Analysis of hourly precipitation characteristics in Kraków, southern Poland, using a classification of circulation types

Robert Twardosz

ABSTRACT

This paper investigates the relationship between maximum precipitation in Kraków and types of atmospheric circulation in southern Poland, as classified by Niedźwiedź. Three characteristics were used to define this relationship: maximum precipitation (P_{max}), its duration (d) and probability of exceedance (p). The input data came from Kraków's uniquely long and homogenous pluviographic record spanning the period 1886–2007. Hourly precipitation values for the maximum precipitation events were identified and arranged in 1–24 hour intervals. They were then processed using the generalized extreme value (GEV) distribution to produce quantiles of maximum precipitation totals in each of the intervals and broken down by the corresponding circulation type. Differences between the development mechanisms are manifested in relationships between precipitation characteristics and their measure of randomness, i.e. exceedance probability. This paper demonstrates that maximum precipitation events depend on their duration d and atmospheric circulation. The maximum short-duration (one-hour) events occur primarily in either of two circulation types: (i) cyclonic with advection from the east and from the southeast or (ii) low-pressure centre and cyclonic trough. Maximum long-duration precipitation events (24 hour), on the other hand, occur in the cyclonic type of circulation with advection from the north and from the northeast.

Key words | circulation types, DDF curves, GEV distribution, Kraków, Poland, rainfall

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INTRODUCTION

The paper investigates the relationships between precipitation and atmospheric circulation, taking into account the probability of exceedance of precipitation depths as a measure of randomness. This topic belongs to the wider area of synoptic climatology that deals with, among other things, the influence of circulation types on the actual values of climate elements (Barry & Carleton 2001). There exist numerous independent classifications of atmospheric circulation, applied at different scales, many of which are defined by the direction of air advection and (anti) cyclonicity of flow (Lamb 1972; Niedźwiedź 1981). By linking precipitation with circulation types, it is possible to explore the causes of precipitation variability.

The full potential of this approach can be achieved with a sufficiently high resolution, e.g. hourly, of precipitation data. The results from such research contribute to a greater understanding of the atmospheric processes associated with heavy short-duration rainfalls, and are often integrated into operational meteorology (Faiers *et al.* 1994). Additionally, Faiers *et al.* (1994) found that improvements in the accuracy of forecasts of heavy precipitation can be used to mitigate many of the problems that these events present to society.

The synoptic approach to precipitation frequency and quantity can be applied at various temporal and regional scales, but depends mainly on the availability of precipitation and synoptic situation records.

doi: 10.2166/nh.2009.056

Most of the literature on the impact of atmospheric circulation on precipitation is based on daily or monthly data. In publications that look at the relationship between hourly precipitation and circulation types, authors typically concentrate on identifying daily precipitation amplitude or daily cycle phase (Faiers 1988, 1993; Faiers *et al.* 1994; Svensson *et al.* 2002; Twardosz 2005, 2007*a*,*b*).

In a few Polish publications dealing with short-term maximum precipitation events (Kupczyk & Suligowski 1997; Bogdanowicz & Stachý 1998; Suligowski 2004; Twardosz 2009), the authors propose formulae for the calculation of the maximum depth or intensity of precipitation in a given time interval and the probability of exceedance. Spatial variation of maximum daily precipitation, taking into account the probability of exceedance and the precipitation origin, was researched by Cebulak (1992) in the upper Vistula drainage basin.

This paper presents a synoptic approach to the maximum precipitation depth-duration-frequency (DDF) curves for short durations (1–24 h) in southern Poland. The study should be able to answer the question of whether there are physically determined differences in the statistical properties of short-duration rainfall generated by different synoptic patterns and, consequently, if they contribute to better forecasting of heavy precipitation events that trigger floods in the Carpathian Mountains and their foreland.

RESEARCH MATERIAL

The study is based on two main inputs: the uniquely long and homogenous pluviographic record of the Kraków Astronomic Observatory of the Jagiellonian University (latitude: 50°04′ N, longitude: 19°58′ E; 206 m a.s.l.) and the catalogue of atmospheric circulation types in southern Poland by Niedźwiedź (1981, 2007).

Continuous pluviographic measurements in Kraków date back to 1886 and the whole data series has been verified for homogeneity, with some minor gaps in the record filled in (Twardosz 2005, 2007*a*,*b*). The hourly precipitation depth data used for this project span the period 1886–2007. The Niedźwiedź (1981, 2007) classification of synoptic situations represents the dynamics of atmospheric processes in southern Poland. Surface synoptic charts of Europe and 700 hPa geopotential height charts provided the basis for this classification. The Niedźwiedź classification is similar to that of Lamb (1972) popular in the United Kingdom (Barry & Carleton 2001).

