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The Variability of Maximum Daily Precipitation and the Underlying Circulation Conditions in Kraków, Southern Poland

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Abstract: This article studies the intra-annual and long-term variability in the maximum daily precipitation totals and their association with atmospheric circulation in Kraków. It investigates daily precipitation maxima by year and by month. The research is based on daily precipitation totals in the years 1863–2021 and draws on the calendar of atmospheric circulation types by Niedźwiedź. It examines the frequency of precipitation maxima in individual months and their variation from one year to another. No statistically significant trend of change in precipitation over the study period has been found. All annual maximum daily precipitation totals in Kraków fall into the category of heavy precipitation (>10 mm), and almost 99% qualify as very heavy (>20 mm). In the summer months, these are about 3–4 times higher than in winter. The share of the daily precipitation maximum in the monthly total exceeds 30% in all months. The maximum daily precipitation occurring on 5 August 2021 was the highest in the period that extends from the start of instrumental measurements. The study period saw 12 cases of maximum precipitation that belong to 'flood-inducing' categories (over 70 mm/day). Such cases of the very heaviest precipitation occurred in cyclonic situations: Cc, Bc, Nc, NEc, Ec and SEc. Most spring and summer maxima were seen on days with a cyclonic circulation. The instances of high daily precipitation in the Kraków area led to the flooding of residential and historic buildings, as well as of municipal infrastructure.

Keywords: maximum daily precipitation; linear trend; atmospheric circulation; urban area; Poland

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Citation: Twardosz, R.; Cebulska, M.; Guzik, I. The Variability of Maximum Daily Precipitation and the Underlying Circulation Conditions in Kraków, Southern Poland. *Water* **2023**, *15*, 3772. https://doi.org/10.3390/w15213772

Academic Editor: Paul Kucera

Received: 21 September 2023
Revised: 15 October 2023
Accepted: 27 October 2023
Published: 28 October 2023

1. Introduction

Precipitation is one of the climate elements that are highly variable in time and space. Both excess and shortage of precipitation is harmful to the natural environment and human activity. Excess rainfall can cause local flooding and even flash floods, while prolonged rainfall deficits can lead to drought. In the temperate geographic zone, huge masses of water can even be produced by a single day's rainfall event, especially when it is of the maximum type. Heavy precipitation belongs to the category of dangerous meteorological phenomena, which, in addition to the ever more frequent heat waves, has a significant impact on residents, cities and their infrastructure [1].

The literature on precipitation maxima is extensive. A vast proportion of it addresses precipitation with specific probability of exceeding a threshold [2], which makes it useful in the practice of environmental engineering, e.g., in land development and the design of urban and industrial areas [3–6]. This stems from the fact that urbanised areas are more vulnerable to flood hazards, which can cause the flooding of buildings, and damage and destruction to technical infrastructure and public and private property which, in turn, translates into financial losses. The risk derives, inter alia, from rapid, short-lived high-intensity rainfall that existing systems of drainage devices, including sewage pipes, cannot fully store and discharge safely to receivers over a short period of time.

This study focuses on the climatological analysis of precipitation maxima based on a secular series of measurements from Kraków. The subject matter in question is important from both a theoretical and a practical point of view [7–9]. Like many other cities in Poland and worldwide, Kraków has been experiencing increasingly frequent events of heavy precipitation [10,11], known to often result in flash floods, which pose a serious threat to the local population. Naturally, then, the question arises concerning the relationship between the long-term changes in precipitation frequency and the types of atmospheric circulation that accompany them.

The purpose of the present study is twofold: (i) it studies annual and long-term variability of annual maximum daily precipitation (AMDP) and monthly maximum daily precipitation (MMDP) in the 159-year period 1863–2021; (ii) the influence of atmospheric circulation on the occurrence of AMDP is investigated. An analysis of the synoptic situations behind two extremely catastrophic rainfall events and their environmental effects is presented. The use of such a uniquely long series of precipitation maxima in an urban area has the potential to provide a better insight into their variability, which can be utilised in forecasting them [6,12]. Precipitation, unlike air temperature, does not show statistically significant long-term changes, but instead demonstrates short-term fluctuations, including periodic ones [7,8,13]. Notably, the absence of statistically significant trends in precipitation change does not mean that water resources are secure, because it must be remembered that global warming has the obvious effect of intensifying the hydrological cycle.

