is observed in both stations. In three other seasons, the opposite changes are observed at Wrocław and Cottbus, similarly to the trends discussed above (Table 1).

The spatial pattern of absolute values (Fig. 2) and their differences between HP and CP, either absolute (Figs. 2 and 3) or relative (Fig. 2, Online Resource 3), are not uniformly distributed in space. The Z test has revealed that basing on grid-to-grid analysis, precipitation sums differ significantly in all corresponding months/seasons. Average annual totals

Table 1 Average sums of precipitations [mm], continentality indices and trends [mm/100 years] in Wrocław and Cottbus in 1891–2010

|	Station	1891–1900	1901–1910	1911–1920	1921–1930	1931–1940	1941–1950	1951–1960	1961–1970	1971–1980	1981–1990	1991–2000	2001–2010	1891–1930	1981–2010	1891–2010	Trend*
Jan.	Wrocław	39.7	27.1	44.4	41.8	26.9	35.7	24.5	25.6	34.7	29.7	25.2	33.3	38.3	29.4	32.4	−10.2*
	Cottbus	44.6	32.5	44.3	39.5	38.3	45.3	35.6	34.1	33.2	41.8	35.8	41.2	40.2	39.6	38.9	−3.4
Feb.	Wrocław	30.9	29.5	25.2	29.3	24.3	36.9	23.1	33.0	23	24.9	27.9	30.3	28.7	27.7	28.2	−1.6
	Cottbus	39.1	35.3	27.4	26.0	33.2	47.6	26.5	35.3	21.1	32.0	34.0	36.8	32.0	34.3	32.9	−1.3
Mar.	Wrocław	41.2	43	38.8	29.6	29.4	32.2	27.6	31.8	23.2	27.3	46.0	35.7	38.2	36.3	33.8	−5.6
	Cottbus	46.0	39.6	39.7	24.7	35.5	34.2	28.9	34.2	28.3	36.5	47.7	43.0	37.5	42.4	36.5	1.3
Apr.	Wrocław	34.5	44.5	47.3	44.3	35.4	38.3	41.7	38.1	40.5	37.3	34.0	31.3	42.7	34.2	38.9	−8.5*
	Cottbus	34.0	45.3	33.7	41.9	36.7	43.5	42.9	43.3	36.8	46.5	36.5	27.4	38.7	36.8	39.0	−2.3
May	Wrocław	72.4	62.9	46.7	58.7	66.0	65.1	49.9	76.4	57.5	56.8	53.3	63.2	60.2	57.8	60.7	−4.4
	Cottbus	69.7	54.2	45.6	49.1	43.5	59.7	39.4	60.9	60.4	53.0	64.9	59.6	54.7	59.2	55.0	4.4
Jun.	Wrocław	59.1	51.5	59.4	78.3	60.4	83.7	58.3	64.8	84.9	83.8	65.5	62.1	62.1	70.5	67.7	13.5*
	Cottbus	61.6	72.3	55.1	79.7	45.9	58.9	55.9	62.9	77.0	54.3	55.6	41.5	67.2	50.5	60.1	−14.9
Jul.	Wrocław	96.2	86.6	88.7	76.6	60.5	69.7	101.5	73.5	104.0	62.8	93.6	91.0	87.0	82.5	83.7	4.0
	Cottbus	84.5	87.3	56.6	85.6	76.5	65.5	116.4	48.9	60.5	50.1	69.2	83.4	78.5	67.6	73.7	−13.6*
Aug.	Wrocław	51.4	65.3	82.3	72.6	67.6	80.6	55.7	89.5	68.3	69.8	54.7	81.0	67.9	68.5	69.9	7.7
	Cottbus	42.7	68.7	84.5	62.7	74.6	74.2	66.8	83.5	59.8	63.4	61.4	70.7	64.7	65.2	67.8	6.1
Sep.	Wrocław	47.4	49.6	41.3	47.3	73.2	31.3	39.9	41.3	54.1	44.1	49.5	42.9	46.4	45.5	46.8	−2.1
	Cottbus	52.8	50.7	45.0	46.4	48.6	34.3	42.9	49.3	59.8	40.2	44.0	49.4	48.7	44.5	47.0	−2.2
Oct.	Wrocław	40.0	29.7	42.1	63.5	50.6	42.5	32.5	37.6	50.3	31.7	31.9	36.9	43.8	33.5	40.8	−8.4
	Cottbus	40.9	36.4	36.2	64.8	53.9	38.1	42.2	36.5	44.8	31.3	33.7	38.8	44.6	34.6	41.5	−8.8
Nov.	Wrocław	27.9	44.0	39.7	44.5	30.2	41.6	27.2	50.7	43.2	37.4	33.2	42.8	39.0	37.8	38.5	4.2
	Cottbus	32.1	48.1	34.9	41.4	39.0	55.4	36.3	42.3	41.9	43.5	35.7	60.1	39.1	46.4	42.6	11.3*
Dec.	Wrocław	34.6	41.2	45.3	33.0	26.4	35.2	33.3	32.8	37.5	36.4	33.1	35.0	38.5	34.8	35.3	−3.9
	Cottbus	42.1	36.7	52.0	36.2	32.2	35.1	43.8	39.4	48.8	52.9	43.5	46.0	41.8	47.5	42.4	9.0*
Winter	Wrocław	105.2	97.8	114.9	104.1	77.6	107.8	80.9	91.4	95.2	91.0	86.2	98.6	105.5	91.9	95.9	−15.6*
	Cottbus	125.8	104.5	123.7	101.7	103.7	128.0	105.9	108.8	103.1	126.7	113.3	124.0	113.9	121.9	114.1	4.4
Spring	Wrocław	148.1	150.4	132.8	132.6	130.8	135.6	119.2	146.3	121.2	121.4	133.3	130.2	141.0	128.3	133.5	−18.4*
	Cottbus	149.7	139.1	119.0	115.7	115.7	137.4	111.2	138.4	125.5	136.0	149.1	130.0	130.9	138.4	130.6	3.4
Summer	Wrocław	206.7	203.4	230.4	227.5	188.5	234.0	215.5	227.8	257.2	216.4	213.8	234.1	217.0	221.4	221.3	25.2*
	Cottbus	188.8	228.3	196.2	228.0	197.0	198.6	239.1	195.3	197.3	167.8	186.2	195.6	210.3	183.2	201.5	−22.3
Autumn	Wrocław	115.3	123.3	123.1	155.3	154.0	115.4	99.6	129.6	147.6	113.2	114.6	122.6	129.3	116.8	126.1	−6.3
	Cottbus	125.8	135.2	116.1	152.6	141.5	127.8	121.4	128.1	146.5	115.0	113.4	148.3	132.4	125.6	131.0	0.3
Year	Wrocław	575.3	574.9	601.2	619.5	550.0	592.8	515.2	595.1	621.2	542.0	547.9	585.5	592.7	558.5	576.8	−15.1
	Cottbus	590.1	607.1	555.0	598.0	557.9	591.8	577.6	570.6	572.4	545.5	562.0	597.9	587.6	568.5	577.2	−14.3
R_{Win}/R_{Sum}	Wrocław	0.61	0.51	0.58	0.57	0.43	0.47	0.39	0.41	0.40	0.45	0.45	0.45	0.57	0.45	0.48	−0.19*
	Cottbus	0.79	0.60	0.68	0.54	0.54	0.68	0.48	0.57	0.76	0.80	0.67	0.68	0.65	0.72	0.65	0.04
R_{Win}/R_{Spr}	Wrocław	0.80	0.68	0.97	0.89	0.63	0.90	0.72	0.65	0.83	0.85	0.68	0.80	0.84	0.77	0.78	−0.06
	Cottbus	0.97	0.80	1.17	0.99	0.91	0.98	0.99	0.81	1.02	1.02	0.81	1.02	0.98	0.95	0.96	−0.01
R_{Aut}/R_{Spr}	Wrocław	0.83	0.86	1.01	1.25	1.22	0.97	0.86	0.93	1.28	1.07	0.92	1.02	0.99	1.00	1.02	0.10
	Cottbus	0.96	1.01	1.09	1.40	1.26	1.04	1.15	1.02	1.28	0.97	0.82	1.20	1.11	1.00	1.10	−0.02
k	Wrocław	69.0	69.6	67.2	64.9	70.9	68.0	72.6	70.1	69.8	70.5	72.0	68.9	67.6	70.5	69.4	3.2*
	Cottbus	65.3	68.2	64.6	64.5	65.0	62.6	68.0	67.4	66.3	62.6	67.2	62.1	65.6	63.9	65.3	−1.7
v	Wrocław	0.49	0.45	0.45	0.44	0.46	0.49	0.57	0.48	0.55	0.49	0.49	0.49	0.46	0.49	0.49	0.06*
	Cottbus	0.45	0.44	0.46	0.49	0.44	0.45	0.53	0.42	0.50	0.42	0.43	0.46	0.46	0.44	0.46	0.00