The most important components of the circulation types are advection direction and (anti)cyclonicity of flow. In total, Niedźwiedź defined 21 types of atmospheric circulation, including 16 advection types, and marked them with a code consisting of the advection sector name and either the letter ‘a’ for anticyclonic systems (Na, NEa, Ea, SEa, Sa, SWa, Wa and NWa) or ‘c’ for cyclonic systems (Nc, NEc, Ec, SEc, Sc, SWc, Wc and NWc). The remaining five types are either advection free or with various advection directions: Ca: central anticyclonic situation, no advection, centre of high pressure; Ka: anticyclonic wedge, sometimes a few non-definite centres or an unconstrained area of higher pressure, an axis of a high pressure ridge; Cc: central cyclonic situation, centre of low pressure; Bc: cyclonic trough or unconstrained area of low pressure, or the axis of the low pressure trough, with various advection directions and systems of fronts separating different air masses; and X: unclassified situations.

Niedźwiedź (1981, 2007) subjectively classified each day’s circulation over Southern Poland from September 1873 until present, and the classification is being continuously updated.

The average annual frequency of the various circulation types in southern Poland, shown in Figure 1, varies widely from 1.1% for the Cc situation to 11.9% with Ka. Climatologists often use a reduced range of 10 circulation types. Additionally, previous research (Niedźwiedź 1981;

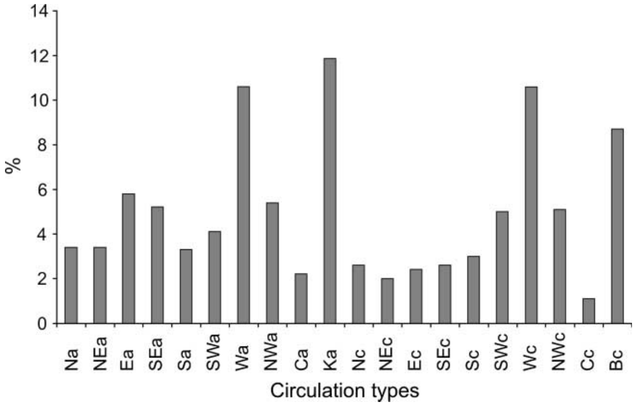

Figure 1 | Frequency (%) of circulation types over southern Poland (1886–2007).

Twardosz & Niedzwiedz 2001; Twardosz 2007*b*) has demonstrated that precipitation associated with certain circulation types did not reveal statistically significant differences in frequency of occurrence and depth. Following the suggestion of Niedźwiedź (1981), the related types are pooled into 5 groups of anticyclonic situations: Na + NEa, Ea + SEa, Sa + SWa, Wa + NWa, Ca + Ka and 5 groups of cyclonic situation: Nc + NEc, Ec + SEc, Sc + SWc, Wc + NWc, Cc + Bc.

OBSERVED PRECIPITATION AND CIRCULATION TYPES

The city of Kraków is located in the South of Poland on the river Vistula in a transition zone between the Carpathian Mountains in the south and the upland belt to the north. The city centre's average annual precipitation total is 670 mm. Summer precipitation total accounts for more than 40% of the annual value and is nearly three times greater than the winter total, providing clear evidence of a highly continental precipitation pattern in Kraków. Available research shows no statistically significant trends in precipitation totals or in the frequency of occurrence of particular circulation types, but only short-term fluctuations (Niedźwiedź *et al.* 2009).

Figure 2 shows that the bulk of the annual number of days with precipitation in Kraków (more than 65%) coincide with cyclonic circulation types, with low pressure centres and troughs (Cc + Bc) and western/north-western circulation (W + NWc) accounting together for 40% of the number of precipitation days. Among the anticyclonic types, most days with precipitation occur in the W + NWa situations.

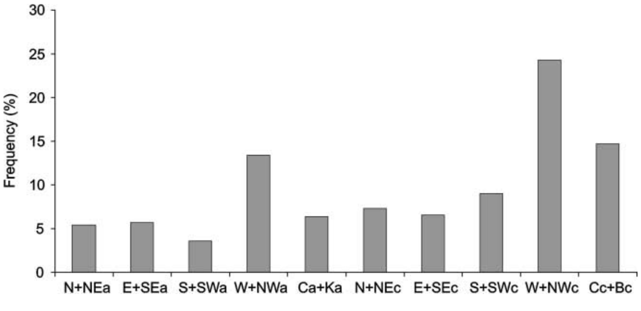

Figure 2 | Frequency (%) of wet days for particular circulation types (1886–2007).

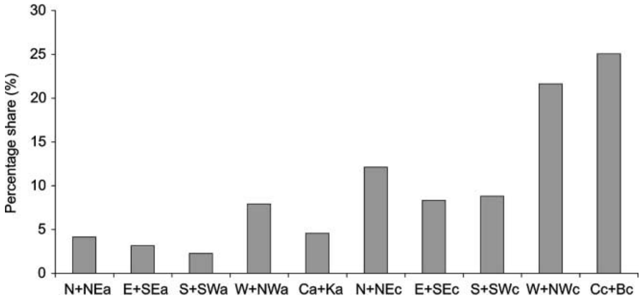

Figure 3 | Share of precipitation of particular circulation types in annual precipitation (1886–2007).