In the former studies of precipitation maxima in Poland, normally only short-term series of precipitation were examined, usually starting in 1951, i.e., when a dense network of weather stations had already been established [13–15]. Cebulak devoted special attention to the examination of precipitation in southern Poland, and especially in the Polish Carpathians [14]. She investigated both the temporal variability and the spatial distribution of precipitation, as well as its relationship to the conditions of circulation prevailing in the area. These studies have shown no significant changes in extreme precipitation.

Recent years have seen the publication of numerous studies concerning the trends in precipitation maxima in different regions of the world [16–21]. For Europe, such an analysis was carried out by Madsen et al. [22], who found a general increase in the volume of extreme precipitation, though without any marked tendencies in the increase in maximum flows. However, few of these studies are based on secular, series of measurements of over 100 years [12].

The overview of the research area presented in Section 2 is the starting point for the research presented in this study. The research into annual maximum daily precipitation (AMDP) and monthly maximum daily precipitation (MMDP) is presented in Section 3.1. In addition to examining the frequency of such precipitation by month, the study also looked at its variability from year to year. Section 3.2 describes the effect of circulation type on the occurrence of daily precipitation maxima. Cases of precipitation maxima assignable to 'flood-causing' categories were distinguished and the underlying synoptic conditions were described for the heaviest such cases.

2. Study Area and Method

The study is based on a homogenous 159-year (1863–2021) sequence of standardised precipitation measurements in Kraków (Figure 1) and on a calendar of atmospheric circulation types for southern Poland by Niedźwiedź [23]. The inputs for the study comprised annual maximum daily precipitation (AMDP) and monthly maximum daily precipitation (MMDP). MMDP indicates the highest value of daily precipitation in the individual months of every year of the 159-year period examined. The meteorological station is located in the Botanic Garden in the centre of Kraków (206 m a.s.l.) (Figure 1). As is noted in a study by Bokwa [24], in the years 1971–2005, the annual totals of precipitation in the city centre are about 80 mm higher than in peripheral areas.

Figure 1. Location of Kraków and of the city centre meteorological station on the map of Europe.

The series of precipitation observations from Kraków employed in this study is one of the longest strings of precipitation measurements in Poland [25] which have been taken at the same location. It meets the condition of uniformity of observation site and homogeneity of measurement. Given its exceptional length, the series is very valuable not only as a means of determining maxima with specific probabilities of exceeding a threshold, but also as an input for studying their evolution in the long run [25]. It should be noted here that precipitation measurements in Kraków have been performed continuously since 1863 with the use of the same type of rain gauge [10,25,26]. Since the end of the 20th century, a pluviograph, an automatic rain gauge, has been in operation concurrently. While measurements and meteorological observations are performed by skilled scientific observers, i.e., meteorologists, qualitative observations of precipitation in Kraków date back to the establishment of the local weather station in 1792. Until August 1849, when precipitation measurements began, only visual observations of precipitation occurrence were recorded. Homogenous daily totals have only been available since 1863 [25]. On the basis of the preserved journals recording daily meteorological observations, information has been gathered about the occurrence of precipitation, its form and accompanying phenomena. Thus, a database of form and type of precipitation was created for Kraków [26]. Information concerning precipitation types has also been used in the present study (see Tables 1–3). Kraków lies in southern Poland (Figure 1), in the valley of Poland's largest river, the Vistula, and occupies an area of approximately 327 km^2 [27]. The river and the surrounding upland area has been a factor behind the intensive territorial expansion of the city. According to Matuszko [28], the area of the city has increased sevenfold in the last 100 years alone, and the population has grown more than ninefold to attain its current size of approximately 800,000.