Ital are values greater than mean for 1891–2010

[a] Statistically significant ($p < 0.05$) due to Mann-Kendall test

in CP vary between 518.8 mm in the lowlands and 1605.8 mm in the Sudetes. For HP, the range is smaller: from 539.6 to 1563.8 mm, respectively (Table 2, Fig. 2). Taking into consideration the annual areal mean (calculated for the AOI), it is clear that the overall amount of precipitation water inflow has decreased by about 20 mm. However, the range and variation in CP is larger—the minima are smaller and the maxima are higher than in HP (Table 2). Annual totals have increased mostly on mountain ridges (by more than 100 mm or 10%—Online Resource 3), and this is more pronounced in the Eastern Sudetes (Fig. 2). The lower parts of the mountains and foregrounds of the Sudetes, as well as the lowlands in the central (Silesian Lowlands) and north-western part (Silesian-Lusatian Lowlands), have less precipitation in CP, up to 40 mm (5%) when compared to HP. The only exception is the area of increased precipitation in the vicinity of the depression of the Moravian Gate, south of the Silesian Highlands (Figs. 1 and 2). Such a pattern is a result of changes observed on a monthly basis. Generally, we can distinguish three groups of months according to the changes in precipitation distribution. The first group, consisting of months from late autumn (November) to early spring (March), is characterised by a general increase in precipitation (Fig. 3), even if areal means do not fully support this thesis (Table 2). The increase in

monthly sums is especially clear in the highest parts of the Sudetes. In some months, there are also areas with decreased precipitation observed in the foregrounds (January, March and November). The second group, characterised by a decrease in precipitation over the whole AOI, includes the spring (April) and autumn (September–October) months. May is relatively similar, but besides the overall decrease, the precipitation in this month has increased over the eastern part of the AOI. The summer months form the third group, without a distinct spatial tendency of differences (Fig. 3, Online Resource 3, Table 2).

