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Circulation types classification for hourly precipitation events in Lublin (East Poland)

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Abstract: The paper presents an objective classification of circulation types for East-Central Europe with application to hourly precipitation events in Lublin (East Poland) from May to September. The development of the classification utilized sub-daily sea-level pressure values (at the main standard synoptic hours, *i.e.* 00, 06, 12 and 18 UTC). Sea-level pressure values and physical quantities (resultant flow direction and total shear vorticity) defined 27 circulation types: a) eight each of the directional cyclonic, transitional, and anticyclonic circulation types, and b) one each of the non-directional cyclonic, anticyclonic, and undefined types. In the years 1961–2010, the highest mean precipitation amount in the study area was recorded for cyclonic non-directional type C, followed by cyclonic types with air flow from the western and northern sectors. Type C was also distinguished by the highest number of precipitation events with high intensity irrespective of their duration, *i.e.* short-term, medium-term, and long-term precipitation events. Moreover, in the class of cyclonic types, precipitation events were considerably longer than in anticyclonic and transitional types. On the other hand, for anticyclonic types, precipitation with high intensity was recorded much more rarely, particularly in the case of advection from the southern sector.

Keywords: circulation types; atmospheric circulation; hourly precipitation; precipitation intensity; East-Central Europe

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1 Introduction

Precipitation is of considerable importance for the functioning of the natural environment, and in a number of areas of human activity. Heavy rains increase the threat of floods, often causing deaths and substantial financial losses. Such events in recent years have led to an increase in the number of studies concerning changes in extreme precipitation events in various regions of the world [1–6].

An increase in global air temperature is thought to be correlated with the intensity of precipitation events [7]. This has been recently observed even in areas with decreasing annual precipitation amounts. Therefore, the assessment of changes in precipitation intensity in the near future should involve the application of climatic models that consider scenarios of greenhouse gas emissions [8, 9].

Poland is located in the central part of Europe, affected in terms of climate by both the Atlantic Ocean and Eurasian continent. Therefore, the area is distinguished by air advection with different thermal and moisture characteristics, which contribute to a high variability of weather types annually. Large-scale atmospheric circulation is an important factor determining *e.g.* the occurrence of extreme precipitation in Poland [10]. In the southern, *i.e.* upland-montane part of Poland, the occurrence of northern sector advection in the summer period often favours precipitation events with long duration, increasing the risk of floods [11–13]. In turn, in the north-western, *i.e.* lowland, part of Poland, considerable precipitation anomalies in summer usually occur during cyclonic circulation from the eastern sector [14, 15]. A considerably lower frequency of intensive precipitation is recorded during anticyclonic circulation, particularly when a high pressure system is located over Poland [15, 16].

The distribution of sea-level pressure largely determines whether months have higher or lower than normal precipitation amounts [17]. The correlation is reflected in the values of air flow indices [18–21]. Precipitation variability assessments in a given area are often performed in relation to the pressure pattern type and direction of air

Figure 1: Physical map of East-Central Europe with location of Lublin[1].

flow. The assessments may involve the application of selected classifications of circulation types (hereafter CTs), which significantly contributed to the development of synoptic climatology [22]. The availability of reanalysis data sets, and the application of methods adopting objective classifications, makes the development of catalogues of CTs possible for particular study areas. The types are usually associated with a period of one day, so the distribution pattern presented is similar to the pressure field over 24 hours [23–25]. It is common knowledge that precipitation is a discontinuous meteorological element with high variability at various temporal scales. The assessment of the effect of large-scale atmospheric circulation on precipitation variability should, therefore, apply a catalogue of CTs that are based on data with higher temporal resolution. Thus, the primary objective of this paper is to:

– present an objective classification of CTs for East-Central Europe based on daily and sub-daily sea-level pressure data;
– assess the usefulness of the classification for determining precipitation variability by performing a comparative analysis with the Grossweterlagen typology (GWL);
– determine differences between catalogues of CTs based on data with varied temporal resolution;
– characterise the large-scale atmospheric circulation over East-Central Europe from May to September, and its impact on precipitation events in Lublin (Fig. 1).

1 Digital elevation data SRTM30 from NASA (https://dds.cr.usgs.gov/srtm/version2_1/Documentation/SRTM_Topo.pdf). Shaded maps produced by scilands GmbH, Göttingen, Germany (www.scilands.de) using free GIS SAGA (www.saga-gis.org).

2 Material and methods

2.1 Source data and applied precipitation indices

This study utilized a series of pluviographic records from the years 1961–2010, obtained from the meteorological station of the University of Life Sciences in Lublin, located in the east suburbs of the Lublin city (51°14'N, 22°38'E, 215 m a.s.l.; Fig. 1). The terrain in this part of East Poland is upland, distinguished by loess valley, especially in the western area. The readings of amount (mm) and duration (min) of precipitation were taken from the Hellmann pluviograph (inlet area of 200 cm^2) in the period May–September. Values were determined in hourly intervals where the total precipitation was at least 0.1 mm an hour. This allowed the calculation of the precipitation intensity (mm/min), as well as the assessment of the efficiency of precipitation events [26] (Table 1):

$$K = \frac{h}{\sqrt{t}} \tag{1}$$

where K is the precipitation efficiency coefficient, h represents precipitation amount in mm while t is the duration of precipitation in min.

Table 1: Scale of precipitation efficiency.

Scale degree	Precipitation efficiency coefficient (K)	Category of rain and symbol
0	0.00–1.00	Normal rain
1	1.01–1.40	Severe rain (A_o)
2	1.41–2.00	Heavy rain (A_1)
3	2.01–2.82	Heavy rain (A_2)
4	2.83–4.00	Heavy rain (A_3)
5	4.01–5.65	Heavy rain (A_4)

All of the precipitation events were divided into three classes by their duration, as follows: short-term ($t \leq 90$ min), medium-term ($270 < t \leq 450$ min), and long-term ($t > 810$ min) [27]. The diurnal cycle of precipitation characteristics was presented according to Central European Summer Time CEST (UTC + 2).

Precipitation intensities with exceedance probabilities of 50%, 10% and 1% were calculated based on a series of values measured during the persistence of a particular circulation type. Similarly, as in the case of duration of precipitation events and duration of particular CTs, the probability of exceedance values were calculated from the Weibull parameters, obtained from the maximum likelihood method [28]. Values of quantiles of the analysed variables were calculated based on the following formula:

$$x = \alpha + \beta (\ln p)^{\frac{1}{\lambda}} \tag{2}$$

where x is the value of quantile; α, β, λ, respectively, represent the location, scale and shape parameter; and p is the probability of exceedance.

2.2 Description of the classification of CTs over East-Central Europe

The assessment of the effect of large-scale atmospheric circulation on precipitation events with varied duration and intensity was based on two catalogues of CTs developed for East-Central Europe (ECE). Their development involved the application of five series of sea-level pressure data, *i.e.* mean daily values (hereafter catalogue ECE_d), and values from four observation terms at 00, 06, 12, and 18 UTC (hereafter catalogue ECE_h). In the latter case, the CTs were interpolated through the remaining hours by equating them to the two hours preceding and three hours following a given observation term. Sea-level pressure values were obtained from the Twentieth Century Reanalysis (20CRv2) [29].

The adopted classification partially employs assumptions proposed by Lityński [30]. According to the author, CTs can be divided in terms of sea-level pressure values into three classes, namely cyclonic, transitional, and anticyclonic. Distinguishing the transitional class in a classification for the central part of Europe is justified. The area shows high variability of the pressure field, manifested in high variability in the location of high and low pressure systems. Therefore, each pressure value from a grid point located in East Poland (φ = 51°15'N and λ = 22°50'E) was ascribed to one of three classes depending on whether the pressure values were below the norm (cyclonic class), around the norm (transitional class), or above the norm (anticyclonic class). The threshold for the classes were the 33rd and 66th percentile of sea-level pressure from the period 1961–2010, calculated separately for each month and each of the five series of data.