An important issue in the assessment of the impact of the circulation on precipitation is to find how much precipitation is contributed by particular types of circulation. It was found that the annual total in Kraków largely depends on precipitation connected with two groups of types Cc + Bc and W + NWc (Figure 3). Their common share amounts to 46%. The remaining three cyclonic groups, N + NEc, E + SEc and S + SWc, also play a significant role. Precipitation occurring in anticyclonic situations contributes to the overall precipitation amounts at 20%.

Figure 4 illustrates the mean number of hours with precipitation broken down by circulation type. The standard error of the mean is also given. On an average wet day in Kraków, precipitation events last approximately five hours. The duration is two hours longer, on average, in cyclonic circulation types and it peaks in the N + NEc situation (Figure 4).

Indeed, with air moving at right angles to the Carpathian ridges, air masses are piled up producing conditions favourable to the development of rain clouds. This orographic effect is also seen in the Kraków precipitation. Large numbers of hours of precipitation are also recorded in the E + SEc situation. The minimum duration is recorded in the Ca + Ka high-pressure non-advection situations. Interestingly, a relatively large number of wet hours occurs in the N + NEa anticyclonic circulation, which normally follows the N + NEc cyclonic situations. In the Carpathian foreland this type of meteorological succession would allow humid air masses and the intensive air flow from the northern sector (perpendicular to the Carpathian range) to cause a build-up of vast systems of rain clouds. As a result, precipitation corresponding to the

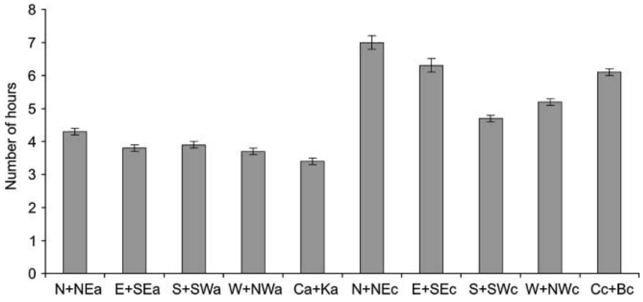

Figure 4 | Mean number of wet hours and standard error of the mean for particular circulation types (1886–2007).

N + NEa circulation type can persist much longer, despite a shift in the pressure system from cyclonic to anticyclonic circulation. In all circulation types, the number of hours with precipitation is lower in summer than in winter. This is the result of a difference in the way precipitation comes about in these two seasons.

A very strong relationship is also displayed between circulation type and maximum precipitation total. In cyclonic situation types, maximum precipitation tends to be heavier, regardless of the duration (Figure 5). The heaviest precipitation observed in Kraków occurred on 9 September 1963, accompanied by a strong thunderstorm. It happened during the E + SEc circulation type, and reached 99.0 mm per hour which is 15% of the mean annual precipitation total. Very heavy precipitation occurs also in anticyclonic circulation types. In summertime, strong thermal convection can cause strong, if short, precipitation of up to 45 mm per hour in Ca + Ka non-advection situations.

In winter, however, when the role of thermal factors becomes less significant, the total precipitation is not large; it reaches a maximum rate of up to 4.5 mm per hour during the S + SWc circulation type.

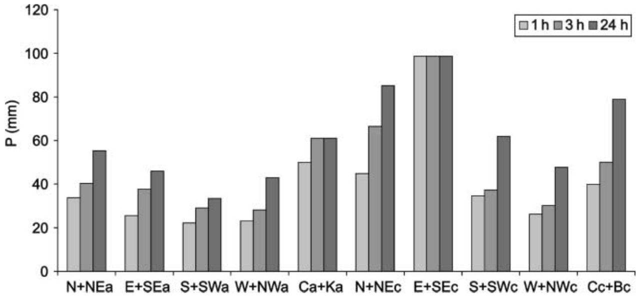

Figure 5 | Maximum observed precipitation with selected duration for particular circulation types (1886–2007).

SELECTION OF STATISTICAL SERIES AND PROBABILITY DISTRIBUTION

In precipitation analysis it is crucial to determine the probability of exceedance of heavy precipitation (maximum precipitation) at a given locality. The large daily precipitation record of more than 100 years was broken down into sub-sets corresponding to anticyclonic and cyclonic situations and further subsets corresponding to cyclonic groups/advection directions: Nc + NEc, Ec + SEc, Sc + SWc, Wc + NWc and Cc + Bc. The circulation types feature a relatively high precipitation frequency, which is sufficient to analyze maximum precipitation.

The dependence between the depths of precipitation, duration of a precipitation event and probability of exceedance of precipitation totals was derived using the annual maximum series approach (WMO 1994; Wilks 2006) at time intervals predefined regardless of the actual duration of precipitation events (1, 2, 3, 6, 9, 12, 15, 18, 21 and 24 hours) and broken down into the particular circulation types mentioned above. At the short end of this spectrum is the 1 hour duration which is the shortest interval normally used for pluviographic recording. At the opposite end is a 24 hour period, i.e. the period used for classifying circulation types.

