

Long-term variability of precipitation series in east central Europe in relation to circulation patterns

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Abstract This paper discusses patterns of annual and monthly precipitation variability at seven weather stations in east central Europe (1851–2007). Precipitation patterns were compared to three simple regional indices of atmospheric circulation, i.e., western circulation, southern circulation and the cyclonicity (C) index and a relationship between precipitation and the North Atlantic Oscillation index was identified. Correlations of the monthly records and multiple regression, using a principal components' analysis, helped determine the statistical significance of the dependence of precipitation on the circulation indices. The Mann–Kendall test revealed no trend to change in any of the precipitation series, but a certain spatial regularity could be discerned in the phase of the annual periodic component. A common feature of the variability in central European annual precipitation is the dry period identified in the 1980s and the first half of the 1990s. In the northern part of the region, above-average precipitation was noted from the

1960s through to the mid-1970s as a result of the frequent prevalence of depressions. South of the divide, the wettest period was recorded at the turn of 1930s/1940s. After a number of very wet years in the last decade of the twentieth century and the beginning of the twenty-first century, precipitation began to fall at all of the region's weather stations. The C index is the strongest circulation-linked factor influencing precipitation in central Europe and it accounts for more than 40% of the variance in spatially averaged wintertime precipitation.

1 Introduction

Central and eastern Europe lies far away from the main centres of atmospheric activity in the northern hemisphere, i.e. the high pressure centre of the Azores and the Icelandic low pressure centre. This region of Europe is characterised by alternating weakly outlined high-pressure systems and shallow low-pressure systems with their related atmospheric fronts (of varying scales) which results in a high variability of precipitation. This variability is also exacerbated by a climate that becomes increasingly continental with distance eastwards from the Atlantic Ocean. A significant role in the precipitation regime is also played by orography. In this light, it is important to take long time series from various physical geographical units into account when investigating temporal variability of precipitation in this European region. Jones and Hulme (1996) attached high importance to such regional records in studies of climate change, because shorter periods often featured trends in an opposite direction to the overall trend. Additionally, the error margins associated with estimations from the general circulation model are higher for precipitation than for air temperature (Bradley et al. 1987). There

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are two main groups of precipitation change studies in central Europe. One group includes studies analysing area precipitation totals across the entire region at the annual (Brázdil et al. 1985; Brázdil 1992; Brázdil and Budíková 1994), semi-annual (Kožuchowski and Marciniak 1988) and seasonal scale (Twardosz 1996; Niedźwiedź and Twardosz 2004). The other group comprises national studies of precipitation variability in a region such as Austria (Auer 1993; Auer and Böhm 1994; Auer et al. 2005), the Czech Republic (Bodri et al. 2005), Poland (Kožuchowski 1985; Ustrnul and Czekierda 2001; Twardosz 1999; Żmudzka 2002; Kożuchowski and Żmudzka 2003; Degirmendžić et al. 2004) and Hungary (Domonkos 2003; Domonkos and Tar 2003). Most of these publications are old, just as is a study by Schönwiese and Rapp (1997) that summarises precipitation trends in various European countries during 1961–1990 and 1891–1990. The main findings of these studies include the fact that there are different trends in eastern and western parts of central Europe and the fact that there exists a trend to increasing precipitation variability in the region.

Some projects also searched for correlation between precipitation and atmospheric circulation. The strongest positive correlation was found between (a) macro-types of western circulation (W) and precipitation for the warm half-year (Kožuchowski and Marciniak 1988) and (b) the cyclonicity (C) index and precipitation during the cold half-year (Lapin and Pisútová 1998; Twardosz 1998, 1999; Wibig 1999, 2001; Niedźwiedź and Twardosz 2004). Steinrück (1999) and Ustrnul and Czekierda (2001) published the results of a detailed analysis of relationships between precipitation and atmospheric circulation in central Europe.

This paper discusses patterns of annual and monthly precipitation variability by presenting a number of long and homogeneous series from central Europe. Seven weather stations with series covering the period 1851–2007 have been used in this paper (Table 1). It is important that the analysis extends to the end of the twentieth century and into the early years of the twenty-first century, since this period

brought extreme precipitation events of increased frequency, most notably the catastrophic rainfall of July 1997 affecting the Carpathian and Sudeten Mts. (Niedźwiedź 1999, 2003b), as well as locally torrential downpours in July 2001. With more extreme rainfall in Austria, the Czech Republic and Germany in turn leading to flooding of the Elbe and Danube in August 2002 (Niedźwiedź 2003a; Hladný et al. 2004; Brázdil et al. 2005), it would seem crucial to determine whether the extreme events had any significant impact on the average monthly and annual precipitation.

2 Data

Projections of future precipitation changes requires an understanding of the past. It is very difficult to prepare such projections because few weather stations have long measurement records or full observation documentation and only a very small number of such records can be regarded as homogeneous. Meteorological data from old observations can be inadequate and sometimes even misleading. This could result from a number of factors, such as changes in the direct surroundings of the station occurring over time, changes to the instruments, observers or measurement methodology etc. Hence, there is a need for additional information, metadata, to provide explanations of any possible doubts and to make any necessary corrections. Only then is the information truly useful for scientific research. Norwegian climatologists Hanssen-Bauer and Førland (1994) demonstrated that some 80% of cases concerning homogeneity problems could be explained by errors in the information on the history of a given station.

The authors established an extended monthly precipitation database that would include:

- All existing long data records to the highest extent possible
- Backward extensions of existing records based on archival material and publications thus far unused, with special attention to ‘metadata’

Table 1 Location of the meteorological stations

	Name of the station	WMO no. or nearest	Geographical coordinates		Altitude (m a.s.l.)
			Latitude	Longitude	
	Wrocław	12 424 ^a	51°07' N	17°03' E	120
	Krakow	12 566 ^a	50°04' N	19°58' E	206
	Warsaw	12 375 ^a	52°13' N	21°02' E	110
	Lvov	33 393	49°49' N	23°57' E	325
	Prague	11 515	50°05' N	14°25' E	201
WMO World Meteorological Organisation	Vienna	11 035	48°15' N	16°22' E	200
	Budapest	12 840	47°31' N	19°03' E	129

^a Nearest

- Verifications of data quality and the correction of any errors

The best quality data comes from the Krakow precipitation records with their documented and verified homogeneity (Twardosz 1997). The remaining quality records originate from Prague's Klementinum, Vienna and Budapest. Data from Wroclaw and Lvov are the most distorted because of changes in the recording sites. These last two sources of data were given much attention in the collection and verification of data published in various sources. We used also the oldest central European data for the period prior to 1890, which were published by Hellmann (1906). Other sources included the Global Historical Climate Network (Vose et al. 1992; monthly data available at <ftp://ftp.ncdc.noaa.gov/pub/data/ghcn/>), the World Weather Records series and the Monthly Climate Data for the World bulletin (also available at <ftp://ftp.ncdc.noaa.gov/pub/data/mcdw/>). These databases were prepared by the National Climatic Data Center (<http://lwf.ncdc.noaa.gov/oa/ncdc.html>).