The directions of air flow and non-directional patterns (pure cyclonic/anticyclonic and undefined type) were determined based on the equations by Jenkinson and Collison [31]. The method is based on a set of indices related to the velocity and direction of geostrophic flow, as well as total shear vorticity, which were calculated using a gridded set of sea-level pressure data. The approach has been repeatedly used for assessing influences of atmospheric circulation on the variability of selected meteorological ele-

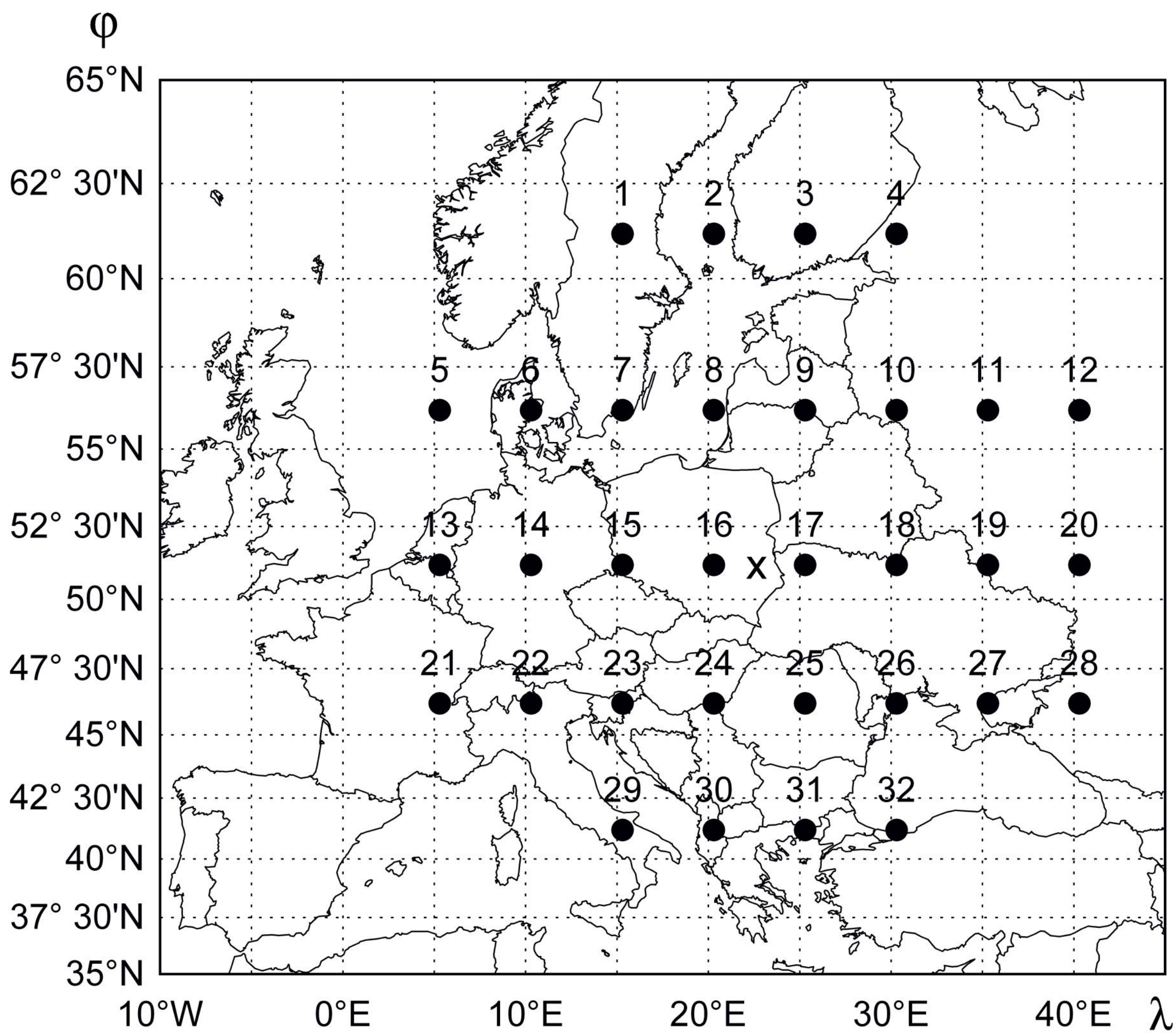

Figure 2: Location of grid points used for the ECE classification. Symbol "x" marks the location of the meteorological station.

ments in various regions of Europe [32–35]. In this paper, daily gridded fields (5°x5° longitude–latitude) of mean sea-level pressure were used over an area from 5°20' to 40°20'E and from 41°15' to 61°15'N (Fig. 2). The circulation indices were then calculated for each grid point using the equations:

– Resultant flow (F)

$$F = \sqrt{W^2 + S^2} \tag{3}$$

– Total shear vorticity (V)

$$V = VW + VS \tag{4}$$

where the components are based on the following equations:

– Westerly flow (W)

$$W = 0.25 \cdot (p_{23} + p_{24} + p_{25} + p_{26}) - 0.25 \cdot (p_7 + p_8 + p_9 + p_{10}) \tag{5}$$

– Southerly flow (S)

$$S = 1.596 \cdot [0.125 \cdot (p_{10} + 2 \cdot p_{18} + p_{26} + p_9 + 2 \cdot p_{17} + p_{25}) - 0.125 \cdot (p_7 + 2 \cdot p_{15} + p_{23} + p_8 + 2 \cdot p_{16} + p_{24})] \tag{6}$$

– Westerly shear vorticity (VW)

$$VW = 1.079 \cdot [0.25 \cdot (p_{29} + p_{30} + p_{31} + p_{32}) - 0.25 \cdot (p_{15} + p_{16} + p_{17} + p_{18})] - 0.938 \cdot [0.25 (p_{15} + p_{16} + p_{17} + p_{18}) - 0.25 \cdot (p_1 + p_2 + p_3 + p_4)] \tag{7}$$

– Southerly shear vorticity (VS)

Table 2: Symbols and description of CTs in the ECE classification.

Symbols	Description
Nc, NEc, Ec, SEc, Sc, SWc, Wc, NWc	Directional cyclonic types (evident advection during cyclonic circulation)
No, NEo, Eo, SEo, So, SWo, Wo, NWo	Directional transitional types (evident advection with a contribution of both low and high pressure systems)
Na, NEa, Ea, SEa, Sa, SWa, Wa, NWa	Directional anticyclonic types (evident advection during anticyclonic circulation)
C	Cyclonic non-directional type (high positive shear vorticity values over the study area)
A	Anticyclonic non-directional type (high negative shear vorticity values and weak geostrophic wind velocity over the study area)
x	Undefined non-directional type (low shear vorticity values and weak geostrophic wind velocity)

$$VS = 1.273 \cdot [0.125 \cdot (p_{12} + 2 \cdot p_{20} + p_{28} + p_{11} + 2 \cdot p_{19} + p_{27}) - 0.125 \cdot (p_{10} + 2 \cdot p_{18} + p_{26} + p_9 + 2 \cdot p_{17} + p_{25})] - 1.273 \cdot [0.125 \cdot (p_8 + 2 \cdot p_{16} + p_{24} + p_7 + 2 \cdot p_{15} + p_{23})] - 0.125 \cdot (p_6 + 2 \cdot p_{14} + p_{22} + p_5 + 2 \cdot p_{13} + p_{21}) \quad (8)$$

Grid points from p_1 to p_{32} correspond to sea-level pressure values (hPa). The flow units (F) are geostrophic, expressed as hPa per 10° latitude at 51°15'N; each unit is equivalent to 0.62 ms^{-1}. The geostrophic vorticity (V) units are expressed as hPa per 10° latitude also at 51°15'N; one unit is equivalent to 0.7×10^{-6} s^{-1}. The direction of flow (D) has been determined using westerly (W) and southerly flow (S).

$$D = \arctan\left(S/W\right), \quad \text{if } W \le 0 \quad (9)$$

$$D = \arctan\left(S/W\right) + 180, \quad \text{if } W > 0 \quad (10)$$

The cyclonic non-directional type (C) included cases with $|V| > 2F$, (if $V > 0$). The anticyclonic non-directional type (A) included cases with $V < -10$ and $V/F < -4$. The undefined type (x) concerned cases with $F < 2$ m/s and $|V| < 12$. The rest of the cases were distributed between twenty-four directional CTs assigned to the three classes proposed by Lityński (anticyclonic, transitional and cyclonic) and eight directions (north, N; northeast, NE; east, E; southeast, SE; south, S; southwest, SW; west, W; northwest, NW). This way, twenty-seven CTs were obtained, *i.e.* 8 each of the directional cyclonic, transitional, and anticyclonic types, and one each of the non-directional cyclonic, anticyclonic, and undefined types (Table 2).