The choice of the optimum model for probability distribution was made by testing empirical series of maximum depths of precipitation for the following theoretical distributions: Gumbel, generalized extreme value (GEV), Weibull and Pearson III (Sevruk & Geiger 1981; Stedinger *et al.* 1993; Coles 2001; Wilks 2006). The parameters of maximum precipitation distribution were estimated by means of the maximum likelihood method (Wilks 2006). The Akaike information criterion (AIC) was applied to select the best distribution out of the four distributions (Akaike 1974).

Of all of the maximum precipitation series analyzed, the lowest AIC was achieved by the GEV distribution (Table 1). This three-parameter distribution model proved to be the best and was finally selected for all maximum precipitation

Table 1 | Akaike Information Criterion values (AIC) of maximum precipitation depths with 1 and 24 hours duration in particular circulation types

	1 hour				24 hours			
Circulation types	Gumbel	Weibull	Pearson III	GEV	Gumbel	Weibull	Pearson III	GEV
Anticyclonic types	719	719	711	709	825	825	825	823
Cyclonic types	745	745	759	745	873	869	869	868
N + NEc	525	525	505	521	912	918	922	911
E + SEc	598	598	557	561	864	865	864	849
S + SWc	580	580	565	570	816	817	819	815
W + NWc	574	574	581	573	795	796	799	794
Cc + Bc	671	671	672	670	912	919	920	915

series. The choice seems to confirm the findings of many recent publications (e.g. Koutsoyiannis 2004*a*,*b*; Overeem *et al.* 2008), where this distribution type proved to approximate maximum values best.

The GEV cumulative distribution function $F(x)$ is defined (Jenkinson 1955):

$$F(x) = \exp\left(-\left(1 + \lambda\frac{x-\alpha}{\beta}\right)^{-1/\lambda}\right) \tag{1}$$

for $\lambda \neq 0$, and

$$F(x) = \exp\{-\exp[-(x-\alpha)/\beta]\} \tag{2}$$

for $\lambda = 0$, where x is maximum precipitation depth, p is probability of exceedance, α is the location parameter, β is the scale parameter and λ is the shape parameter of the distribution. The GEV quantile function, the inverse of Equations (1) and (2), is given by:

$$x = F^{-1}(1-p) = \alpha - \beta\{[\ln(1-p)]^{-\lambda} + 1\}/\lambda \tag{3}$$

for $\lambda \neq 0$, and

$$x = F^{-1}(1-p) = \alpha - \beta\ln[-\ln(1-p)] \tag{4}$$

for $\lambda = 0$.

DDF CURVES ACCORDING TO CIRCULATION TYPES

Quantiles of maximum precipitation depth as a function of duration

Quantiles of maximum precipitation in all of the durations and broken down into circulation types were calculated using the maximum likelihood method and the GEV distribution. The relationship maximum precipitation depths-duration-frequency (DDF) for individual atmospheric circulation types is presented at four levels of probability of exceedance: 1, 5, 20 and 50% (Figures 6 and 7).

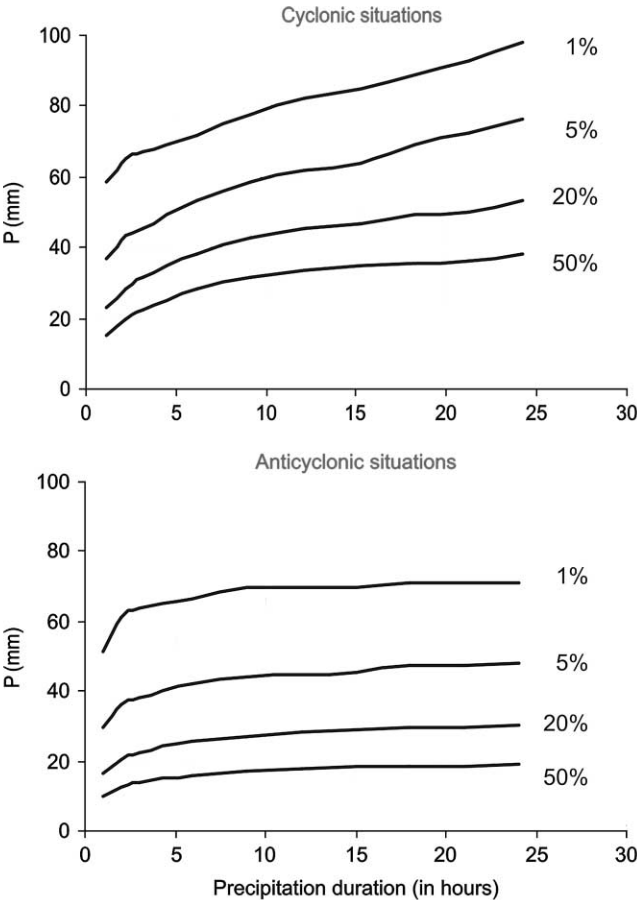

Figure 6 | Quantiles of maximum precipitation depth as a function of their duration in cyclonic and anticyclonic circulation types (1886–2007).