However, they had to be compared with other sources (Scheremetova 1981). Up until 1918, data on Lvov was published in different Austrian meteorological yearbooks and Polish publications (Sprawozdania Komisji Fizjograficznej PAU) and, following that date, in the Polish Meteorological Service's yearbooks (1919–1938) up to 1938. From this date onwards, the data for Lvov was held and made available by the Soviet and then Russian meteorological services (Razuvaev et al. 1993). Records were originally taken at the university station in the city centre and then they moved to the airport in the 1930s. Despite these changes, after the relative homogeneity test (Alexandersson 1986; Štěpánek 2006) with Krakow data and averages for all seven stations, we revealed no significant lack of homogeneity in the series.

The Wroclaw data series was the most difficult to align. Observations were first recorded at Wroclaw University and the Botanical Gardens (Hellmann 1906). In the 1930s, an additional station was established at the airport and a new weather station was opened in the southeast of the city in 1946. The Botanical Gardens station, which had undergone the least change, was chosen as the reference point for all the other points in Wroclaw. Sources used included German meteorological and precipitation yearbooks published up to 1945 (Meteorologisches Jahrbuch), as well as materials from the archives of the Institute of Meteorology and Water Management (IMWM) in Warsaw, as well as Polish meteorological and precipitation yearbooks. The Botanical Gardens records were compared to both the data from Wroclaw University (1946–2002) and the IMWM synoptic station at the airport (initially located at 'Gądów Mały' and, as of 1963, at 'Strachowice'). The Botanical Gardens station was found to

best represent Wroclaw's precipitation patterns and the records were fully aligned.

As regards Warsaw, sources included research published by Gorczyński (1911), yearbooks and the archives of the Institute of Meteorology and Water Management in Warsaw. The series of records originates from just one station at the Astronomical Observatory in the Botanical Gardens and is fully homogeneous.

The stations in Prague (Klementinum) and Vienna (Hohe Warte) had never been moved (Auer 1993; Auer et al. 2005) and there has been no question of a lack of homogeneity in the case of these records. When compared with Vienna, the Budapest series did not display any serious homogeneity disruptions (except for the fact that the recording site was moved to Lorinc airport in 1996).

Altogether, the materials collected provided reliable precipitation data from seven stations (Table 1; Fig. 1) for the period between 1851 and 2007. A comparison was made between the materials collected in this project and the latest daily records made available under the IMPROVE project (Klein Tank et al. 2002). However, this database lacks certain data from Poland which is potentially available in Polish publications and archival material.

All the other data series were tested against the Krakow series as a reference point using the Alexandersson (1986) standard normalised homogeneity test. The *Anklm* package downloaded from the Internet (<http://www.sci>.



Fig. 1 Meteorological stations taken into consideration

muni.cz/~pest; Štěpánek 2006) was used for this purpose. After eliminating several incorrect values, the tests revealed that at a significance level of 5%, there were no grounds for considering any of the precipitation series as non-homogeneous.

3 Methods

Selected statistical characteristics were used to analyse monthly and annual precipitation during the period between 1851 and 2007. The long-term variability curves were smoothed out with the 11-year Gauss low pass filter (von Storch and Zwiers 1999; Schönwiese 2000). We decided to apply the 11-year averaging period to remove short-term fluctuations shorter than 11-year solar cycle. Using the odd time interval, we could have placed each calculated average value exactly in the middle of the smoothing window. The Mann–Kendall test was used for the analysis of precipitation trends. Correlations between monthly series of precipitation were calculated at seven sites. Because of the naturally strong asymmetry of the precipitation distribution, a $\log(P+20)$ transformation was applied with the 20 factor selected so as to minimise the skewness of the outcome distributions. The spatial variability of the annual and semi-annual phase of the precipitation harmonics was also analysed.

Precipitation patterns were compared to selected atmospheric circulation characteristics with the use of regional circulation indices for 1874–2007, determined on the basis of a calendar of circulation types developed by Niedźwiedź (1981, 2007) from a sample area of central Europe within a radius of about 300 km from a grid point located near Krakow (50° N, 20° E). For the purpose of this analysis, three simple indices were derived through modification of the method proposed by Murray and Lewis (1966) using the number of days with specific circulation patterns (Niedźwiedź 1996, 2000, 2002), i.e. W circulation, S circulation and C index.

The western circulation index, expressing the intensity of westerly circulation within the zone, was measured by the summation of scores (points) for days with different directions of air flow as follows: +2 for W, +1 for NW and SW types, –2 for E and –1 for types NE and SE. Positive values of this index occur when there is a distinct predominance of air advection from the west, whilst negative ones point to a strong easterly air flow.

The index of southerly circulation was calculated by the summation of scores allocated as follows: +2 for type S, +1 for types SW and SE, –2 for type N and –1 for types NW and NE. Hence, high positive values of index S point to an intensive meridional advection of air masses from the south, whilst negative ones point rather to advection from the north.

The third index, the cyclonicity index, was found to have the highest impact on precipitation patterns in central

Europe (Niedźwiedź and Twardosz 2004). The cyclonicity index was calculated by the summation of scores (points) for days with particular forms of circulation as follows: +2 for centre of cyclone Cc or trough Bc, +1 for other cyclonic situations northern cyclonic (Nc), NEc, Ec, SEc, Sc, SWc, Wc and NWc, –1 for advective anti-cyclonic types northern anti-cyclonic (Na), NEa, Ea, SEa, Sa, SWa, Wa and Nwa, –2 for centre of anti-cyclone Ca or wedge Ka. Thus, positive values of C mean a measure of domination of cyclonic types of circulation over anti-cyclonic ones during the particular period (month, season, year). Index C for Poland is not well correlated with the North Atlantic Oscillation (NAO) Index (Niedźwiedź 2002) and can therefore be useful as an additional tool in explaining the variability of precipitation.

We also used the most important macro-scale index for the European climate, the NAO Index defined by Hurrell (1995) as the normalised pressure difference between a station on the Azores and one on Iceland. We applied an extended version of the index based on the normalised pressure difference between Gibraltar and Reykjavik (Jones et al. 1997), updated on the Climate Research Unit website (<http://www.cru.uea.ac.uk/cru/data/nao.htm>).

The relation between precipitation and circulation indices was investigated by calculating Pearson's correlation coefficients separately for each station and each month. The significance of the multiple regression coefficients, whereby the circulation indices were the independent variables and the seven monthly precipitation series were the dependent variables, was verified. Finally, regression coefficients were calculated for indices versus the first principal component analysis (PCA1) extracted from seven precipitation series.