Similarities in the values of precipitation characteristics between the CTs were determined by means of a cluster analysis applying the complete linkage method and Euclidean distance. Two precipitation classifications were developed based on these methods. In the first case, the indices considered included the total precipitation amount from the entire study period and precipitation rate, defined as the ratio of the amount of precipitation of a given type to the number of hours it occurred. In the second case, indices included values of conditional probability of the occurrence of precipitation at a given time (≥ 0.1 and ≥ 1.0 mm). In both cases, CTs were categorised into several classes. This made it possible to differentiate them in terms of precipitation amount (classification I) and conditional probability of precipitation occurrence (classification II).

2.3 Comparison with the Grosswetterlagen typology (GWL)

The detailed analyses were preceded by an attempt to assess the usefulness of the ECE classification proposed in the paper. The ECE_d catalogue was compared with the Grossweterlagen typology (GWL) developed for Central Europe, which is the classification of CTs by Hess-Brezowsky [36] modified by Gerstengarbe and Werner [37]. Its development involved the use of surface synoptic maps and geopotential height charts at the 500 hPa level, with consideration of direction of air flow and location of pressure systems. A total of thirty CTs were distinguished, additionally grouped in Grosswettertypen (GWT) by air mass advection [37]. The typology has been used in numerous papers investigating Central Europe [38–42].

The ECE_d and GWL classifications differ in the method of determining the CTs, and in the number of weather types distinguished. Therefore, comparison of the two classifications required application of the method presented by Buishand and Brandsma [43]. Based on the method, which used daily values of precipitation, monthly values of the mean-squared-error skill scores were cal-

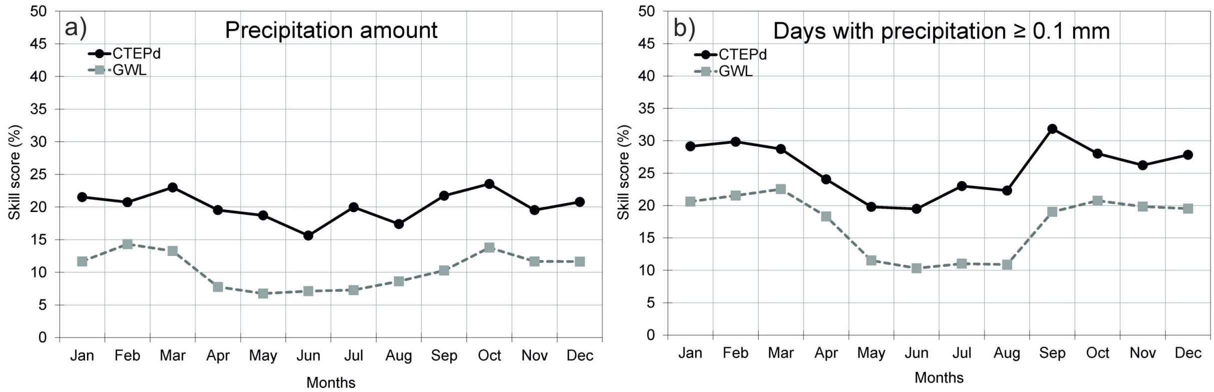

Figure 3: Annual course of mean squared error skill score (%) for the ECE$_d$ and GWL classifications in relation to (a) daily values of precipitation amount (mm) and (b) number of days with precipitation ≥ 0.1 mm in Lublin from 1961 to 2010.

culated separately for each classification. The skill score specified to what degree precipitation variability in a given month is determined by the changing of weather types. The index was calculated based on percentage of explained variance (from 0 to 100%). Higher values of the index suggest higher usefulness of a given classification, due to the higher variance of mean values of the analysed variable between the types. The objective of comparing the two classifications was met by applying total precipitation amounts and number of days with precipitation ≥ 0.1 mm, obtained from the meteorological station in Lublin. The skill score (S) was calculated as:

$$S = \left(1 - \frac{MSE_{class}}{MSE_{ref}}\right) \times 100\% \quad (11)$$

where MSE_{class} is the mean squared error of the predictions from classification schemes. MSE_{ref} is the mean squared error for the reference predictor. Both components can be obtained based on the equations as follows:

$$MSE_{class} = \frac{1}{n}\sum_{i=1}^{n}\left(y_i - \bar{y}_{k(i)}\right)^2 \quad (12)$$

$$MSE_{ref} = \frac{1}{n}\sum_{i=1}^{n}(y_i - \bar{y})^2 \quad (13)$$

where y_i is the value of a specific variable on day $i(i = 1, \ldots, n)$ for a specific calendar month. The averages for the K circulation types are denoted as $\bar{y}_1, \bar{y}_2, \ldots, \bar{y}_K$ and the overall average as $\bar{y}$.

The application of ECE$_d$ classification results in a higher skill score than that of the GWL in all calendar months (Fig. 3). This fact proves that ECE$_d$ has a stronger relationship with precipitation variability in Lublin than GWL. In the case of daily total precipitation amounts, the monthly skill score values showed no substantial variance in a year. Slightly higher values occurred only in the cold part of the year (Fig. 3a). There was higher difference in skill score when comparing the number of days with precipitation ≥ 0.1 mm between the cold and warm half of the year (Fig. 3b). The above findings suggest higher variance of mean values between the CTs for both of the precipitation indices from October to March. Therefore, atmospheric circulation over East-Central Europe, defined by direction of air flow and the pressure pattern type, plays a more significant role in precipitation variability in the cold half year relative to the warm one. Similar relationships were also found in the area of Vojvodina (Serbia) [44]. This may be due to increased influence of precipitation formation processes at the local scale (*e.g.* convective activity) in the warm period.

2.4 ECE classification at the daily and sub-daily scale

In order to determine the differences between the ECE$_h$ and ECE$_d$ catalogues for the period from May to September (1961–2010), total precipitation amounts relating to each of the CTs were calculated. Hourly values corresponding to a given type were added up in the case of ECE$_h$, and daily values in the case of ECE$_d$ (based on data from 00 to 23 CEST).

In approximately 1/3 of weather types, differences in precipitation amounts corresponding to the same CTs in both of the catalogues amounted to ≥ 20% (Fig. 4). The ECE$_d$ catalogue, in comparision to the ECE$_h$, underestimated the precipitation amount corresponding to types Ec, SWa, and NWa to the highest degree. In turn, it overestimated the values for types SEa, So, SWo, and A. Based

Table 3: Mean values of selected precipitation indices from May to September in Lublin (1961–2010).

Months	Mean precipitation amount (mm)	Mean number of days with precipitation ≥ 0.1 mm	Mean number of days with precipitation in classes					
			0.1–1.0 mm	1.1–5.0 mm	5.1–10.0 mm	10.1–20.0 mm	20.1–30.0 mm	>30 mm
May	55.6	12.6	4.3	4.7	2.0	1.2	0.3	0.1
June	65.6	12.7	3.6	4.9	2.3	1.5	0.4	0.2
July	76.4	13.0	3.7	4.6	2.2	1.6	0.6	0.3
August	72.6	11.1	3.4	3.9	1.8	1.1	0.3	0.6
September	59.5	12.1	3.8	4.6	2.0	1.3	0.2	0.2

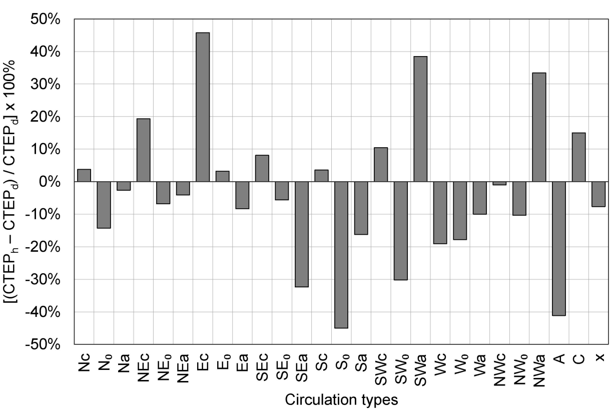

Figure 4: Differences (%) in total precipitation amount (mm) in Lublin from May to September between CTs in catalogues ECE_h and ECE_d.

on the above findings, only the ECE_h catalogue was used for further analyses.