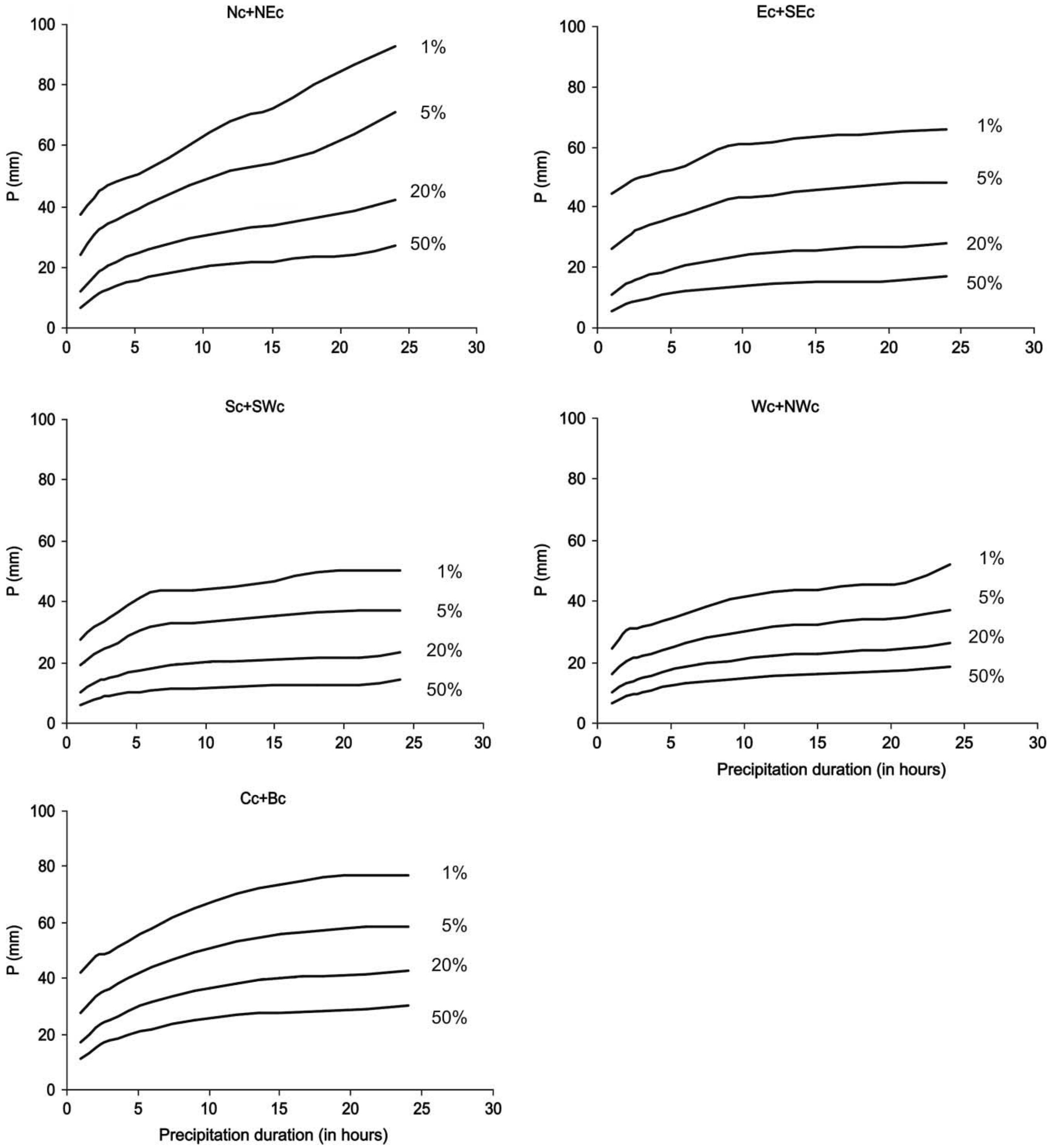

Figure 7 | Quantiles of maximum precipitation depth as a function of their duration in particular cyclonic circulation types (1886–2007).

The DDF curves reveal that maximum precipitation depth displays various rates of increase of dependence on duration. The greatest increase was observed for short-duration events ranging from 1 to 3 hours regardless of the circulation type, which is explained by a short-duration high-intensity precipitation.

The amount of precipitation in anticyclonic circulation types is mainly driven by the intensity of free convective processes. This means that the precipitation depths are only slightly greater in prolonged events (Figure 6). In anticyclonic situations, precipitation events lasting for more than three hours showed no significant increase in amount of precipitation in function of their duration. As far as 100 year precipitation events are concerned, the increase in precipitation depth over the entire range from 1–24 hours is only 20.0 mm.