4 Averages and probability distributions of precipitation series

In central Europe, despite climatic similarities, precipitation patterns display a considerable variability in time and space. Orographic conditions are also a crucial factor influencing precipitation variability in this relatively limited area. The Sudeten and Carpathian Mts. constitute the main barrier dividing central Europe into two separate parts with different precipitation regimes. At the beginning of the twentieth century, de Martonne (1909) noted this north/south climatic divide by defining the Polish and Danube climate types in his world climate classification.

Basic information on the pluviometric features of climate is provided by means of an annual precipitation analysis allowing the simple identification of years featuring values above and below the long-term average. Amongst the seven selected stations, Krakow and Lvov recorded the highest precipitation values (Figs. 2 and 3); as both stations are

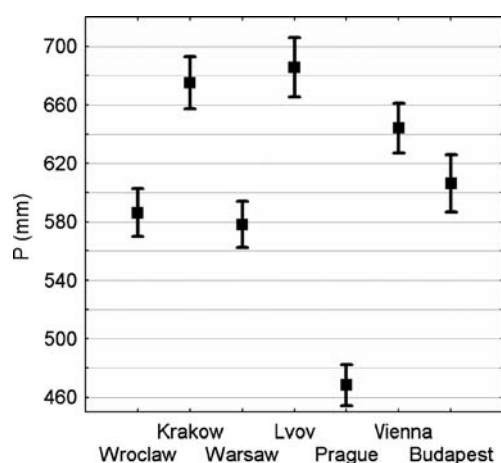


Fig. 2 Annual precipitation averages (*squares*) with 95% confidence intervals (1851–2007)

located north of the Carpathian range, the high values can be explained by the orographic effect occurring at the time of advection from the northern sector (Niedźwiedz 1999, 2003b). Prague received the least precipitation, which can be explained by the location of the city in a mid-mountain basin nearly completely surrounded by mountain ranges. Overall, the northern stations received nearly 10% more precipitation than the southern sites and displayed lower variability.

In order to fulfil the necessary assumptions for the statistical test for the significance of the correlation coefficient, the variables have to be approximately normally distributed. Since it is natural for precipitation data (here, monthly sums) to have a skew distribution, the log transformation has been applied. Because of the general possibility of a value of zero precipitation, some constant value has to be added before determining the logarithm. It has been found that, generally, for all series, the added value of 20 (for monthly sums in millimeter) gives the minimal asymmetry coefficient of the resulting distribution (Fig. 4).

For the example given in Fig. 4, the asymmetry coefficient of the monthly precipitation sums is 1.4 ± 0.2 , whilst after transformation, it is only 0.03 ± 0.2 . The p value of the Shapiro–Wilk test for normality is 0.72, which confirms good normality. This can be seen in the right histogram with the normal curve fitted.

5 Phase of annual cycle of precipitation

Natural periodicity in climate variables is mainly that of the period $T=1$ year and its harmonics, i.e. $T=6$, 4 and 3 months. Statistical significance of periodic components in precipitation series has been tested having in mind the phase as the main goal. So the consistency of phase in three non-overlapping sub-periods of equal length has been

chosen as the testing ‘statistic’ (where the number of three parts is arbitrary). The test is based on visual inspection of the figures and is not based on a strict calculation of p value of the relevant statistics because the final result is based on consistency of phase over the area of research, whilst the spatial distribution of phase would be difficult to subject to a strict statistical test.

The phase is obtained by fitting the data (monthly series) to a sinusoid of the relevant period, $T=1$, $1/2$ and $1/3$ year (Fig. 5). Such a method seems to be better than simply taking the phases from a Fourier analysis, since in the Fourier transformation, the precise periods depended on the series length and would only approximate the values of interest.

Figure 6a demonstrates that the phases of the annual component in three sub-periods and seven sites are consistently close to the average value of 85° . However, there is no statistical significance in the differences between sites based on the variance within the three sub-periods. For $T=1/2$ year (Fig. 6b), the situation seems to be better. However, the most important factor is the correlation between independent results of the phase calculation for $T=1$ and $T=1/2$ year. The p value of relation (correlation coefficient) given in Fig. 6c is equal to 0.006; moreover, the slope of the linear relationship is not far from the expected value. Since the values of phases are given here in degrees, shift of the series in the time domain results in twice as large a change of phase for the $T=1/2$ year component than in the case of the annual component. After removing the southernmost location, Budapest, the regression slope (2.5 ± 0.6) is completely consistent with the expected value of 2; however, for the complete data, the slope is slightly too large: 3.9 ± 0.9 . The most critical argument, however, for the climatological (as well as the statistical) significance of phases is its pattern on the map (Fig. 6d), which seems to be in agreement with independent expectations coming from, for example, the orography.

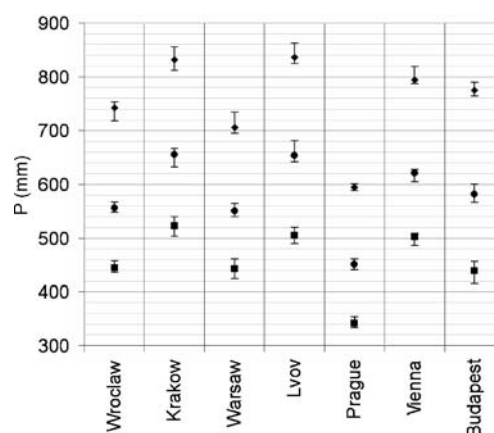
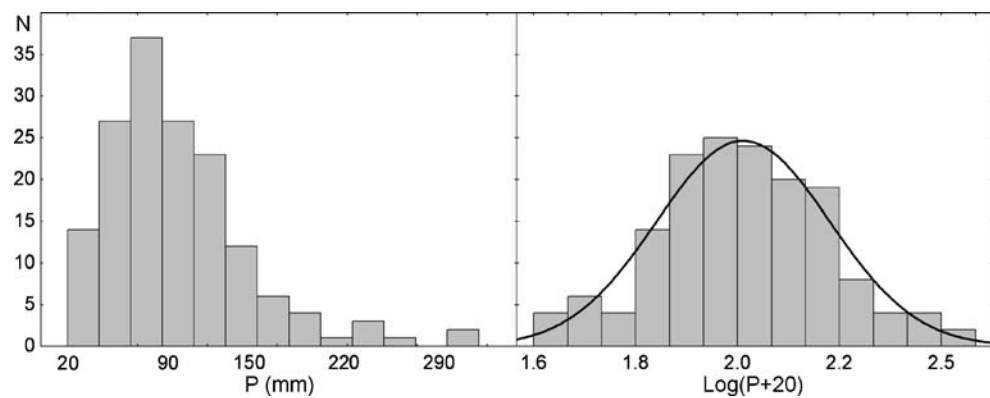


Fig. 3 Distribution of annual precipitation (1851–2007), as indicated by quantiles, 0.1, 0.5 and 0.9 (given with $\pm 1\sigma$ errors)

Fig. 4 Histograms of precipitation values from a typical series (Krakow, January, 1851–2007), before (*left*) and after transformation of data by the $\log(20+P)$ transformation (*right*)



The periodic component with $T=1/3$ year has a consistent value between sites, since the standard deviation ($n=7$) is only 15° . The next harmonic $T=1/4$ gives a standard deviation significantly larger— 40° —a value not far from the standard deviation, 104° , representing a completely randomly distributed angle.