3.2 Changes in precipitation regime

Changes in mean monthly totals have led to a significant modification of the precipitation regime in the region, both in time and space. The only feature which has not changed is the month of maximum precipitation, which is July both for HP and CP (Fig. 4 (A1 and A2)). February (especially for the eastern part of the AOI), January and March are the driest months (Table 2, Fig. 4 (B1 and B2)). One maximum and one minimum in the annual cycle are typical for a continental pluvial regime. In CP, the distribution of months with minimum precipitation totals has changed over most of the AOI. The area of February's minimum has shifted to the east, and
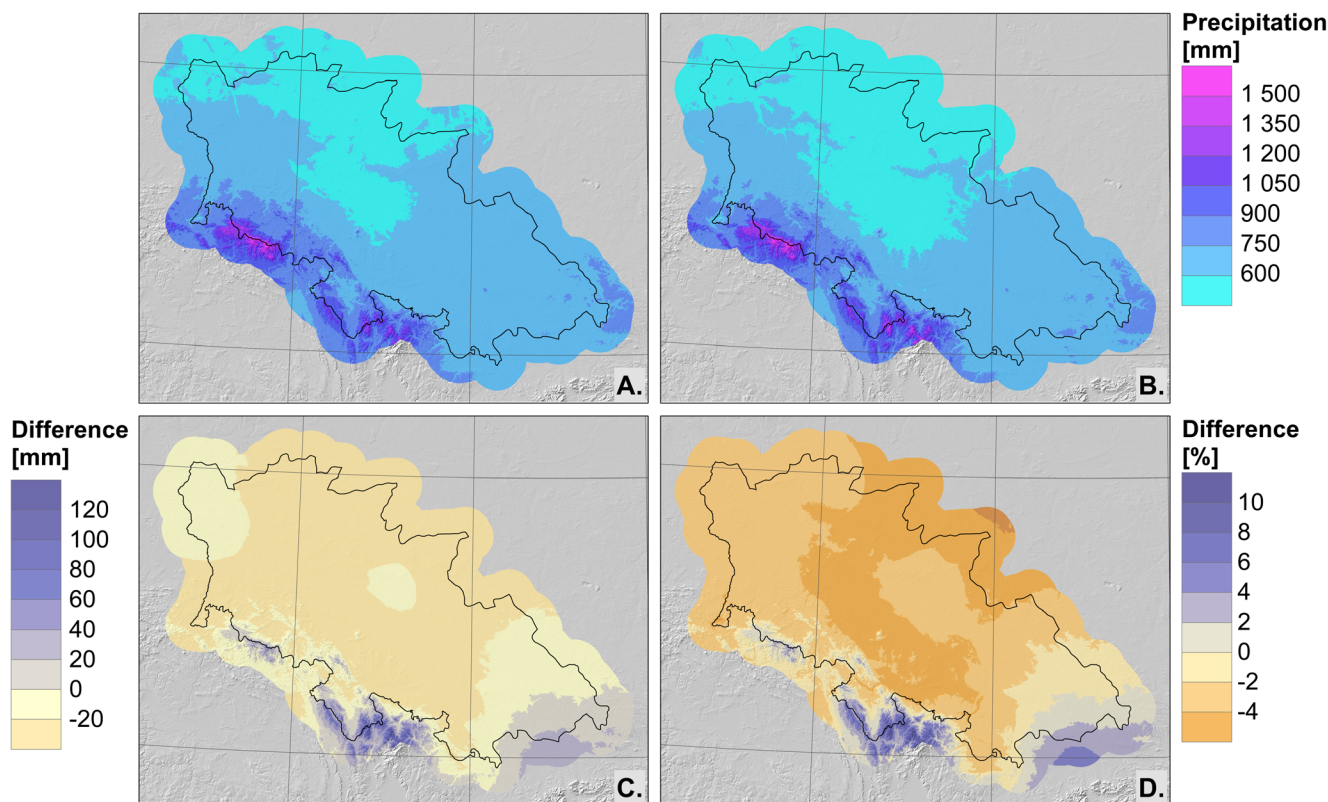
Fig. 2 Mean annual precipitation totals (**a** 1891–1930, **b** 1981–2010), and absolute (**c**) and relative (**d**) differences between mean annual precipitation totals in 1981–2010 and 1891–1930
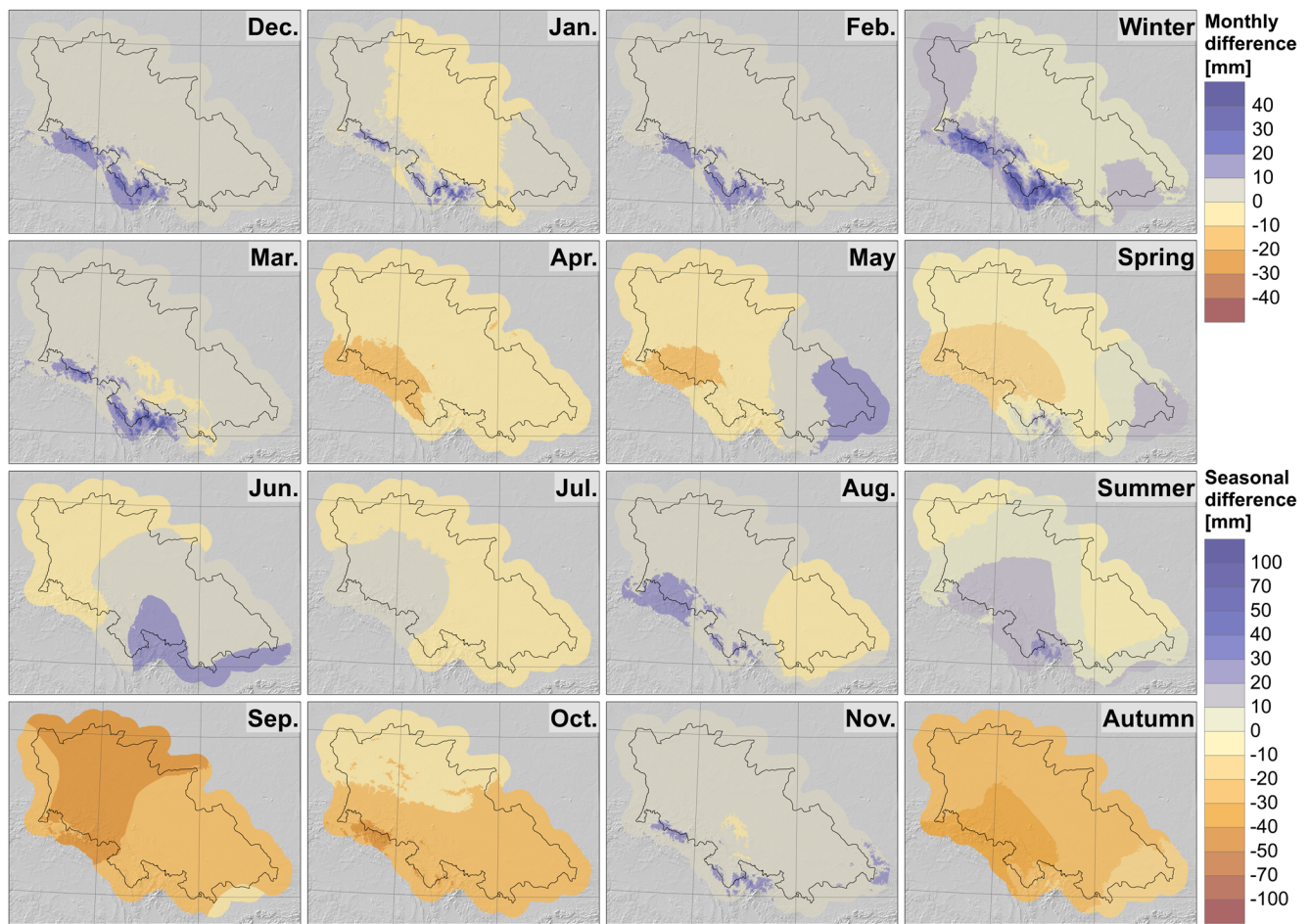
Fig. 3 Absolute differences between mean monthly and seasonal precipitation totals in 1981–2010 and 1891–1930