In cyclonic circulation types, the depth of precipitation is primarily driven by the speed of convection in the frontal zone and in other air convergence areas (Bluestein 1993; Twardosz 2007*a*,*b*). The duration of a precipitation event may vary widely depending on the front type. Of all those advection situations, N + NEc situations showed the highest rate of increase in amount of precipitation across the entire duration spectrum (Figure 7). A circulation from this sector brings in cold air that, during the warm parts of year, absorbs heat from warmer ground and develops unstable stratification favourable to the emergence of rain clouds and to the development of heavy precipitation. Under this circulation, the precipitation depths during a 24 hour period range from 21.0 mm at 50% exceedance probability to 56.2 mm at 1% exceedance probability. A high rate of increase in precipitation depth ranging from 19.0 mm ($p = 50\%$) to 35.0 mm ($p = 1\%$) is also associated with the low-pressure centre and cyclonic trough types. In both of the circulation groups (N + NEc and Cc + Bc), intense precipitation was mainly generated by slow-moving active cold-front surfaces or by low-pressure centres associated with heavy and long-duration precipitation (Cebulak 1992; Twardosz & Niedźwiedź 2001). This is explained by the favourable conditions for vapour condensation offered by a zone with slow-moving fronts and convergent winds combined with a very unstable air stratification (Bluestein 1993).

The lowest rate of increase in precipitation depth, seen in 1–24 hour precipitation events at all levels of probability of exceedance, was observed to accompany the S + SWc cyclonic circulation types. This is the result of the dominant role in creating precipitation of the warm front combined with advection from the south or southwest (Twardosz 2007*b*). In southern Poland, these circulation types increase air temperature which is further boosted by the precipitation hampering *foehn* effect. Blowing from S + SW, the warm Polar maritime or tropical air cools down near the ground leading to a stable stratification of the lower atmospheric layer and producing conditions unfavourable to precipitation.

Maximum precipitation depth as a function of precipitation duration at selected levels of probability of exceedance

Figure 8 compares precipitation depth and duration. These are broken down into individual cyclonic and anticyclonic types and shown at three selected levels of exceedance probability (50, 5 and 1%).

Cyclonic situations clearly stand out across the entire range of duration, i.e. from 1 to 24 hours, and at all levels of probability of exceedance. The corresponding one-hour maximum precipitation values range from 15.4 mm (at $p = 50\%$) to 58.6 mm (at $p = 1\%$), and the 24-hour values increase to 38.5 mm and 98.0 mm, respectively. This pattern would confirm very high rates of convection attributed to these situations.

Depths of short-term precipitation may also prove very large in anticyclonic situations, but only at low probabilities ($p < 1\%$) (Figure 8). The author's earlier research (Twardosz 2005) shows that conditions right for strong mass precipitation (thermal storms) can occur in non-advection situations of the high-pressure centre or anticyclonic wedge Ca + Ka.

In cyclonic circulation types, maximum precipitation events occur in association with a moving low-pressure centre or the convergence of winds in a cyclonic trough area. Only long-duration (more than 18 hour and $p \leq 5\%$) precipitation events, accompanying advection from the north or northeast (N + NEc), produce higher total values. In the Cc + Bc circulation group, intensive precipitation is typically associated with the passage of a low-pressure centre with an active front system (Niedźwiedź 1981). Often more than one front passes during a 24 hour period and there are records of 4–6 fronts per day in Poland (Parczewski 1964). A meteorological situation with active fronts favours the development of longer precipitation events and, as a consequence, leads to higher overall precipitation. Large amounts of rainfall from N + NEc circulation are the result of air masses