3 Results

3.1 Characteristics of precipitation

In the study area, precipitation from May to September accounted for approximately 61% of the annual total. The highest monthly total precipitation amounts occurred in July and August, and the lowest in May (Table 3). In all of the months, days with low (1.1–5.0 mm) and very low (0.1–1.0 mm) precipitation amount were predominant. Daily precipitation of more than 20 mm was rare. In the period from May to September, the shortest precipitation events occurred between 13 and 16 CEST (Fig. 5a). This could be related to the formation and development of thermal convection resulting from ground heating during the day, which frequently results in the development of cumulus and cumulonimbus clouds, usually accompanied by precipitation with a short duration [45].

The thermal and dynamic properties of the atmosphere also determined the diurnal course of other precipitation indices (Figs 5b–5d). In the analysed months, precipitation events usually occurred in the afternoon (between 15 and 20 CEST) and were characterised by the highest intensity (Fig. 5d) and maximum amount of water reaching the ground (Fig. 5c).

The highest mean intensity values, irrespective of their duration, occurred in July and August (Table 4). July was characterised by the highest number of precipitation events and shortest mean duration. The highest mean precipitation amount and the highest number of heavy precipitation events (categories A_2 to A_4) occurred in August. From May to September, short precipitation events prevailed, with a maximum number of short events in July (Fig. 6). Precipitation events of more than 7.5 h were relatively rare in all of the months analysed. The longest continuous precipitation event began at 03 CEST 05.09.1992, and ended at 02 CEST 07.09.1992. During that event, precipitation of 78.9 mm was recorded.

3.2 Frequency of occurrence of CTs

During the study period over East-Central Europe, the anticyclonic non-directional type (A) had the highest number of hours. It occurred the most frequently in July and August (Fig. 7). The cyclonic non-directional type (C) occurred in the study period more seldom than type A. A maximum number of type (C) events occurred in May, when easterly air flow was prevalent. In the following months, atmospheric circulation was of a different character. In June, it was dominated by NW and N air flow; in July and August, W, NW, N and NE air flow; and in September, S, SW, W and NW air flow. Irrespective of the month, there were few cases of directional cyclonic types with air advection

Table 4: Description of precipitation events in Lublin from May to September (1961–2010).

Months	Mean amount (mm)	Mean duration (min)	Mean intensity (mm/min)	Total number of events in precipitation categories					
				Normal rain	Severe rain (A_o)	Heavy rain (A_1)	Heavy rain (A_2)	Heavy rain (A_3)	Heavy rain (A_4)
May	2.5	47.4	0.039	895	23	12	3	2	–
June	3.1	49.6	0.047	908	30	18	3	5	2
July	3.3	40.4	0.057	980	35	35	7	7	3
August	3.6	53.2	0.055	775	37	25	10	10	4
September	2.8	64.9	0.032	902	13	8	2	3	1

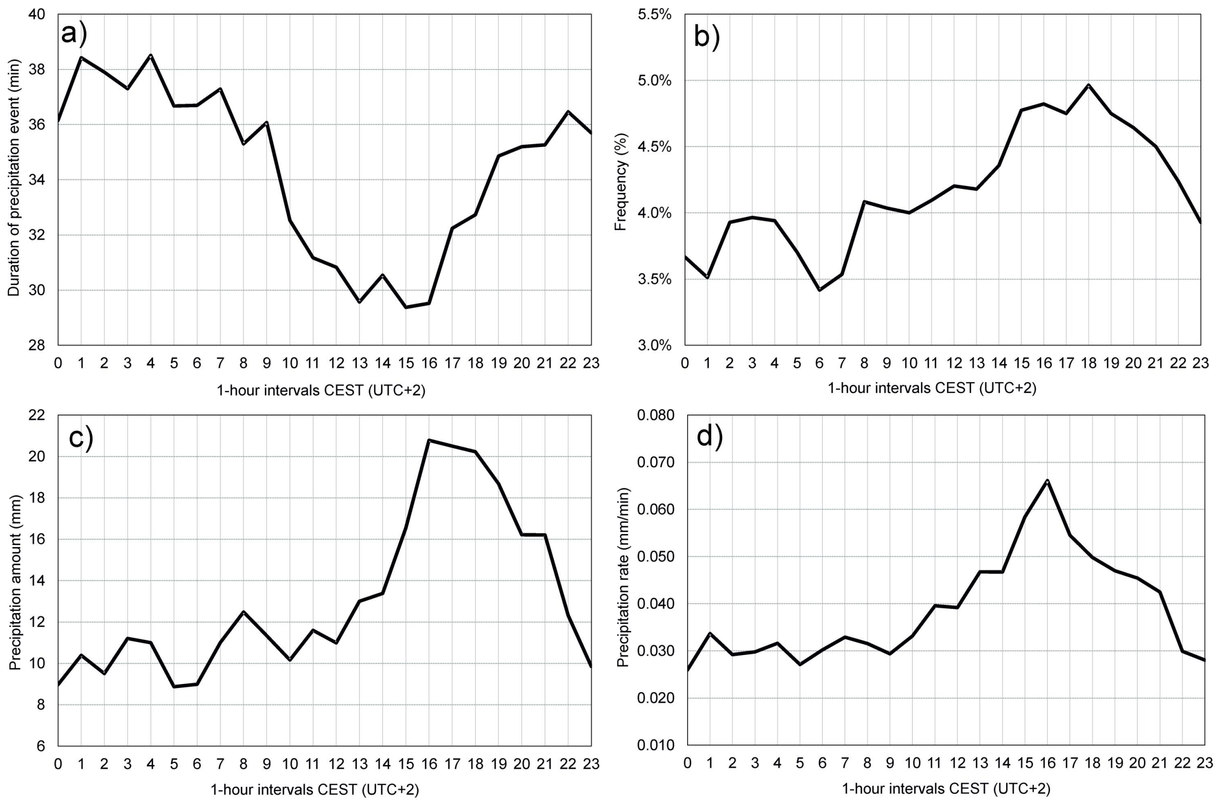

Figure 5: Daily mean course of (a) duration, (b) frequency, (c) amount, and (d) intensity of precipitation in Lublin from May to September (1961–2010).

from the eastern sector (NEc, Ec, and SEc) and directional anticyclonic types from the southern and western sector (Sa, SWa, Wa, NWa) (Fig. 7).

The analysis of the persistence of CTs showed that longer sequences of hours were recorded for anticyclonic types and the shortest for transitional types. Apart from the cyclonic type (C) and anticyclonic non-directional type (A), considerably longer sequences were recorded for types with air flow from the eastern sector (Fig. 8). The two longest recorded sequences of hours with the same type had a total duration of more than 6 days. During these sequences, cyclonic types, *i.e.* type C, persisted continuously for 156 hours (between 01.05.1974 and 08.05.1974), and type NEc for 150 hours (between 30.08.1989 and 05.09.1989). In comparison to east directional CTs, the length of sequences for the remaining types was considerably shorter, particularly for those with air flow from the western sector (Fig. 8).

3.3 Application of the ECE classification to characterize precipitation

Considerable differences in mean precipitation amounts for the period from May to September were observed be-

Table 5: Circulation type classification in relation to two precipitation indices in Lublin from May to September.

Number of class	Name of class	Circulation types	
		Classification I	Classification II
Ia	Very wet	C	C, NEc
Ib	Wet	Nc, NEc, Sc, Wc	Nc, NWc
Ic	Moderately wet	Ec, SEc, SWc, NWc, x	Ec, SEc, Sc, SWc, Wc
IIa	Slightly above normal	NE_0, E_0, NW_0	N_0, NE_0, E_0, NW_0, x
IIb	Slightly below normal	N_0, NEa, SE_0, W_0	NEa, SE_0, W_0
IIIa	Dry	Na, Ea, SW_0, NWa	Na, Ea, S_0, SW_0, SWa, Wa, NWa
IIIb	Very dry	SEa, S_0, Sa, SWa, Wa, A	SEa, Sa, A

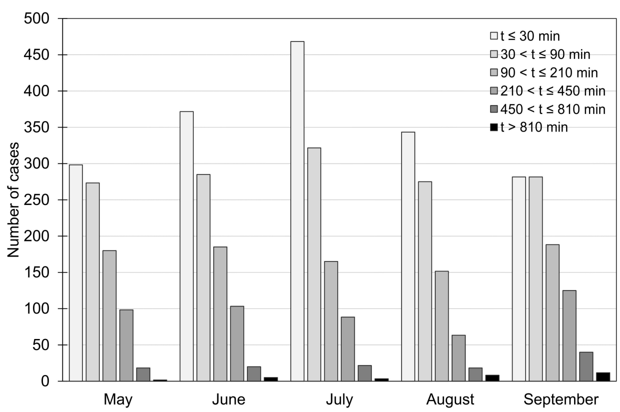

Figure 6: Number of precipitation events in Lublin of various duration (1961–2010).