January is the driest month for the central AOI. Due to a strong decrease in spring and autumn precipitation, in some areas, the lowest totals are now observed in April or October, especially over the mountains, and in the western and northern parts of the AOI (Fig. 4 (B1 and B2)).

The change of pluvial regime is confirmed by the analysis of clusters of stations and their spatial distribution. Four clusters have been determined using SSB statistics and the k-means method. Two of them can be considered to be continental: cluster 1 (named: continental 1)—unimodal, typically continental, and cluster 2 (continental 2)—with slightly higher precipitation in winter. The majority of stations in HP belong to these two clusters. Cluster 1 is more typical for stations at low elevations in the Sudetes and in their foreground. Cluster 2 is more characteristic of lowland stations, even if in some parts a mosaic of both clusters is observed (Fig. 4 (C1)). For CP, none of the stations belongs to cluster 2. Cluster 1 is shifted toward the east, and a large number of stations located in the western and northern parts of the AOI are classified as belonging to cluster 3 (transitional). Cluster 3 stations are characterised by the following modification of an annual course: summer and winter seasons are relatively similar to

these of cluster 2 (Table 3). However, the significant decrease in April and October constitutes a new type of regime with possible minima occurring not in winter, but in one of these 2 months (Table 3, Fig. 4 (B2 and C2)). This type is in fact a transitional form between clusters 1 and 2, and cluster 4 (named superoceanic after Kożuchowski and Wibig 1988), which is typical for highly elevated areas. In HP, this type was limited only to the highest parts of the Western Sudetes, but is now also observed on the highest parts of the Eastern Sudetes. It is likely that cluster 4 was still present in the highest part of the Western Sudetes in CP, even if it is not visible on the map (Fig. 4 (C2)). It is difficult to verify because there was only one meteorological station (Śnieżka—Fig. 1) in CP located above 1000 m a.s.l. in this region, in comparison to six stations in HP. The annual cycle of cluster 4 is bimodal, with a dominating maximum in summer, a secondary maximum in winter and two minima—in spring and autumn (Table 3).

As a result of the quantitative changes in the annual cycle, as well as the changes in spatial distribution of precipitation between HP and CP, the modification of the continentality characteristics expressed in various indices is also observed. The most important features are the decreased totals in autumn

Table 2 Areal statistics of precipitation totals [mm] in SW Poland in the periods 1891–1930 and 1981–2010

Month/season	1891–1930				1981–2010				Difference between 1981 and 2010 and 1891–1930			
	Mean	Min	Max	Std	Mean	Min	Max	Std	Mean	Min	Max	Std
Jan.	39.3	21.6	131.7	7.73	39.2	18.1	155.5	10.40	−0.1	−7.2	35.1	3.13
Feb.	31.4	19.6	101.6	6.84	35.6	22.8	117.7	7.94	4.1	−0.1	29.7	2.17
Mar.	39.3	30.7	105.5	6.66	43.4	30.9	136.3	9.15	4.1	−2.7	44.9	3.19
Apr.	47.2	34.5	112.4	8.40	39.2	30.0	96.0	6.93	−8.1	−22.5	−3.6	1.95
May	65.8	52.4	122.3	9.43	64.2	49.3	104.2	9.62	−1.6	−18.5	15.0	6.94
Jun.	70.7	57.1	146.9	9.87	73.5	53.1	138.3	12.05	2.8	−8.6	15.6	5.79
Jul.	92.0	74.0	177.7	11.60	90.5	71.2	186.4	12.00	−1.6	−7.2	9.7	3.53
Aug.	72.4	56.6	148.5	9.80	75.9	61.5	167.5	10.78	3.6	−4.6	19.0	4.74
Sep.	71.6	60.2	155.1	9.15	53.3	39.1	135.4	10.22	−18.3	−22.2	−9.6	3.09
Oct.	50.5	39.0	124.4	8.91	38.5	31.6	92.9	6.15	−12.0	−31.4	−6.9	3.23
Nov.	41.2	31.6	115.4	6.88	44.8	32.1	135.0	8.77	3.6	−0.7	23.1	2.66
Dec.	41.2	26.0	127.9	8.13	45.4	25.9	155.4	10.48	4.2	−0.7	35.8	2.75
Winter	111.9	72.2	361.2	22.39	120.2	72.1	428.6	28.54	8.3	−5.3	100.6	7.08
Spring	152.4	118.0	339.6	23.41	146.8	116.4	336.4	23.27	−5.5	−18.9	26.2	7.55
Summer	235.1	191.2	471.4	30.55	239.9	185.9	491.5	33.09	4.8	−6.6	27.3	7.14
Autumn	163.3	134.1	391.6	24.34	136.6	106.5	359.8	24.53	−26.7	−34.8	−11.5	4.15
Year	662.7	539.6	1563.8	95.60	643.5	518.8	1605.8	103.46	−19.2	−38.8	139.8	12.31