The average total annual precipitation in Kraków over the long-term (1863–2021) is 683 mm, which is 90 mm higher than the average in Poland [27]. Precipitation ($\geq$0.1 mm) is recorded on an average of 180 days a year, including 19 days with heavy precipitation ($\geq$10 mm). Days with very heavy precipitation ($\geq$20 mm) account for 3% of all days with precipitation [29].

This study has determined the frequency of maximum daily precipitation totals by month and year over the study period. It describes the share of daily precipitation maxima in the annual and monthly precipitation totals, and the influence of atmospheric circulation types on the prevalence of maximum precipitation is investigated. A description of the calendar of atmospheric circulation types employed is provided in Section 3.2. The frequency of precipitation maxima in the presence of the various types of circulation was analysed. In order to take the seasonality of circulation processes into account, the analysis was not only performed for the whole year, but also by season. Cases of precipitation maxima assignable to the 'flood-inducing' categories, i.e., with totals over 70 mm, have been separately identified [30]. The type of circulation was determined for each instance of flood-causing precipitation. The synoptic conditions behind two catastrophic precipitation events are described. The study analyses the distribution of the geopotential field and air temperatures at the 500 hPa and 850 hPa isobaric levels, as well as of the CAPE index [J/kg] [31].

3. Discussion and Results

3.1. Annual and Long-Term Maxima of MMDP and AMDP

In Kraków, daily precipitation maxima (the highest amount of precipitation in the year—AMDP) occur from March to November; their earliest occurrence in a year was recorded on 28 March 1993 and the latest on 22 November 1878, but over 90% of the precipitation maxima were observed in the months May to September alone. Their highest frequency is noticeable in the summer months, with the maximum in July—27%, which is associated with strong convection. In the 159-year period under study (1863–2021), the average AMDP was 42.7 mm, and its standard error was 3.4 mm. Over the timespan under investigation, such precipitation ranged from 17.5 mm (28 March 1993) to 103.4 mm (5 August 2021), with the difference between the lowest and highest AMDP amounting to 85.9 mm. In Kraków, all annual maximum daily precipitation totals fall into the category of heavy precipitation (≥10 mm), and almost 99% qualify as very heavy (≥20 mm). Daily precipitation of over 50 mm accounted for 26%, and only two cases represented precipitation of more than 90 mm, i.e., of sufficient size that it may cause hydrological hazards. Precipitation of such high intensity is generated by strong convective processes in the atmosphere, which are manifested by a storm. In Kraków, every second daily maximum (78 days) entailed a storm, every fourth of which was hailstorm (18 days). Snowfall may also represent the highest daily precipitation in a year. Kraków saw two such cases over the 159-year period: on 22 November 1878 and 28 March 1993, with precipitation totalling 31.2 and 17.5 mm, respectively. Due to it producing snow cover, heavy snowfall poses a great threat to city transport and a structural hazard to building roofs. One highly consequential event worth recalling in this context was a construction disaster that occurred on 28 January 2006, 60 km west of the centre of Kraków, in which the accumulation of a thick layer of snow on a hall roof caused the death of dozens of people [26]. In Kraków, precipitation maxima could also take the form of sleet. This also happened twice: on 16 April 1916 and on 8 November 1952, with precipitation totalling 78.8 and 29.1 mm, respectively.

A catastrophic storm with hail hit Kraków on 9 September 1963. In addition to its exceptionally high total quantity (99 mm), it was also very intensive to a degree not recorded by previous observations and measurements that had started in the second half of the 19th century. Its actual duration was 3 h (15.00–18.00 CET, UTC+1), and hourly precipitation totals were, respectively, 98.7 mm, 0.2 mm and 0.1 mm. According to Niedźwiedź [10], as much as 30 mm of rain fell over a duration of 5 min, which accounted for nearly 50% of the average precipitation that month. The highest intensity was recorded in the first 60 min of the storm, with the fall reaching 98.7 mm, i.e., nearly the entire total volume (Figure 2). On 5 August 2021, there was intense rainfall that totalled more than 103 mm, which became the highest diurnal precipitation total in Kraków from the start of instrumental observations. Of this, 77 mm of rain fell in the afternoon, between 5 pm and 10 pm local time (CET, UTC+1) (Figure 2).