6 Spatial precipitation patterns

The correlation matrix for seven sets of data consists, in fact, of 21 values. In total, 12 such matrices are given in Fig. 7a since an independent matrix is calculated for each month (Walanus 1998). Correlation coefficients r are transformed by Fisher's z -transformation to obtain a normal distribution which is better for graphical visualisation. The grey band corresponds to a 95% confidence interval. Precipitation values were transformed by $\log(P+20)$ to obtain a distribution closer to normal (see Fig. 4). Almost all correlation coefficients are positive; the highest values are generally obtained for October and the winter months. This should be attributed to the general pattern of

circulation prevailing across central Europe in the autumn and winter seasons, i.e. vast high-pressure systems that are not favourable to precipitation, or a frequent passage of low-pressure systems from the Atlantic and the accompanying very large systems of atmospheric fronts. For the summer months, the correlation is weaker. This is when much of the precipitation comes from local downpours with uneven spatial coverage, a typical feature of a continental climate. Geographical correspondence also seems to be well reflected (for example, Vienna–Budapest, Prague–Wrocław).

The correlation matrix for four indices shows consistent negative correlation C-NAO in each month. Index W is positively correlated with NAO; however, the correlation is not significant in summer. Index S, if it exhibits any correlation at all, would only exhibit it with NAO in winter.

7 Long-term changes

The standard Mann–Kendall test has been used to search for a systematic trend (rise or fall) in precipitation as well as circulation indices over a long-time span. Generally, no

Fig. 5 Three exemplar years from the monthly precipitation series for Krakow and its four periodic components: $T=1$, $1/2$, $1/3$ and $1/4$ year, with the fitted phases and amplitudes

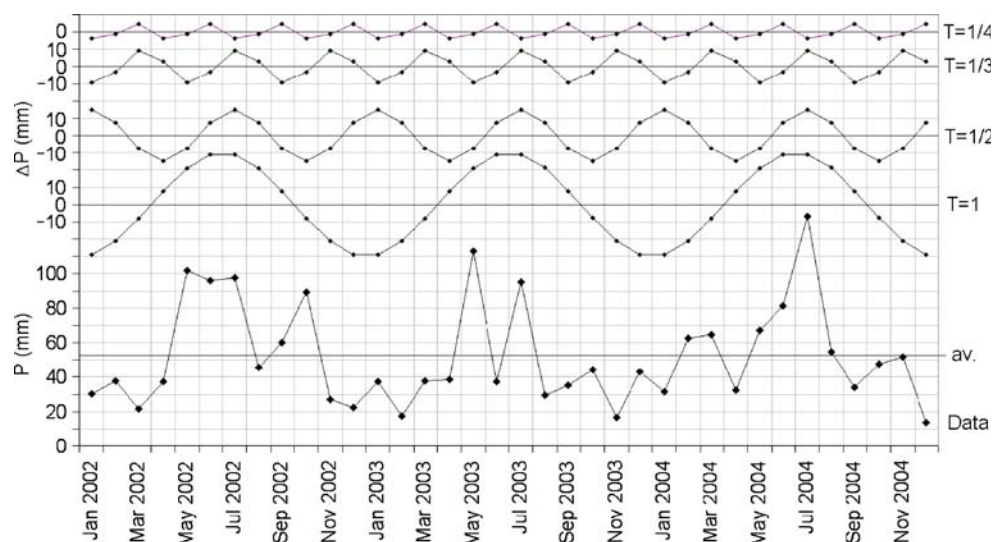


Fig. 6 Phase of annual and half-year harmonic components (sinusoid) of the monthly precipitation series (**a**, **b**). The series were divided into three non-overlapping sub-series in order to obtain an indication of stability as well as the statistical significance of phase. Scatter diagram (**c**) of half-year phases v. $T=1$ year phases. Spatial distribution of phase of the yearly harmonic component (**d**); the day of maximal value of the harmonic component is given