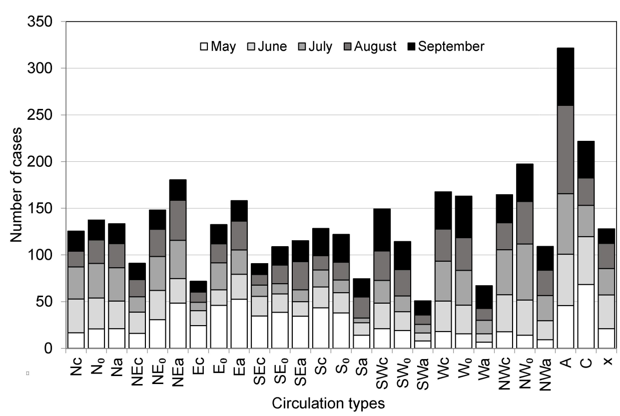

Figure 7: Average number of cases with CTs over East-Central Europe in particular months (1961–2010).

tween the main three classes of CTs (Fig. 9). In cyclonic types, higher values (20–25 mm) were associated with types with air flow from south to north-east. Substantially lower values were associated with transitional types (5–10 mm), and particularly anticyclonic types (< 5 mm). The lowest mean precipitation amounts were observed for types from precipitation classes IIIa and IIIb (classification I; Table 5), *i.e.* anticyclonic (A) and directional anticyclonic types, with air flow from the southern sector. The highest mean precipitation amount (> 55 mm) was recorded for the cyclonic non-directional type (C) (Fig. 9).

Considerably higher values were also associated with cyclonic rather than anticyclonic types in the case of another index: conditional probability of hours with precipitation > 0.1 mm in particular types (classification II; Table 5). The lowest values were recorded for type A, SEa and Sa (< 1.5%; Fig. 10a), followed by SWa, Wa, So, and Ea (< 3%; Table 6). The highest values of the index (> 17%) associated with type C (class Ia; Fig. 10b), followed by NEc, Nc, and NWc. Their occurrence also resulted in higher conditional probability of hours with precipitation ≥ 1.0 mm (Table 6).

In cyclonic and transitional situations the frequency of precipitation in Lublin was similar throughout the day (Fig. 11). A slightly higher incidence was recorded in the late afternoon and evening, which may be affected by the thermal convection combined with the passage of a cold front. Anticyclonic situations are distinguished by a certain increased incidence of precipitation between 7 and 11 CEST. This can be explained by the fact that during the night, in anticyclonic conditions, the air is cooled radiatively to the condensation point, resulting in formation of low-level stratified clouds, which could lead to light rain or drizzle in the morning hours.

Directional types E+SE and S+SW were characterized by significant differences in the frequency of precipitation throughout the day (an afternoon and evening maximum, and a night minimum; Fig. 12). In cyclonic types, air masses flowing from these directions to East-Central Europe are usually formed over the Black Sea or the Mediterranean region and are characterized by high values of air temperature and specific humidity. This contributes to the intensification of a vertical flow and the development of precipitation clouds in the second half of the day. In directional types W+NW, the differences between the first

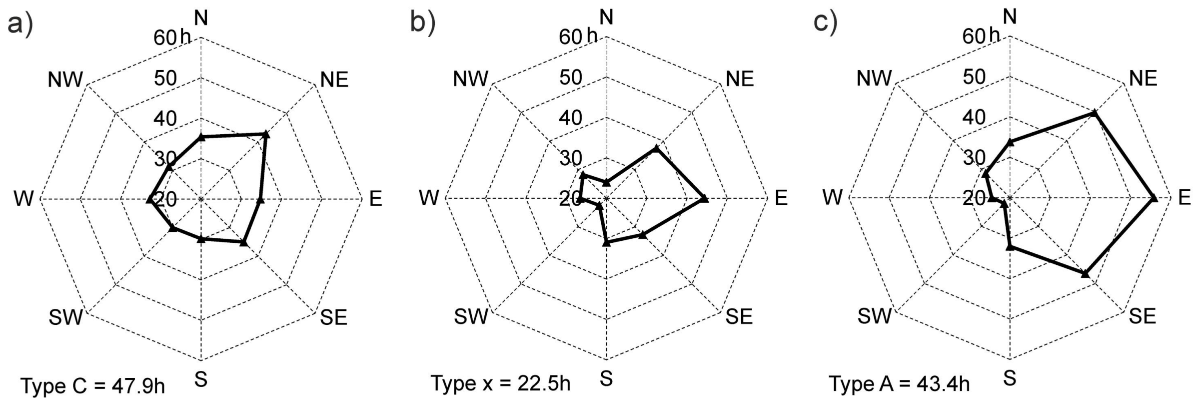

Figure 8: Persistence of CTs (in hours) with an exceedance probability of p = 10% for (a) cyclonic, (b) transitional, and (c) anticyclonic CTs over East-Central Europe from May to September (1961–2010).

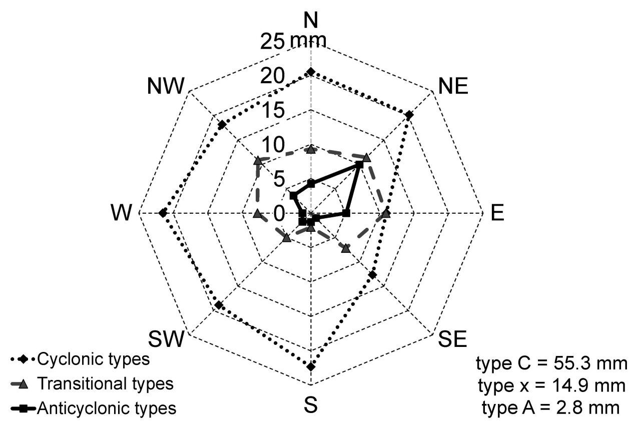

Figure 9: Mean precipitation amount (mm) in Lublin for particular CTs over East-Central Europe from May to September (1961–2010).

and the second half of the day were lower (Fig. 12). In the warm half of the year, the advection from the west and north-west brings relatively cold and humid air toward East-Central Europe. Cold fronts generally move under the cyclonic types W+NW, and therefore occurrence of precipitation events are not associated so clearly with the time of day.

The indices for differentiation of CTs are also based on the duration of precipitation events. In the class of cyclonic types, precipitation events were considerably longer than in anticyclonic and transitional types. Apart from type C, the highest values of the index occurred with directional cyclonic types, with air flow from north to south (Fig. 13a). The disproportion between the eastern and western sector in the class of transitional and anticyclonic types was more significant than for cyclonic patterns (Figs 13b–13c). In both of the classes, southern and south-western directions also had low values. In general, the characteristics of precipitation duration were in accordance with the persistence of particular types over East-Central Europe (Fig. 8).

Precipitation events recorded during anticyclonic CTs were usually short ($t \leq 90$ min). Only types NEa and NWa contributed slightly to precipitation events with a duration of several hours (Table 6; Figs 14). In cyclonic and transitional types, the contribution of medium-term and long-term precipitation events was considerably higher, particularly in the case of air flow from north-west to east. The highest contribution in all the three classes of precipitation came from non-directional type C. Its presence was recorded in as much as ~40% of cases of long-term precipitation events ($t > 810$ min).

In the case of precipitation events with a short duration ($t \leq 90$ min), the maximum intensity of precipitation with a probability of occurrence of 1% was similar in the main three classes of CTs (Fig. 15a). This suggests that the most intensive precipitation could result from not only the dynamic processes occurring in the atmosphere (*e.g.* during storms on cold fronts, related to cyclonic circulation), but also thermal processes (storms developing in a non-gradient pressure field or on the edge of the high pressure system as a result of strong heating of the ground leading to intensive thermal convection). The highest maximum precipitation intensity occurred during cyclonic types. Even greater variation between the classes was observed with an increase in the duration of precipitation events (Fig. 15b).