*Min* minimum, *Max* maximum, *Std* standard deviation

and spring and increased (but differing subregionally) figures in winter (Fig. 3). Analysis of all the five pluvial continentality indices for HP and CP and their quotients leads us to the conclusion that even such a small region can be divided into areas with opposing trends of pluvial regime change. A stronger continental signal is observed in the north-eastern to eastern foregrounds of the Sudetes, together with lower parts of the large concave forms in the mountains. The changes between HP and CP reveal that in these parts of the AOI, the continental features have been preserved, or even enhanced, especially when analysing R_{Win}/R_{Sum}, k and v indices (Fig. 5 (A1–A3, D1–D3, E1–E3)). The only exception is the R_{Aut}/R_{Spr} ratio (Fig. 5 (C1–C3)) which, in accordance with the stronger decrease in autumn than in spring, indicates a greater continentality over the whole region (slightly less in the West Sudetes). The changes in R_{Win}/R_{Spr} (Fig. 5 (B1–B3)) suggest a decrease in continental influences over almost the whole of the AOI, but it is stronger in the western part, especially in the mountains.

4 Discussion and conclusions

The relation between circulation and precipitation is not as straightforward as in the case of other climatic elements, e.g. air temperature (Ustrnul and Czekierda 2001). However, Degirmendžić et al. (2004) estimate that in Poland, about 44% of precipitation variability in February and 46% in July

are determined by circulation processes. Besides the influence of circulation, the formation of favourable conditions for rainfall is dependent mostly on orographic features, convection and the humidity of the air masses. All these features lead to diversified precipitation conditions, especially in areas with complex relief (Ustrnul and Czekierda 2001).

Full statistical analysis of the correlation between atmospheric precipitation and circulation is beyond the scope of this paper. However, some general conclusions can be drawn, based on the analysis of changes in circulation (Table 4) with respect to the role of orography. When analysing circulation-precipitation dependencies, one should remember that not only the most precipitation-favourable synoptic situations are important. In Poland, these are mostly northern to north-eastern to eastern flows (Ustrnul and Czekierda 2001). Those which bring lower intensity, but relatively more frequent precipitation, are also substantial (in Poland—western flows). Many studies report a significant increase in the frequency of winter zonal circulation over the recent years (e.g. Werner and Gerstengarbe 2010; Hoy et al. 2014). The same is found in this study, except that the period of greater precipitation is not only winter itself but the whole November–March interval. All these months are characterised by a general increase in precipitation totals due to a more frequent inflow of humid Atlantic air masses (Table 4). The thesis regarding the crucial role of zonal circulation in the November–March period is also supported by the analysis of cyclonal and Atlantic low circulation types, which are more frequent in CP. The
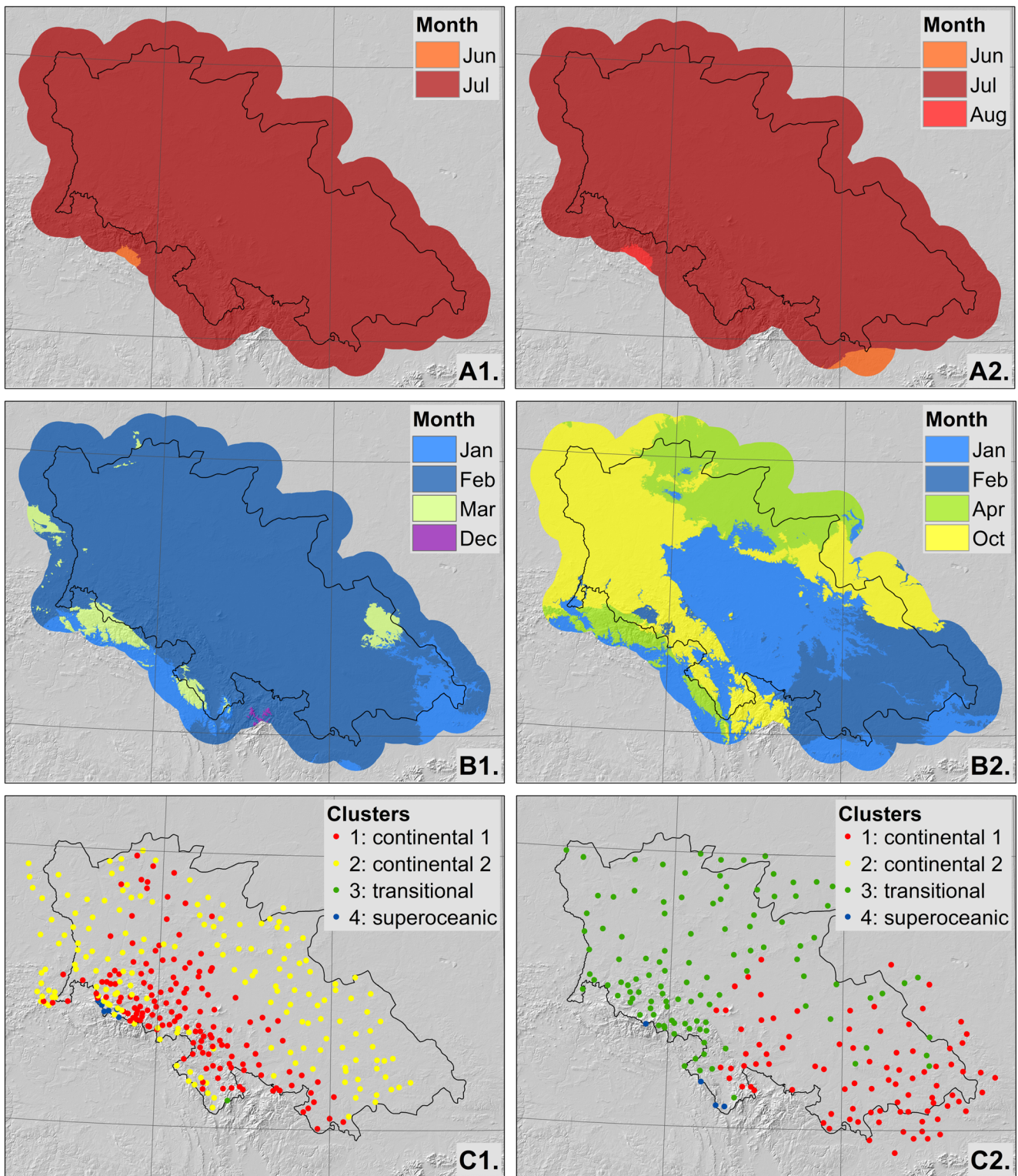
Fig. 4 Months of occurrence of maximum (row A) and minimum (row B) precipitation totals and clusters of stations belonging to a particular type of precipitation regime (row C) in the periods 1891–1930 (column 1) and 1981–2010 (column 2)