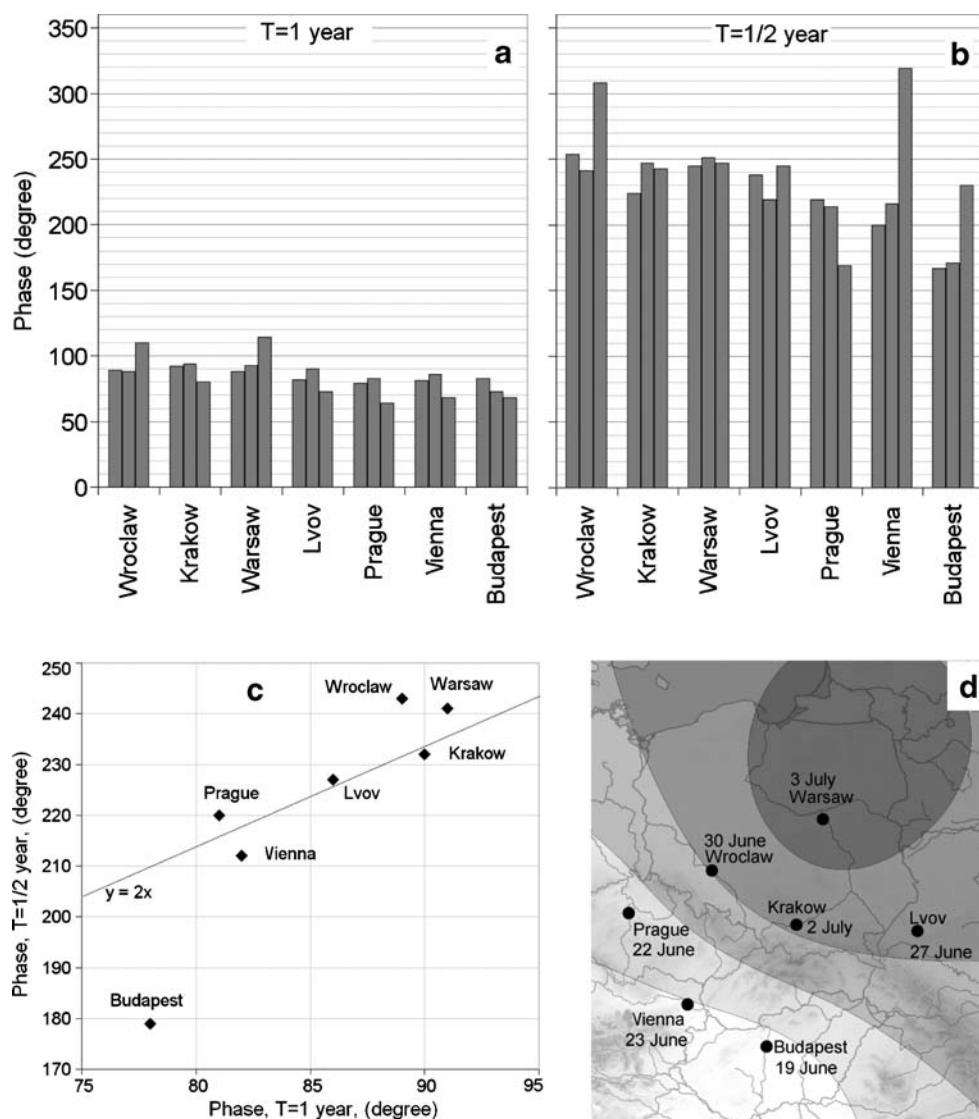


Fig. 7 Correlation matrix of monthly series of precipitation for seven stations (**a**) and for four circulation indices (**b**). Correlation coefficients are given graphically, separately for each month in order: Jan, Feb, ... Dec. A band showing the 95% confidence limits is shown

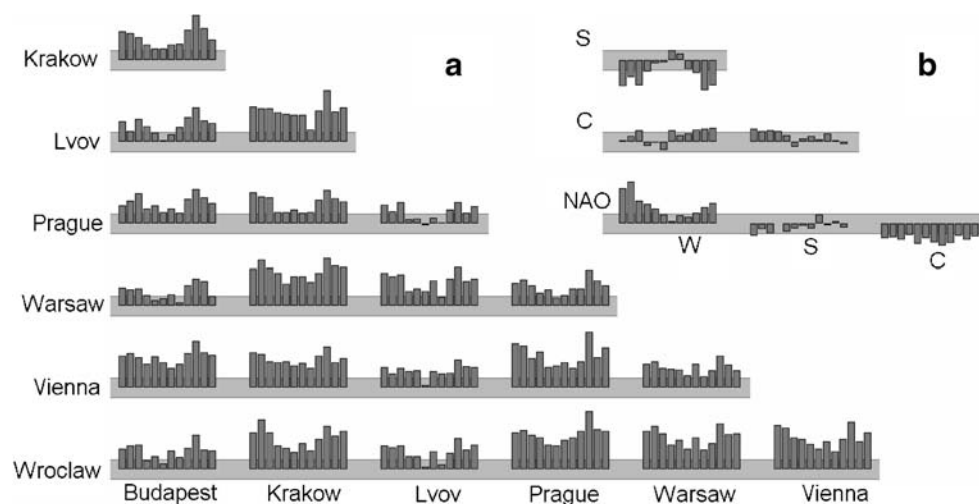


Table 2 The Mann–Kendall test values for annual precipitation series

Wroclaw	1.1
Krakow	0.6
Warsaw	1.0
Lvov	1.9
Prague	1.1
Vienna	0.5
Budapest	−2.3

Approximately, normally distributed values of the Mann–Kendal statistic are standardised to unit variance

trend has been found (Table 2), which was compatible with the conclusions of the Intergovernmental Panel on Climate Change (IPCC) report (IPCC 2007; Trenberth et al. 2007). This is attributable to the overall high variability of precipitation in central Europe, which means that only a very large change would come out as statistically significant. As was aptly noted by Kożuchowski (2004), we are dealing with irregular fluctuations and a movement of surplus and deficit precipitation, rather than a sustained trend. According to his study, Poland lost 15 mm of precipitation during the entire twentieth century, whilst the second half of the century saw a trend of precipitation increasing by 15 mm. Indeed, the vector and the scale of a trend strictly depend on the length of the record analysed. Looking for a trend in fragments of a longer series requires great care in the assessment of the significance of an outcome, which is why this study looks at complete series. In Table 2, the value for Budapest exceeds the critical value 1.96 associated with the standard significance level $\alpha = 0.05$; however, it must be mentioned that this station is cited here because it is an extreme and as such is by no means significant. Also, the average value of the Mann–Kendall statistic for all seven sites is not significant (standardised value $z = 1.47$). The fact that for seven stations as many as six have the same sign (+) of Mann–Kendall statistic would be treated as a significant result; however, a calculation based on the binomial distribution gives a p value $0.063 > 0.05$.

Having in mind the main goal of the analysis, i.e. a correlation of precipitation with the circulation indices, the precipitation series were shortened to begin in 1874 (finishing in 2007). Taking monthly series separately (Fig. 8) gives some indication that, maybe, February and November follow a positive trend, whilst October a negative; however, no statistical significance can be assigned to that observation. The excess of the 3σ limit in the case of the Budapest series for October, also visible in Fig. 8, cannot be treated as significant (3σ is equivalent to $\alpha = 0.0027$) since it is the only one such a value amongst a total number of $7 \times 12 = 84$ tests performed (Prokop and Walanus 2003).

The indices used give no significant Mann–Kendall test results, despite the C index which gives a p value 0.00001

with a positive trend. That index, however, exhibits a specific clear pattern of change in time which is not discussed here.

Long-term annual precipitation patterns are rather irregular (Fig. 9), as was mentioned by earlier publications seeking to identify their cyclical nature (Kożuchowski and Marciniak 1988; Kożuchowski and Wibig 1988; Brázdil 1992; Kożuchowski and Žmudzka 2003; Degirmendžić et al. 2004). Through the application of the AnClim-software (Štěpánek 2006) based on the power spectrum method (maximum entropy spectrum analysis), the authors identified weak 3.2–3.7 year periods. On the southern side of the mountain ranges, there was also a 5-year period and in Prague, a period of 7.8 years. North of the mountains, there were periods of 6.6 years (Wroclaw), 17–18 years (Lvov and Warsaw) and 34 years (Krakow).