Among cyclonic types, the probability of very high intensity, short-term precipitation events was rather similar. It was only slightly higher in the case of types C and SWc (Fig. 16a). In the class of transitional and anticyclonic types, the probability of intensive precipitation was low when air flow was from the southern and western sector. In the case of advection from north to east, the probability

Table 6: Selected characteristics of CTs over East-Central Europe in relation to precipitation events in Lublin from May to September (1961–2010).

Circulation types	1	2	3	4	5	6	7	8	9	10	11	12
Nc	13.2	5.0	22.5	27.3	3.2	1.1	248	7	3	–	2	–
No	6.7	2.3	36.8	11.4	18.8	1.0	180	6	2	–	–	–
Na	3.7	1.0	35.4	10.2	–	0.6	105	–	1	–	–	–
NEc	15.4	5.9	27.0	20.5	4.6	1.4	203	12	11	3	2	–
NEo	7.9	2.4	29.3	16.7	0.3	0.9	219	4	4	–	–	–
NEa	4.4	1.5	30.9	25.8	3.0	1.0	127	4	3	–	–	2
Ec	11.3	3.9	25.6	25.2	7.6	1.4	122	6	3	–	–	2
Eo	6.4	2.1	32.4	16.0	8.0	1.2	152	6	2	2	3	–
Ea	2.8	0.7	22.9	22.9	–	0.9	68	1	3	–	–	3
SEc	9.9	3.9	25.9	14.8	3.0	1.3	135	9	12	2	–	–
SEo	4.3	1.4	35.0	11.7	3.6	1.1	68	6	3	2	–	3
SEa	0.9	0.4	28.1	34.4	–	0.2	26	–	–	–	–	–
Sc	9.4	3.8	22.3	12.7	7.1	1.6	162	14	9	2	7	–
So	2.4	0.5	43.0	9.3	–	0.6	62	2	–	–	3	–
Sa	1.2	0.5	40.7	25.9	–	0.4	19	1	–	–	–	–
SWc	10.7	3.7	33.1	13.9	–	1.2	283	9	6	–	3	–
SWo	3.6	1.2	49.2	4.1	–	1.1	88	4	–	2	1	–
SWa	2.3	1.2	34.3	17.1	–	0.5	25	1	–	–	–	–
Wc	10.6	3.8	35.6	13.6	0.4	1.2	382	9	5	2	2	–
Wo	5.3	1.6	49.8	6.2	–	0.9	200	4	1	–	–	–
Wa	2.4	0.5	56.3	–	–	0.5	30	1	–	–	–	–
NWc	12.5	4.0	30.4	12.8	3.1	0.8	403	2	–	–	2	–
NWo	6.4	1.8	44.3	19.2	1.6	0.8	288	1	–	–	–	–
NWa	3.2	0.9	43.8	7.6	3.8	0.4	70	2	2	–	–	–
A	0.8	0.2	32.5	22.1	–	0.5	45	1	2	–	–	–
C	17.8	6.8	23.7	13.0	11.9	1.3	583	20	15	10	3	–
x	7.6	3.2	28.5	9.4	1.0	1.1	167	6	11	2	–	–

Explanations: 1–2 – (1) conditional probability of hours with precipitation ≥ 0.1 mm and (2) ≥ 1.0 mm (%); 3–5 – relative contribution in (3) short-term ($t \leq 90$ min), (4) medium-term ($270 < t \leq 450$ min) and (5) long-term ($t > 810$ min) precipitation events (%); 6 – precipitation efficiency, *i.e.* ratio of precipitation amount to the total number of hours with a given circulation type (mm); 7–12 – the number of events in relation to precipitation categories: (7) normal rain, (8) category A_0, (9) category A_1, (10) category A_2, (11) category A_3, (12) category A_4.

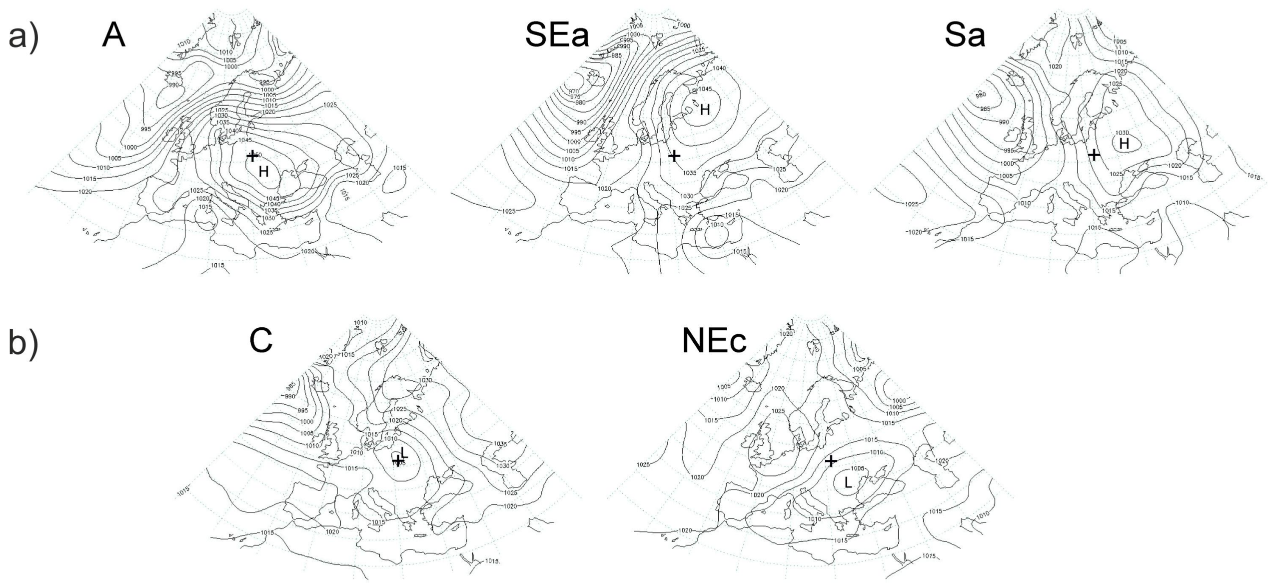

Figure 10: (a) Very dry and (b) very wet CTs over East-Central Europe according to the classification II. Figures illustrate daily mean sea-level pressure fields on selected days from May to September (1961–2010).

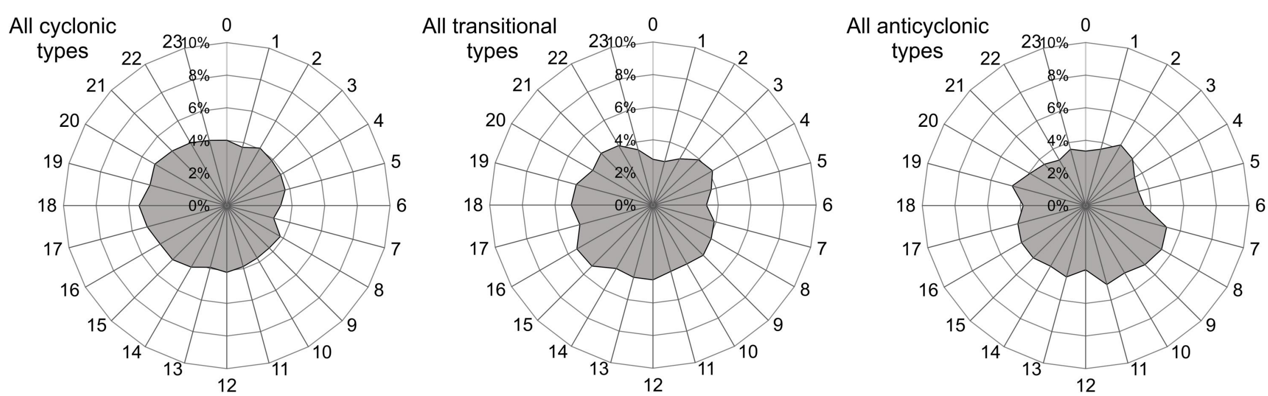

Figure 11: Diurnal distribution of precipitation frequency in three classes of CTs (1961–2010).