winter monsoon (dry, cold air masses) in CP is, conversely, less frequent. The increase in the NAO index (excluding December) is also observed. In the November–March period,

greater differences in rainfall totals are observed in higher parts of the Sudetes as the effect of orographically induced precipitation in western and south-western flows. It is more

Table 3 Mean monthly and seasonal totals [mm] in clusters exhibiting different precipitation regimes

Month/ season	Precipitation regime			
	Continental 1: cluster 1	Continental 2: cluster 2	Transitional: cluster 3	Superoceanic: cluster 4
Jan.	39.0	46.7	42.5	120.8
Feb.	32.3	36.5	38.5	93.5
Mar.	43.1	43.3	47.4	95.9
Apr.	49.8	50.7	40.4	83.5
May	76.7	67.1	63.8	96.8
Jun.	81.8	74.7	73.1	116.1
Jul.	98.0	95.6	94.3	141.3
Aug.	78.6	76.4	81.6	124.1
Sep.	61.3	56.1	54.4	100.5
Oct.	50.7	54.3	40.2	92.8
Nov.	45.5	46.0	47.2	97.0
Dec.	42.5	48.1	48.4	113.7
Winter	113.7	131.3	129.5	328.0
Spring	169.7	161.2	151.5	276.2
Summer	258.4	246.6	248.9	381.5
Autumn	157.5	156.4	141.8	290.3
Year	699.3	695.5	671.8	1275.9

evident on the windward, south side of the Sudetes, where winter sums are greater by as much as 41% at the same height (Sobik et al. 2014). In general, all these facts confirm the thesis regarding the role of zonal circulation and its interaction with orography (Uvo 2003). Both effects can be additionally enhanced by the seeder-feeder mechanism at the highest parts of mountain ranges (Dore et al. 1999).

On the contrary, the increase of measured annual precipitation sums can be partly explained by changes in contribution of solid and liquid precipitation in annual totals. The mechanism is simple but rather difficult to quantify and very hard to spatialise as it requires continuous monitoring of precipitation form, as well as of air temperature and wind speed. Therefore, it goes far beyond the scope of this paper. However, what should be mentioned is that the increase in air temperature observed in Poland is in accordance with global tendency (IPCC 2014; Wibig and Głowicki 2002), and it is also clearly noticed in the highest parts of the Sudetes (Mt Śnieżka), where an increase in winter air temperature and annual duration of days with temperature above zero is evident (Migała et al. 2016). Climate normals of air temperature on Mt. Śnieżka for the period 1891–1930 and 1981–2010 reached the value of 0.1 and 1.2 °C, respectively (Migała et al. 2016). The changes of thermal regime means, among others, shorter winters and changes of precipitations forms with greater proportion of mixed and liquid precipitation, especially in winter (Twardosz et al. 2012; Taskinen and Söderholm 2016). For

solid precipitation, gauge undercatch at the same wind speed is higher than for rain (Wagner 2009), so the observed increase in November–March precipitation sums in the Sudetes may be partly caused by lesser measurement losses in changing thermal conditions.

The sheltering role of the Sudetes is seen in the northeastern and eastern foregrounds and lowlands, where in some regions and months (January), the totals are lower in CP than in HP (Fig. 3). This can be additionally enhanced by the warming and drying influence of the Foehn wind developing in the Sudetes, typically during south-westerly and westerly circulation.

The second group of months (April–May, September–October) is characterised by a relatively uniform decrease in precipitation over the whole or the majority of the AOI. It suggests that the role of local factors, e.g. topography, is less significant in this case than the role of circulation. All these months in CP are characterised by a decreased frequency in westerly and north-north-easterly circulation, whereas the occurrence of southerly and south-westerly flows increases, especially in spring, as compared with HP (Table 4). Generally, the air masses moving from the south are dry, and south-west Poland is further sheltered by the mountain ranges of Central Europe, including the Alps. This is partly in opposition to the statements of Degirmendžić et al. (2004), who observed (for all 4 months considered here; significant only for March) the trends of increasing rainfall totals in Poland in 1951–2000. The authors claimed that this is largely dependent upon the southern circulation enhancement due to migratory cyclones, moving north from the Mediterranean Sea basin.