The two catastrophic daily rainfall events triggered traffic difficulties, causing interruption to car and tram transportation due to water flowing along city streets. A thunderstorm in September 1963, with electrical discharges and heavy hail, caused mass killing of birds in the city centre. Lakes formed in many places. Overhead tram and telephone lines were damaged. Basements, boiler rooms, warehouses, schools, theatres, and—as the press (Echo Krakowa [32], Gazeta Krakowska [33,34]) was reporting in the aftermath—even residential premises were flooded.

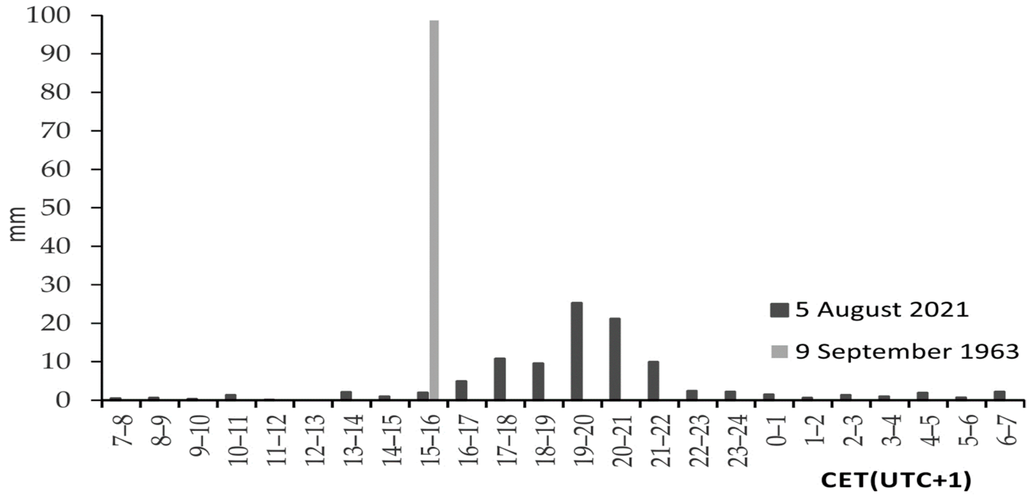

Figure 2. Intra-day evolution of rainfall on 9 September 1963 and 5 August 2021.

As a result of rainfall in August 2021, storm drains and sewer pipes failed to cope with the excess water, due to which the streets became the beds of 'storm rivers'. Residential buildings, especially in the south-eastern area of Kraków, were also flooded.

Some precipitation maxima had a very large share in the precipitation totals of the respective years (Figure 3). The 159-year period saw five daily maxima whose share in the annual total exceeded 10%, with three maxima exceeding 11%: on 5 August 2021 (11%), 24 June 1989 (11.6%) and 9 September 1963 (12.7%) (Table 1). The precipitation totals amounted to 103.4, 79 and 99 mm, respectively. The lowest share (2.4%) in the annual total was demonstrated by the daily maximum on 23 February 1966, when precipitation amounted to 24 mm overall. No statistically significant trend of long-term change at a significance level of 0.05 is found in the entire series of precipitation maxima (AMDP). However, short-term fluctuations in AMDP are clearly discernible (Figure 4). Periods with high precipitation totals occurred at the turn of the 20th century and in the 1960s. These periods coincide with timespans of high annual precipitation totals [26].