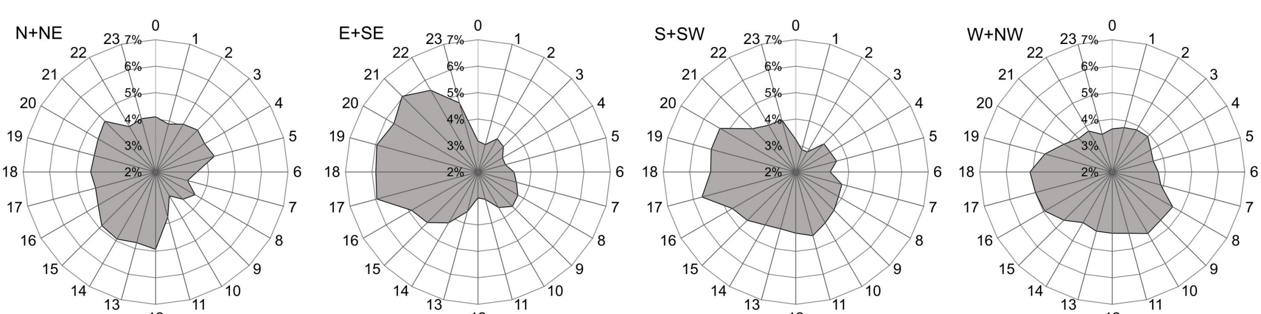

Figure 12: Diurnal distribution of precipitation frequency in particular groups of directional CTs (1961–2010).

was similar to cyclonic types (Figs 16b–16c). In medium-term precipitation events, in comparison to short-term ones, the threshold values specifying the probability of exceedance of precipitation intensity of $p = 10\%$ were lower by one order of magnitude in cyclonic types (Fig. 16d). In

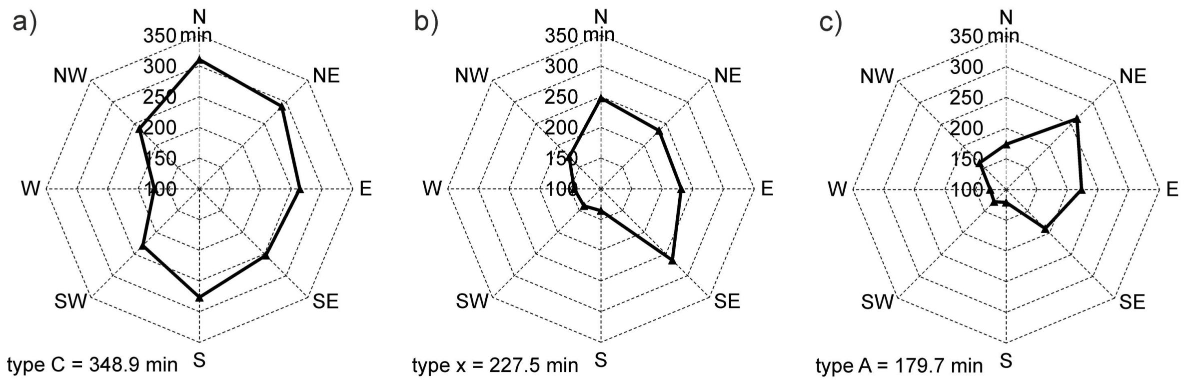

Figure 13: Duration of precipitation events in Lublin with an exceedance probability of 10% for (a) cyclonic, (b) transitional, and (c) anticyclonic CTs over East-Central Europe from May to September (1961–2010).

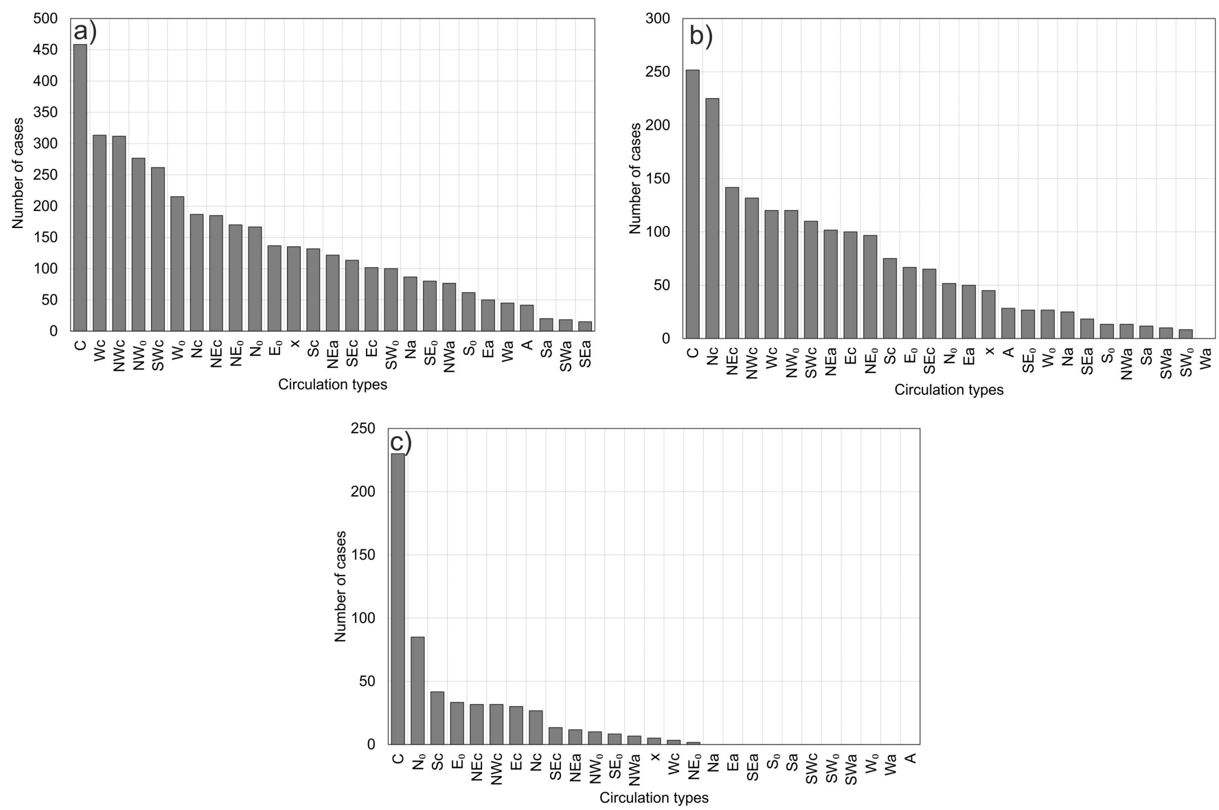

Figure 14: Number of cases of CTs over East-Central Europe for (a) short-term, (b) medium-term, and (c) long-term precipitation events in Lublin from May to September (1961–2010). Note that the scale of the Y-axis is different between the figures.

this case, higher precipitation intensities were recorded for types with air flow from north to south.

4 Discussions and conclusions

The present work shows that the application of the proposed objective classification of CTs for East-Central Europe (ECE) is justified in an analysis of the large-scale atmospheric circulation conditions of precipitation in Lublin (East Poland). The skill score values show that the variability of precipitation in the study area was better accounted for with the ECE rather than the Grosswetterlagen typology (GWL). Furthermore, the values for the objective weather types were very similar to those obtained in Pärnu (Estonia) [34], and higher than in De Bilt (Netherlands) [43]. However, the skill score values do not exceed 30% in most months, showing that the ECE scheme has rel-

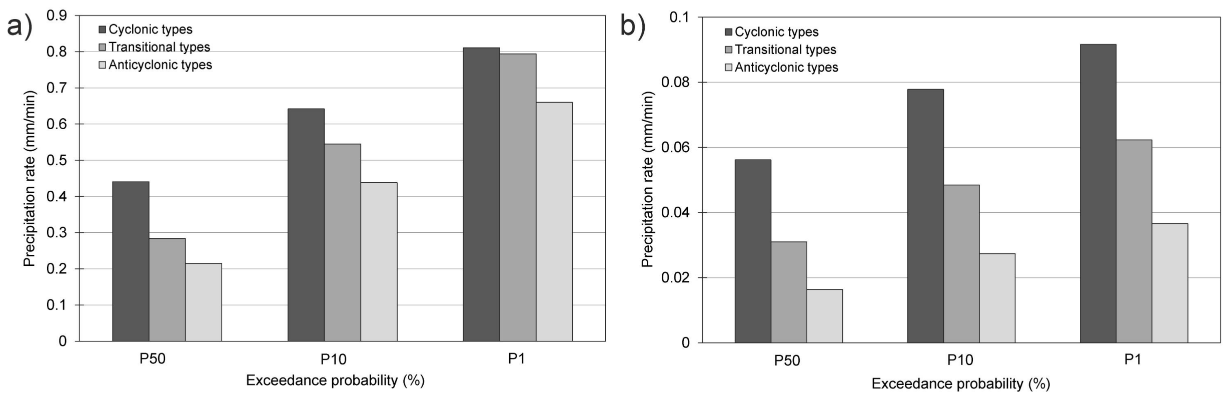

Figure 15: Intensity (mm/min) of (a) short-term and (b) medium-term precipitation events in Lublin with an exceedance probability of 50%, 10%, and 1% for cyclonic, transitional, and anticyclonic classes of CTs over East-Central Europe from May to September (1961–2010). Note that the scale of the Y-axis is different between the figures.