The spatial pattern of differences in precipitation totals between HP and CP for the summer months is not clear. It is because summer rainfalls are mostly convective in origin and the precipitation field is much more variable than in the case of large-area precipitation.

The spatio-temporal changes between HP and CP have also led to significant changes in the precipitation regime. The continental features are preserved or enhanced in the northeastern-eastern foregrounds of the Sudetes. On the contrary, they have been weakened in the north-western and eastern lowlands and, most clearly, in the highest parts of the Sudetes. The latter subregion is also characterised by a bimodal (summer and winter maxima) distribution of precipitation. Such features are sometimes called a "superoceanity" of mountains (Kożuchowski and Wibig 1988). Consequently, the hypothesis regarding substantial quantitative and spatial changes in the precipitation regime of south-west Poland is confirmed. Future climate scenarios for the end of the twenty-first century in south-west Poland project a further increase in precipitation in winter and a significant decrease in summer. The increase in both the spring (after an initial decrease in 2021–2050) and autumn seasons is also projected (KLIMADA 2013). All this means that further weakening of
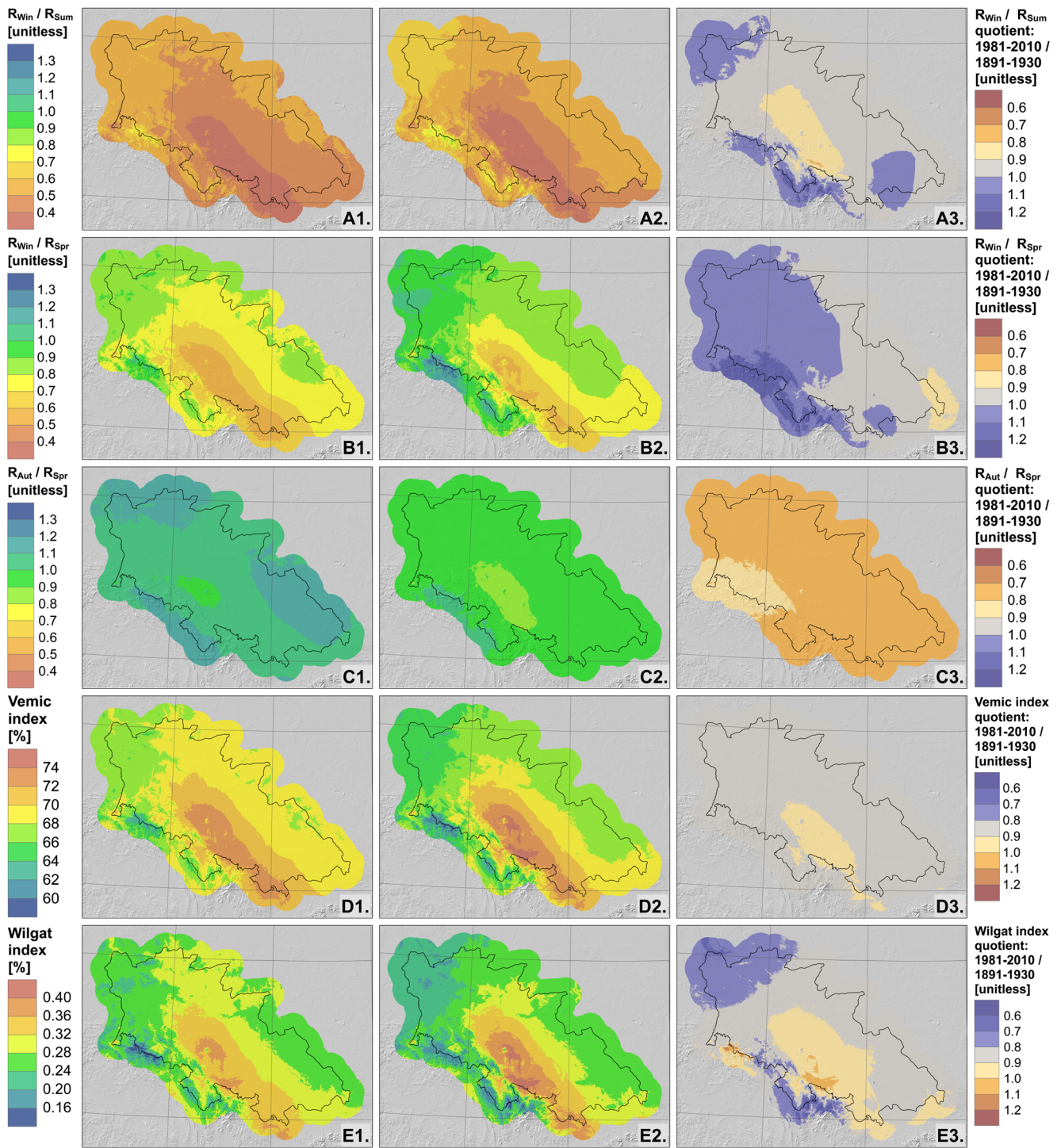
Fig. 5 Continentality indices: R_{Win}/R_{Sum} (row A), R_{Win}/R_{Spr} (row B), R_{Aut}/R_{Spr} (row C), Vemic—k (row D) and Wilgat—v (row E) in the periods 1891–1930 (column 1), 1981–2010 (column 2) and their quotients (column 3)

the pluvial continental regime is likely to be observed in south-west Poland.