Significant periods in fluctuations were recorded in Krakow, the most central of all the stations in the region. This station recorded relatively high precipitation during 1893–1919 and 1958–1972 and a trend to above-average precipitation lasted between the mid-1990s and the early twenty-first century. Precipitation below the long-term

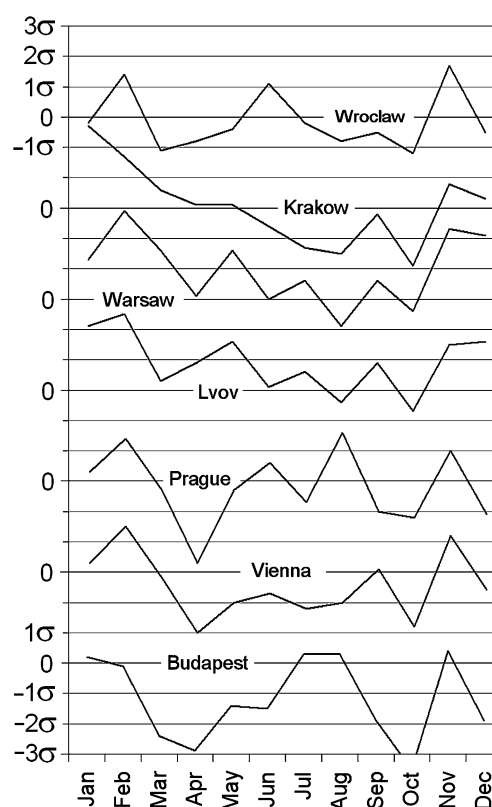
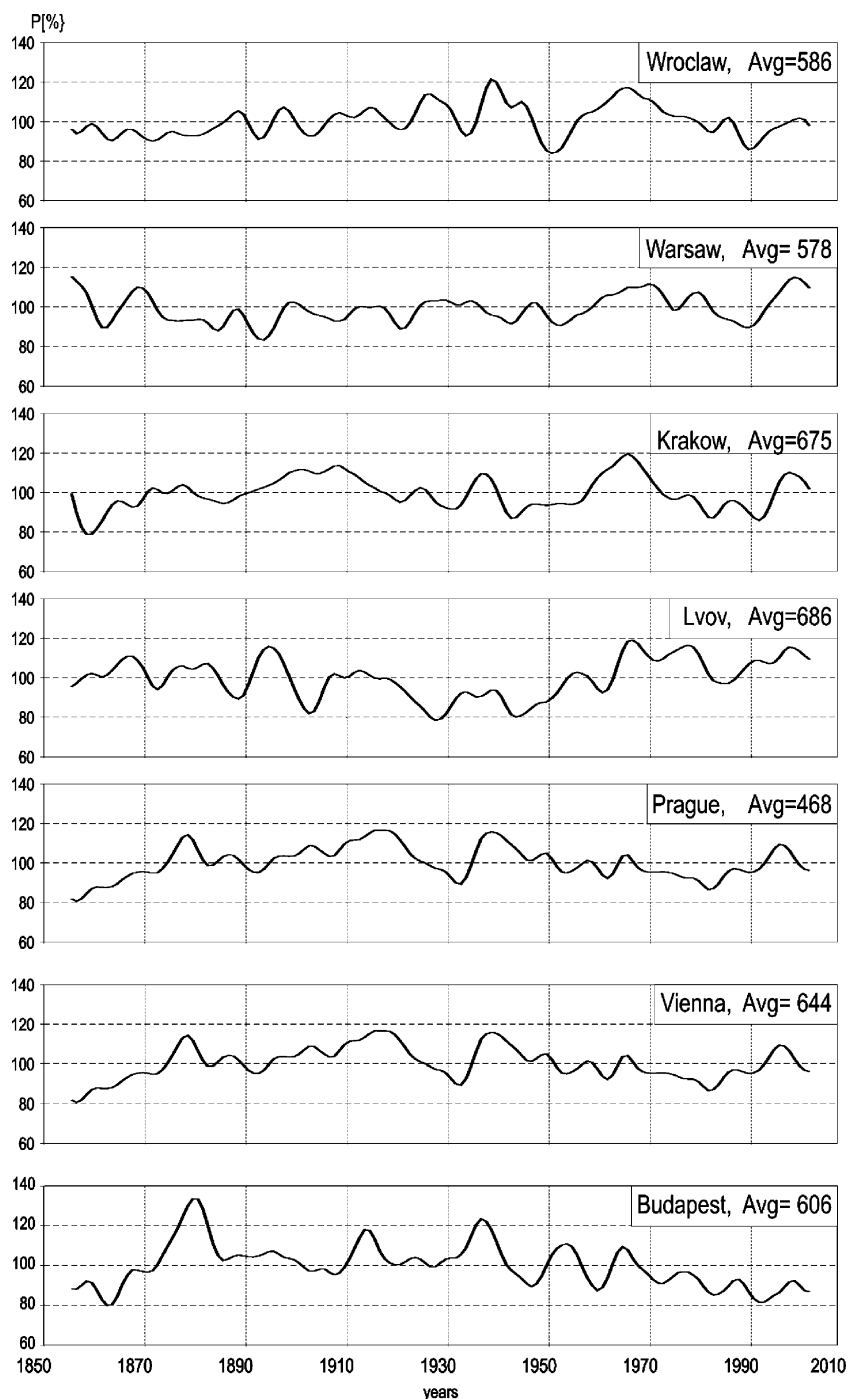


Fig. 8 The Mann–Kendall test values for monthly precipitation series (1874–2007). Each plot is given around the 0 value (indicating no trend). The distance between horizontal lines is equal to 1σ of the normally distributed Mann–Kendall statistic. The description of x-axis for Budapest and Wroclaw is the same for all the other stations

Fig. 9 Deviations of annual precipitation totals (relative values in %) from the long-term average (1851–2007)—Avg (mm). The curves are smoothed by the 11-year Gauss low pass filter



mean has clearly persisted for several years now. There are also rather compact periods with lower precipitation: 1856–1870, 1942–1957 and 1973–1993. Precipitation fluctuations in Krakow are regarded as representative for southern Poland (Cebulska et al. 2007), with the exception of the mountains and Silesian Lowland (Wroclaw).

Distinct dry and wet periods can also easily be traced in Lvov, the most continental of the stations selected, just as in Krakow. However, in contrast to Krakow, precipitation

in Lvov was not so regular. The second halves of the nineteenth and twentieth centuries were marked by prevailing wet years, whilst the first half of the last century was dominated by low-precipitation years.

The Warsaw precipitation series revealed two wet periods, before 1860 and 1960–1981. The driest period was recorded in 1982–1993 when none of the annual values so much as equalled the long-term average. In Wroclaw, the second half of the twentieth century brought a similar

precipitation pattern as for Warsaw. The wettest period in this city occurred during 1938–1946 and then between 1955 and 1981.

Prague featured the most balanced pattern, particularly over the last 50 years. There was a distinct dry period during 1857–1874. The latter period coincided with similar dry periods in Budapest and Vienna. Budapest and Vienna recorded much higher precipitation fluctuation with wet periods during the 1870s and at the turn of the 1930s and 1940s. In Budapest and Vienna, just as in weather stations to the north of the Carpathian Mountains, the dry period from the 1980s until the early 1990s was followed by a wetter period that ended at the beginning of the twenty-first century.