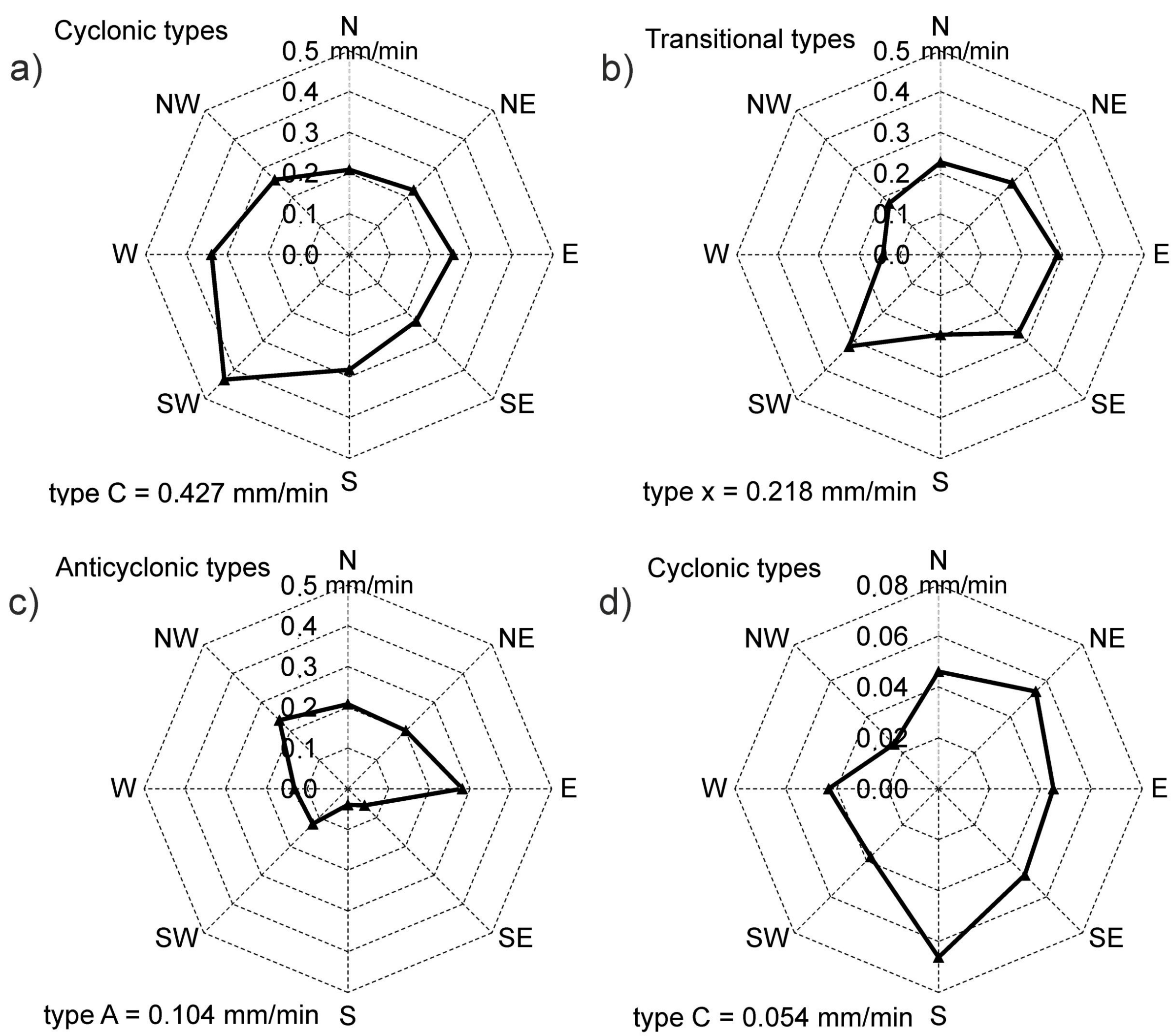

Figure 16: Intensity (mm/min) of (a-c) short-term precipitation events in Lublin with an exceedance probability of 10% for cyclonic, transitional, and anticyclonic CTs over East-Central Europe from May to September (1961–2010). Intensity of (d) medium-term precipitation events for cyclonic CTs is also presented.

atively poor performance when explaining temporal variability of precipitation. The reason may be that the ECE classification was not based on information related to precipitation formation processes such as dynamics of atmospheric fronts, thermodynamic conditions of the lower atmosphere and the role of orography. The relatively poor performance may also be caused by the subjectivity of thresholds used in the classification to determine cyclonic, transitional and anticyclonic CTs. Nevertheless, the ECE classification may be useful for different statistical downscaling methods for projection of precipitation in East-Central Europe.

The comparison of the two catalogues of CTs based on mean daily (ECE_d) and sub-daily sea-level pressure values (ECE_h) showed differences in total precipitation amounts corresponding to each of the CTs. In certain cases, differences reached up to 40%. This suggests that in reference to precipitation, the temporal resolution of data used for the development of the catalogue of CTs can have a substantial impact on the study results.

Over East-Central Europe, non-directional type A had the highest frequency from May to September. It was accompanied by considerably negative vorticity values, unfavourable for the development of clouds and precipitation. A high frequency of type A in the summer period was also observed in the region of southern Scandinavia and Estonia [33, 34]. The paper shows that a higher frequency of type A in a warm part of the year causes a significantly lower total precipitation amount and lower number of hours with precipitation. In turn, non-directional type C was characterised by substantially positive correlation with precipitation indices, and very high precipitation event frequency (with a maximum in May). Type C had the highest number of precipitation events with high intensity, as well as the highest frequency in short-term, medium-term, and long-term precipitation events. Directional cyclonic types also provided a considerable contribution to the total precipitation amount. In contrast, the contribution of directional transitional and anticyclonic types, and particularly those with air flow from the southern sector, was substantially lower. In Portugal, a southern air flow in the summer period also favoured the occurrence of periods with no precipitation [35].

In Lublin, similar to Cracow (South Poland) [46], the diurnal cycle of precipitation shows a stronger relationship to direction of air flow than the type of pressure system. In Cracow, with the exception of CTs with air flow from S and SW, the highest incidence of precipitation is also recorded in the late afternoon and evening, and the lowest at night and in the early morning. In turn, maxima for the S and SW circulation is observed at night and in the early morning due to modified thermal and humidity properties of air masses. This is caused by the fact that the orographic barrier of the Carpathians plays a significant role in the diurnal cycle of precipitation frequency in Cracow [46]. In the case of Lublin, topography does not significantly affect precipitation, and therefore the highest frequency of precipitation in the S and SW circulation is often observed between 17 and 20 CEST.

The study also showed that the substantially longer lifetime of the CTs with air flow from the eastern sector is reflected in the duration of precipitation events. Moreover, in cyclonic and transitional types, the probability of short-term precipitation events with very high intensity was similar, and the maximum corresponded with south-westerly air flow. In anticyclonic types, precipitation with high intensity was recorded more seldom, particularly in the case of advection from the southern sector. This may be due to relatively low humidity and high temperatures of air masses moving from North Africa or Southern Europe.

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