The changes described above have important environmental and socio-economic consequences. Increased winter precipitation in the mountains raises the flooding risk, even if the coincidental rise in air temperature increases the frequency of rainfall instead of snowfall. The increased frequency of high water stages has been reported by Walega et al. (2016). Climate change projection also suggests that changes in cyclone track may increase the extreme precipitation events (Nissen et al. 2013). Drier springs and autumns increase the risk of droughts and lengthen the period of enhanced wildfire

Table 4 Mean differences [days] of selected circulation forms/types between the periods 1981–2010 and 1891–1930 (according to Grosswetterlagen classification—Online Resource 2) and mean NAO indices in the periods 1981–2010 and 1891–1930

Circulation form/type	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Winter	Spring	Summer	Autumn	Year
Zonal (Z)	3.36*	0.54	0.16	-2.36*	-2.53*	0.60	-2.02*	-4.94*	-0.48	-0.41	-0.91	-0.19	3.72*	-4.69*	-6.33*	-1.77	-9.05*
West (W)	3.36*	0.54	0.16	-2.36*	-2.53*	0.60	-2.02*	-4.94*	-0.48	-0.41	-0.91	-0.19	3.72*	-4.69*	-6.33*	-1.77	-9.05*
Mixed/half-meridional (H)	-0.36	0.07	3.02*	2.89*	2.73*	1.73*	-0.35	2.38*	2.07*	2.22*	1.30*	1.16	0.90	8.70*	3.81*	5.62*	19.09*
South-west (SW)	0.45	0.31	1.41*	1.88*	2.63*	2.61*	2.07*	2.31*	2.48*	3.72*	1.91*	1.04*	1.82*	5.96*	7.00*	8.12*	22.91*
North-west (NW)	0.28	1.45*	1.88*	-1.35*	-0.85*	-2.51*	-3.66*	-1.73*	1.00*	0.34	1.15*	0.31	2.04*	-0.31	-7.88*	2.50*	-3.63*
Central European high (HME)	0.11	-1.64*	1.16*	2.49*	1.23*	1.50*	1.93*	1.02	-1.93*	-1.48*	-1.16*	-0.05	-1.57	4.88*	4.47*	-4.56*	3.24
Central European low (TME)	-1.20*	-0.05	-1.43*	-0.13	-0.28	0.13	-0.69*	0.78*	0.52*	-0.36*	-0.60*	-0.14	-1.39*	-1.83*	0.22	-0.44	-3.43*
Meridional (M)	-3.20*	-0.64	-3.16*	-0.48	-0.34	-1.99*	2.20*	2.40*	-1.75*	-1.71*	-0.62	-1.27	-5.01*	-3.89*	2.70*	-3.95*	-10.02*
North (N)	0.52	1.32*	-0.07	1.08	-1.86*	-1.45*	0.13	0.55	-0.99	-0.92*	0.20	1.91*	3.79*	-0.80	-0.72	-1.68*	0.62
Nort-heast (NE)	-1.24*	-1.04*	-1.62*	-2.34*	-1.59*	-1.53*	-1.80*	-0.23	-1.81*	-0.52*	-0.06	0.25	-2.02*	-5.54*	-3.56*	-2.37*	-13.46*
East (E)	-1.02*	0.75*	-0.49	-1.13*	-0.59	-0.73*	1.81*	2.31*	-0.45	-0.79*	0.09	-0.93*	-1.19*	-2.20*	3.42*	-1.14*	-1.09
South-east (SE)	-0.25	-0.41	-0.81*	-0.74*	0.54*	0.30*	0.55*	0.17*	0.19	0.19	-0.61*	-1.20*	-1.85*	-1.01*	1.02*	-0.59	-2.42*
South (S)	-1.21*	-1.26*	-0.17	2.65*	3.16*	1.42*	1.51*	-0.40	1.69*	0.33	-0.24	-1.30*	-3.74*	5.66*	2.54*	1.83*	6.33*
Anticyclonic (A)	-2.47*	-2.28*	0.03	-1.22	-2.41*	-2.58*	-2.28*	1.01	-4.31*	-1.30	-4.21*	-1.21	-5.95*	-3.60*	-3.84*	-9.81*	-23.19*
Cyclonal (C)	2.34*	2.30*	0.08	1.34*	2.34*	3.00*	2.19*	-1.10	4.21*	1.45*	4.12*	0.98	5.63*	3.78*	4.08*	9.79*	23.29*
Continental high (CH)	-1.36*	-1.56*	0.80*	-0.79	0.23	-0.87	2.08*	3.16*	-4.12*	-2.33*	-1.63*	-1.35*	-4.28*	0.25	4.36*	-8.08*	-7.73*
Atlantic low (AL)	4.03*	2.83*	4.12*	-0.92	0.61	1.06	0.60	-4.10*	2.28*	1.95*	2.12*	0.30	7.17*	3.81*	-2.43*	6.36*	14.92*
Winter monsoon (WM)	-2.50*	-0.01	-3.20*	-3.81*	-1.00	-3.35*	-0.41	2.08*	-3.12*	-2.45*	-1.64*	-1.80*	-4.30*	-8.02*	-1.66	-7.21*	-21.18*
Summer monsoon (SM)	3.49*	3.98*	3.94*	-2.07*	-4.55*	-2.46*	-2.93*	-4.33*	1.20	1.03	3.84*	3.07*	10.54*	-2.67*	-9.71*	6.08*	4.27
NAO 1891–1930	0.28	0.33	0.28	0.39	0.02	-0.30	0.04	-0.10	0.07	-0.37	0.24	0.21	0.27	0.23	-0.12	-0.02	0.09
NAO 1981–2010	0.51	0.55	0.76	-0.02	-0.09	-0.72	-0.19	0.23	-0.54	0.09	0.24	-0.47	0.20	0.22	-0.22	-0.07	0.03

*Statistically significant ($p < 0.05$) change in frequency of circulation types between corresponding months/seasons in 1981–2010 and 1891–1930

risk. Dry springs hinder the germination of crops, but dry autumns are favourable for ripening, e.g. of high-quality grapes.

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