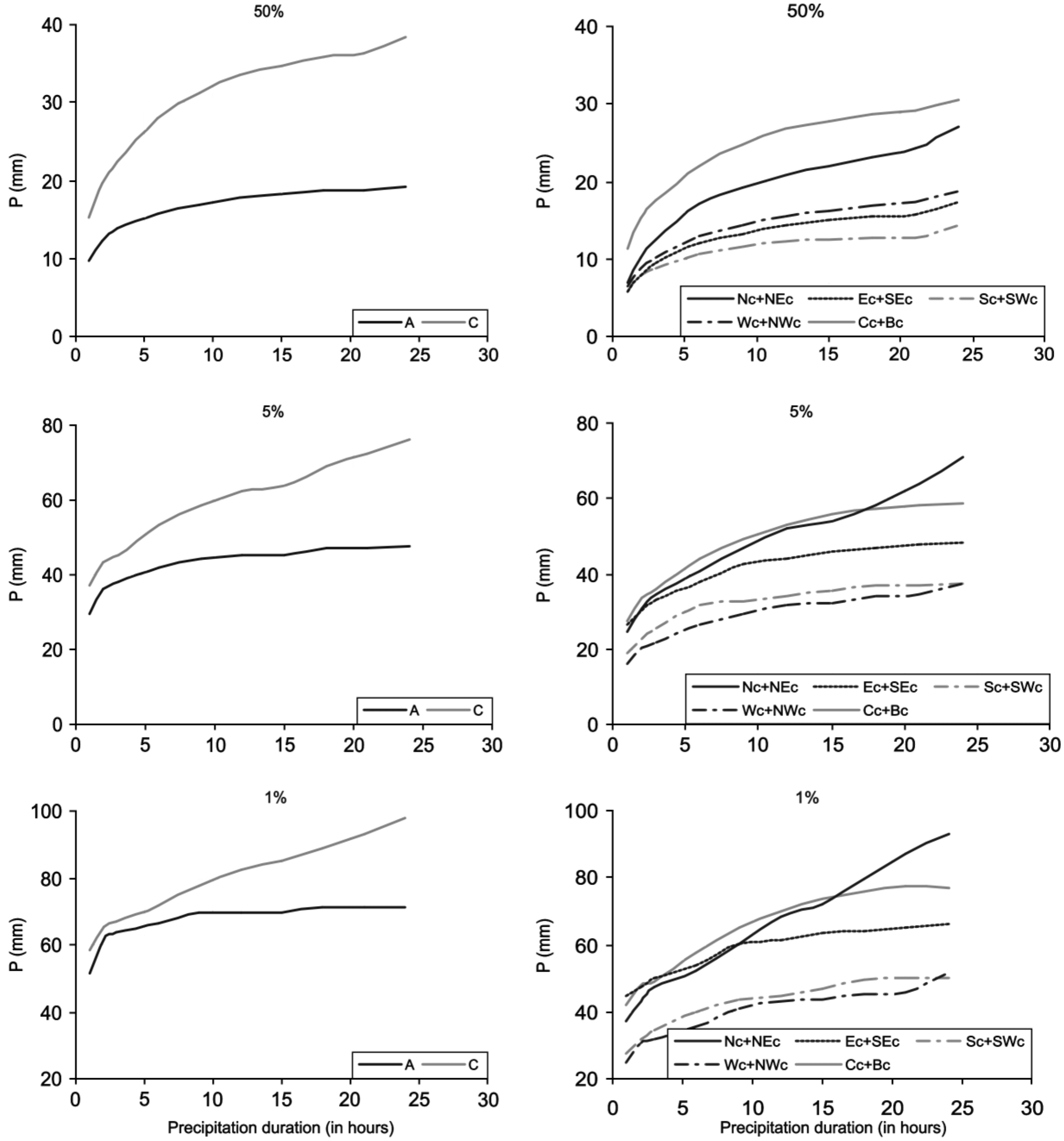

Figure 8 | Quantiles of maximum precipitation depth as a function of their duration for 50, 5% and 1% probability of exceedance in particular circulation types (1886–2007).

building up on contact with the slopes of the Carpathians. This orographic effect is also felt in Kraków in the form of increased precipitation. Heavy precipitation of this type is mainly driven by stark thermal contrasts over the territory of Poland caused by intense advection perpendicular to the Carpathian Mountain range. In these circumstances, a stationary front can develop and remain active for several days. In July 1997, a weather system like this caused catastrophic flooding in southern Poland (Niedźwiedź 1999).

Compared to the remaining types, the E + SEc circulations tended to produce significantly heavier precipitation across the duration spectrum and especially at the lower-end probabilities ($p \leq 5\%$). This should be explained by a higher degree of activity displayed by warm fronts arriving from that sector. According to a study by Parczewski (1964), warm fronts associated with intense precipitation zones arrive in Poland also from the southeast. Cyclonic situations with active warm fronts moving in from the Hungarian Lowland and from southern Ukraine originate around the Mediterranean (Morawska-Horawska 1971). At lower probability levels, precipitation depths associated with the S + SWc and W + NWc are similar.

Probability of exceedance curves of maximum precipitation depths at 1- and 24-hour duration

The impact of the (anti)cyclonicity of flow on precipitation depths was investigated across the entire probability spectrum. Precipitation values based on the shortest and longest durations, i.e. 1- and 24-hours, were selected for this purpose (Figure 9). The probability curves show that the heaviest precipitation events, regardless of their duration, occur in cyclonic circulation types. In the case of maximum one-hour precipitation, cyclonic types generated greater precipitation depths than anticyclonic types by 5.9 mm (at $p = 50\%$) and by 7.0 mm (at $p = 1\%$). With 24-hour maxima, the differences were 19.7 mm (at $p = 50\%$) and 28 mm (at $p = 1\%$), respectively.

The chart on Figure 10 shows the variation of maximum precipitation in groups of cyclonic circulation. Plotted curves show the highest values of one-hour precipitation versus probability in groups Cc + Bc and E + SEc. In both groups, the $p = 5\%$ quantile stood at 27.0 mm. As the duration increased, the highest totals were associated with circulation group N + NEc, across the probability spectrum ($p \leq 20\%$). For a long-duration event to yield a lot of rain, air requires high levels of humidity. During the warm half of the year, the highest vapour concentration is indeed associated with circulation from the northern sector or in the central-low pressure or cyclonic trough circulations (Niedźwiedź 1981).