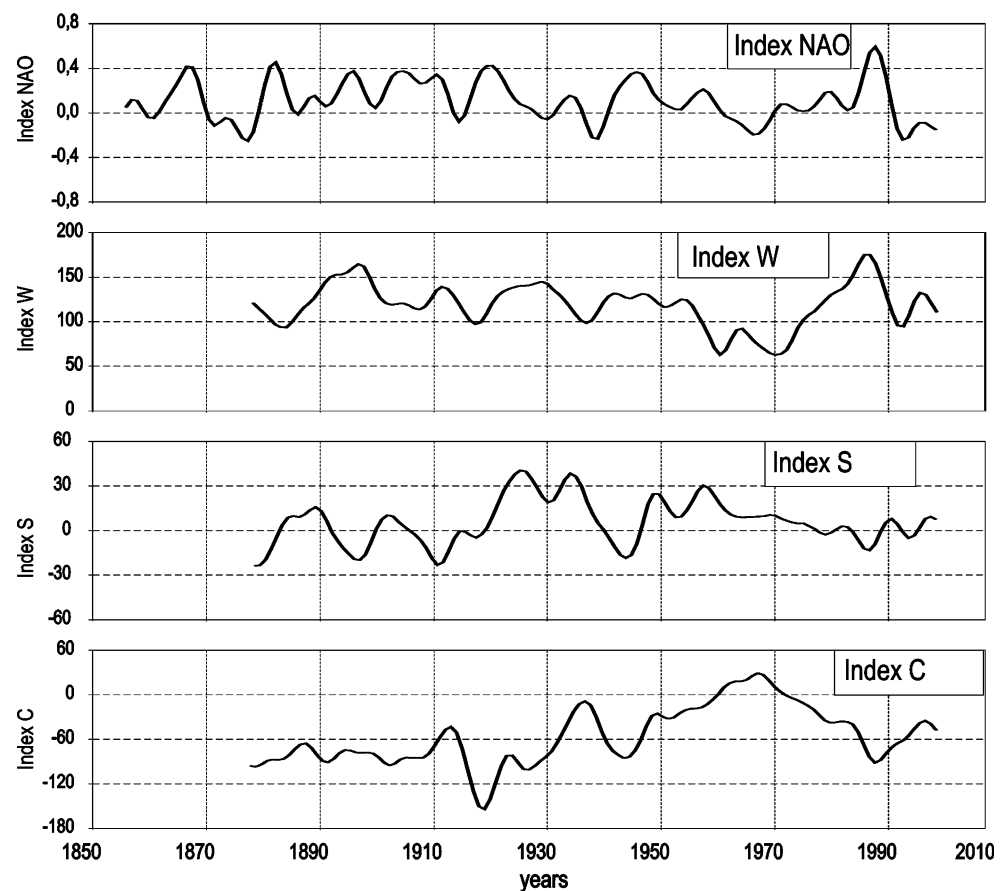
Therefore, there are a number of similarities, as well as differences, between precipitation patterns across central Europe. The similarities would include the dry period of the 1980s and the first half of the 1990s. On the northern side of the Carpathians and Sudeten Mts., the wettest period spanned the 1960s and mid-1970s and coincided with the frequent occurrence of low pressure systems (Fig. 10). Indeed, during 1963–1976, it was cyclonic systems that occurred far more often in central Europe than anti-cyclonic systems.

At a global scale, as one reads in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change

(IPCC 2007; Trenberth et al. 2007), the global trend in mean annual precipitation on land over the period from 1900 to 2005 is statistically insignificant. There is a relatively long sustained period of increasing annual precipitation from 1950 to 1990. The precipitation peaks mostly during the middle of that period, i.e. 1960–1980, whilst very dry spells were recorded during 1950–1958 and again in 1982–1995. Central Europe occupies a transitional zone between Scandinavia, with its increasing wintertime precipitation (Førland and Hanssen-Bauer 1995) and the Mediterranean, with its significant trend of falling precipitation (Maheras et al. 2004). On the southern side of the mountains, the highest precipitation values were recorded at the turn of 1930s and 1940s, a finding also noted in other publications (Brázdil et al. 1985; Auer 1993). After a series of very wet years during the 1990s and at the beginning of the twenty-first century, all weather stations in the region recorded a distinct reduction in precipitation.

A 30-year precipitation scenario for Krakow, based on a Fourier's harmonic analysis, envisages this falling trend lasting until 2015, after which precipitation should start increasing again (Cebulska et al. 2007). A trend to increasing precipitation is also envisaged by modellers; the HadCM2 GS climate model features an increase in

Fig. 10 The 11-year Gauss low pass filter for annual circulation indices



atmospheric precipitation in our climatic zone in the future, i.e. in the mid-twenty-first century, alongside progressive climatic warming (Kożuchowski 2004). This increase is estimated at approximately 30% of the total precipitation. It must be noted, however, that even the author of the scenario has admitted its very large margin of uncertainty. Certain studies show that the amount of precipitation falling in Poland is mainly controlled by the atmospheric circulation and in particular by the frequency of cyclones migrating across central Europe (Degirmendžić et al. 2004). Indeed, Niedźwiedź and Twardosz (2004) found that over 60% of the precipitation variability recorded in Krakow in certain months during 1961–1990 was dependent on changes in the cyclonicity index.

8 Impact of circulation on precipitation patterns

In general, the circulation index C explains precipitation well at all seven sites in central Europe. The correlation is positive and statistically significant ($\alpha=0.05$) for all months and all sites (Fig. 11).

Increased cyclonic activity in central Europe is conducive to higher precipitation. Low-pressure areas generated in the Mediterranean, with their systems of active atmospheric fronts (migrating NE according to the Vb van Bebber track), yield very high precipitation totals in the Carpathian Mountains (Morawska-Horawska 1971; Twardosz 2007). Atlantic depressions play a greater role in shaping the precipitation of northern Poland. They are behind the greatest correlation coefficients with the zonal circulation indices (W) recorded at weather stations in lowland Poland, i.e. where low-pressure areas move freely from west to east unimpeded by orographic barriers. This effect was particularly strong in Warsaw and Wrocław, although the correlation of precipitation with the W index was weak at these stations (Fig. 11). South of the Carpathian Mountains (Budapest), on the other hand, the correlation coefficients were negative in each month. It is worth highlighting that the p value, in case of full agreement of the correlation sign ($\pm$) for all 12 independent correlation coefficients, is 0.002 ($=2^{-11}$ – the probability of 12 coins landing on the same side), which means that the significance is high.

The meridional circulation index S consistently correlates with precipitation in the case of Lvov, Krakow and Warsaw. A negative correlation of precipitation and the meridional circulation index means that precipitation increases at a time of increased advection from the northern sector. This could be explained by the air masses being blocked above the Carpathian slopes inducing precipitation to reach far into the mountain foreland. This orographic effect is also visible in large-scale precipitation at Krakow and Lvov. Indeed, advection from the north or northeast produced recorded events that yielded more than 80 mm per day in Krakow (Twardosz and Niedźwiedź 2001) and more than 100 mm in the Carpathian Mountains (Cebulak 1992).