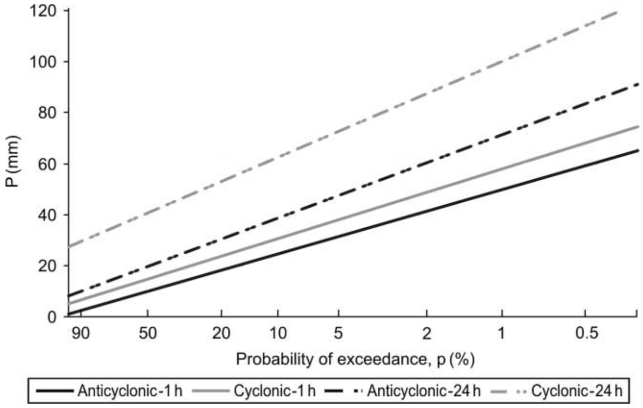

Figure 9 | Exceedance probability curves of maximum precipitation depths with 1 hour and 24 hour duration in anticyclonic and cyclonic circulation types (1886–2007).

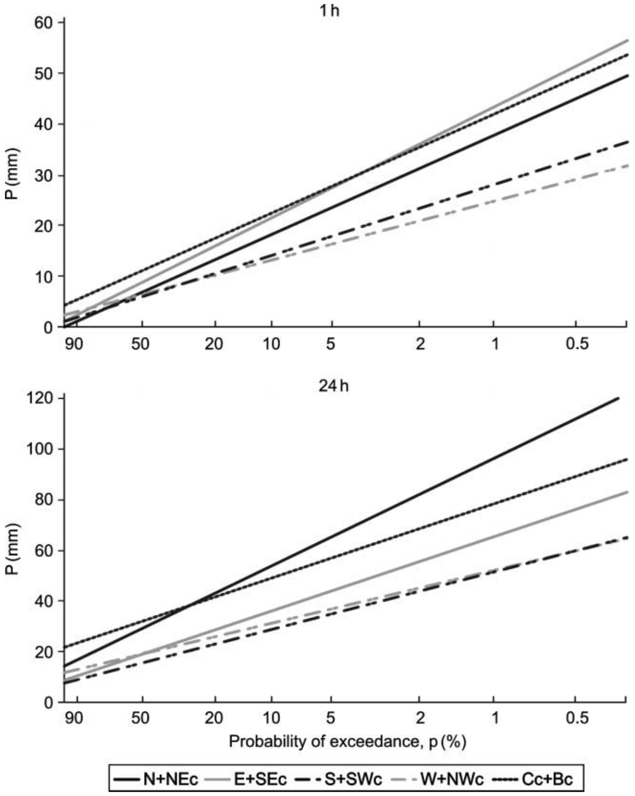

Figure 10 | Exceedance probability curves of maximum precipitation depths with 1 hour and 24 hour duration in particular cyclonic circulation types (1886–2007).

CONCLUSIONS

The large pool of precipitation data was broken down by a classification of circulation pattern. This opened this data to detailed analysis at individual characteristic level, taking into account the differences in precipitation development mechanisms. Differences between the development mechanisms are manifested in relationships between precipitation characteristics and their measure of randomness, i.e. exceedance probability.

The following conclusions result from the research study.

- Of the theoretical models evaluated, the three-parameter GEV distribution was found to offer the best approximation of maximum precipitation depths.
- Maximum precipitation depths depend on the duration and the associated atmospheric circulation type. The greatest rate of increase in precipitation depth is observed in short-duration events (ranging from 1 to 3 hours) regardless of the circulation type, which is explained by a short-duration high-intensity precipitation.
- In cyclonic types, this increase in quantity is maintained across the range of durations. The greatest rates of increase are recorded in cyclonic circulations from the north and northeast N + NEc.
- In anticyclonic types, precipitation events longer than 3 hours only add minor amounts to the overall precipitation depths because of different processes involved in the development of precipitation in these meteorological situations.

The maximum short-duration (1 hour) events occur primarily in either of two circulation types: cyclonic with advection from the east and from the southeast E + SEc; or low-pressure centre and cyclonic trough Cc + Bc. Maximum long-duration precipitation events (24 hour), on the other hand, occur in the cyclonic type of circulation with advection from the north and from the northeast N + NEc.

ACKNOWLEDGEMENTS

I am deeply grateful to Professor Tadeusz Niedźwiedź for making the catalogue of circulation types for 1886–2007 available to me, and to two anonymous reviewers for their helpful comments and suggestions which helped to improve this paper. I thank Dr Martin Cahn and Professor Stanisław Węglarczyk for reviewing the English.

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First received 4 July 2008; accepted in revised form 29 May 2009. Available online November 2009