The NAO index only correlates well with winter precipitation in Budapest (Fig. 11). A statistically significant correlation between wintertime precipitation and the North Atlantic Oscillation was also demonstrated at numerous stations in Rumania (Tomozeiu et al. 2005) and in Belgrade (Tošić and Unkašević 2005). However, the negative values for all sites for the second part of the year seem to indicate some regular dependence because there are only very few exceptions to this rule.

Another approach to investigating dependence of precipitation on circulation indices would naturally be based on the multiple regression method. The regression has been performed independently for all sites, as well as for the first principal component. The PCA performed for seven monthly series of precipitation gave a simple result. The first component explains as much as 54% of the variance. The impact of the next components are generally lower (12.8%, 10.3%, 6.6%, 4.9% and 4.7%) so, even the second principal component only seems to represent noise. From the last column in Table 3 (PCA1), it is clear that indices C and S are strongly significant as well as W. The p value which describes the strength of the relationship $PCA1 = f$ (NAO) is higher than the typical level taken to represent significance, $0.068 > 0.05$; however, it is not much higher. NAO only explains precipitation well in Budapest and also, to some extent, in Lvov. These results are difficult to explain at the moment. p values for dependence on NAO are completely non-significant for other sites. The index C is the only one which has the highest significance at all sites; however, S is only weaker in the case of Budapest

Fig. 11 Correlations between precipitation and circulation indices, see Fig. 7 for explanation

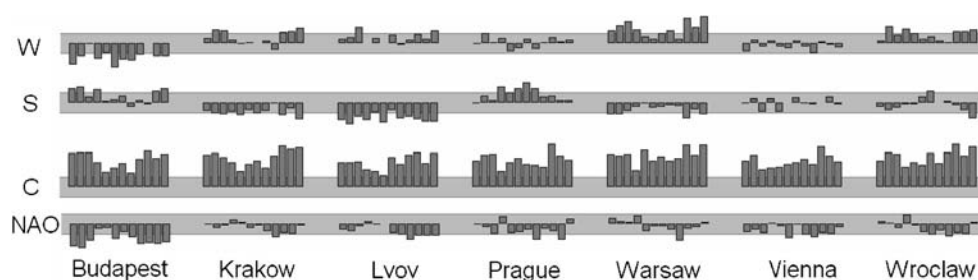


Table 3 p values of multiple regression coefficients, which indicate how important are given circulation indices in explaining precipitation at a given site

	Wroclaw	Krakow	Warsaw	Lvov	Prague	Vienna	Budapest	PCA1
W	0.2	0.004	0.000014	0.12	0.00007	0	0	0.00086
S	0	0	0	0	0	0	0.022	0
C	0	0	0	0	0	0	0	0
NAO	0.2	0.8	0.6	0.017	0.4	0.92	0.000004	0.068

Zero means p value $< 10^{-6}$, i.e. the highest calculable statistical significance. Values < 0.05 are indicated in bold. Monthly series are used for 1874–2007. The result for the first principal component (which comprise 54% of precipitation data variance) is also given

PCA1 first principal component analysis

(where NAO takes over the role). The W index is clearly insignificant in Wroclaw and Lvov and almost uniformly highly significant for the rest of the sites investigated.

This analysis has confirmed that regional atmospheric circulation indexes can be very useful in evaluating precipitation variability. According to New et al. (2001), approximately 8% of the temporal and spatial variability of precipitation is linked to the El Niño Southern Oscillation. Negligible at the global scale, the NAO impact is limited to the moderate latitudes of the northern hemisphere. Around the rim of Atlantic Ocean, it accounts for 10% of the variance in the annual precipitation variability. In central Europe, this influence is even lower at just below 4%, but more than 40% of the wintertime and 24% of the annual precipitation variance, spatially averaged, is explained by the cyclonicity index C (Fig. 12).

The increases in short-term strong precipitation identified in the late twentieth century/early twenty-first century

and the current decline in precipitation totals are therefore linked to the changing activity of Atlantic depressions. These are manifested by both the fluctuations of the cyclonicity index and the westerly circulation index.

9 Conclusions

This paper presents various regional aspects of precipitation variability using homogeneous long-term records, with monthly resolution, of seven selected weather stations across east central Europe.

- In central Europe, precipitation fluctuates greatly both in time and space. After air circulation, the mountain ranges of the Carpathian and Sudeten Mts. have the strongest influence on precipitation patterns.
- The Mann–Kendall test showed no changing trend in any of the precipitation series studied, but a certain spatial regularity could be discerned. The test statistics change from a strongly negative value in Budapest to positive values that grow northeastwards.
- A common feature of east central European annual precipitation variability was the dry period of the 1980s and the first half of the 1990s. In the northern part of the region, above-average precipitation was noted from the 1960s through to the mid-1970s as a result of the frequent prevalence of depressions. South of the divide, the wettest period was recorded at the turn of the 1930s/1940s.
- After a series of very wet years in the 1990s and early twenty-first century, all weather stations studied have begun recording declining precipitation totals.
- The strongest circulation-linked factor influencing precipitation in east central Europe is the cyclonicity index, which explains more than 40% of the wintertime and 24% of the annual precipitation variance, spatially averaged.

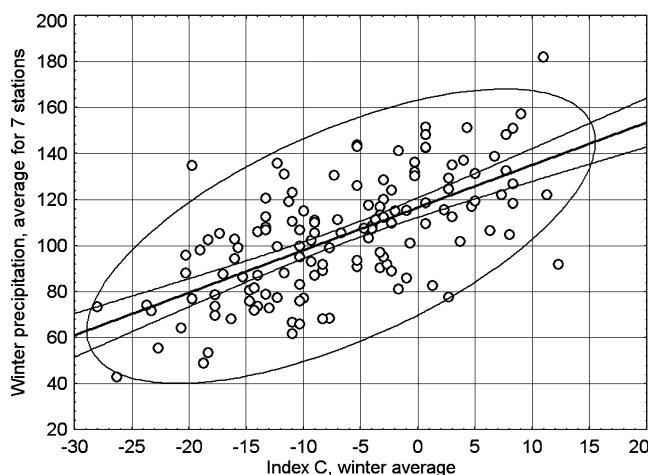


Fig. 12 Scatter diagram illustrating dependence of winter precipitation totals (P) on cyclonicity index (C), (1874–2007). A normal distribution ellipse is given, representing the 0.95 probability limit, as well as a regression line with confidence limits. The correlation coefficient $r=0.643$ (p value < 0.000001); regression equation: $P=116.6+1.85 \times C$

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