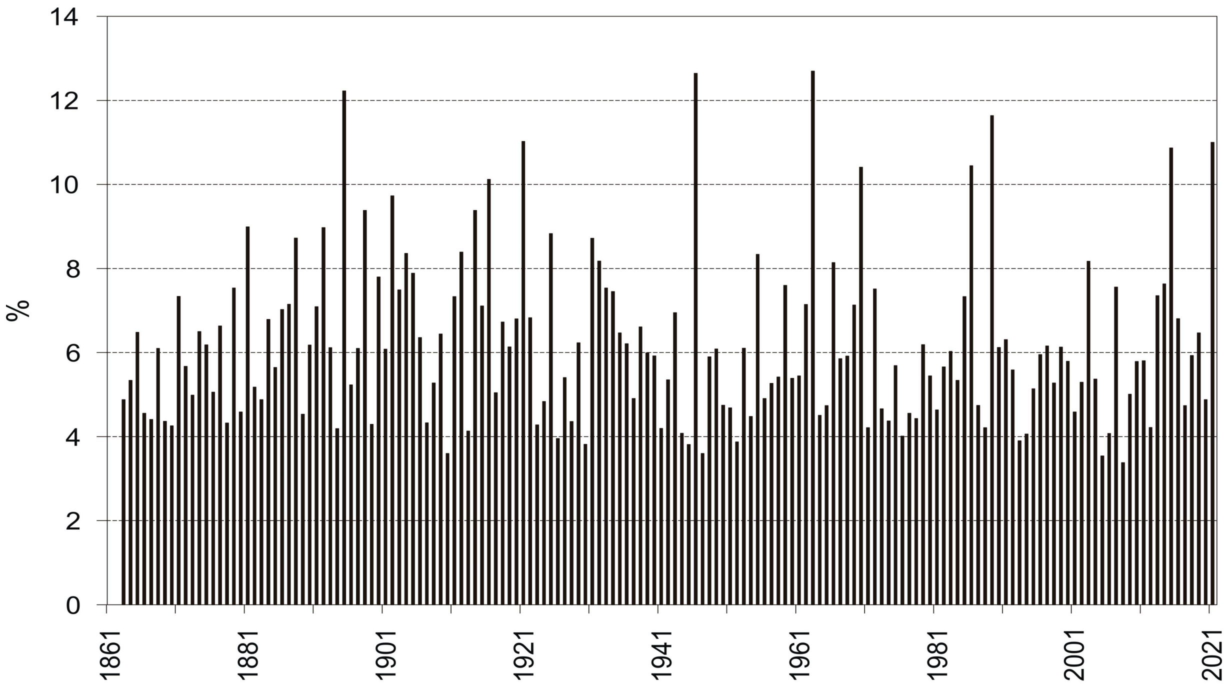

Figure 3. Share (%) of annual maximum daily precipitation (AMDP) in the annual total (1863–2021).

Table 1. Statistical characteristics of maximum daily precipitation (MMDP) by month (1863–2021).

	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
P_{min}	1.6	0.9	0.2	0.4	3.8	5.8	5.1	4.0	3.4	0.0	0.0	1.5
Year	1894	1901	1904	2009	1930	1930	1965	1911	1941	1951	2011	1972
P_{avg}	8.6	8.3	10.2	14.0	21.5	26.5	28.0	26.2	19.1	14.3	12.1	9.3
P_{med}	7.7	7.4	8.9	11.9	17.6	23.0	24.4	23.5	17.2	13.0	11.6	8.2
P_{max}	25.0	24.0	29.5	78.8	83.9	79.0	85.2	103.4	99.0	43.8	36.8	27.4
Year	1970	1966	2004	1916	1912	1989	1970	2021	1963	1939	2009	1961
$P_{max}/\Sigma P_m$	45.5	30.8	45.7	53.0	36.4	31.5	44.6	43.2	58.7	34.1	47.5	40.5
$P_{max}/\Sigma P_y$	3.1	2.4	4.4	10.1	8.4	11.6	10.4	11.0	12.7	6.0	5.0	4.3

Notes: Explanatory notes: P_{min}—the lowest maximum daily precipitation (mm); P_{avg}—average maximum daily precipitation (mm); P_{med}—median maximum daily precipitation (mm); P_{max}—the highest maximum daily precipitation (mm); $P_{max}/\Sigma P_{m/y}$—share of P_{max} in the monthly/annual total (%).

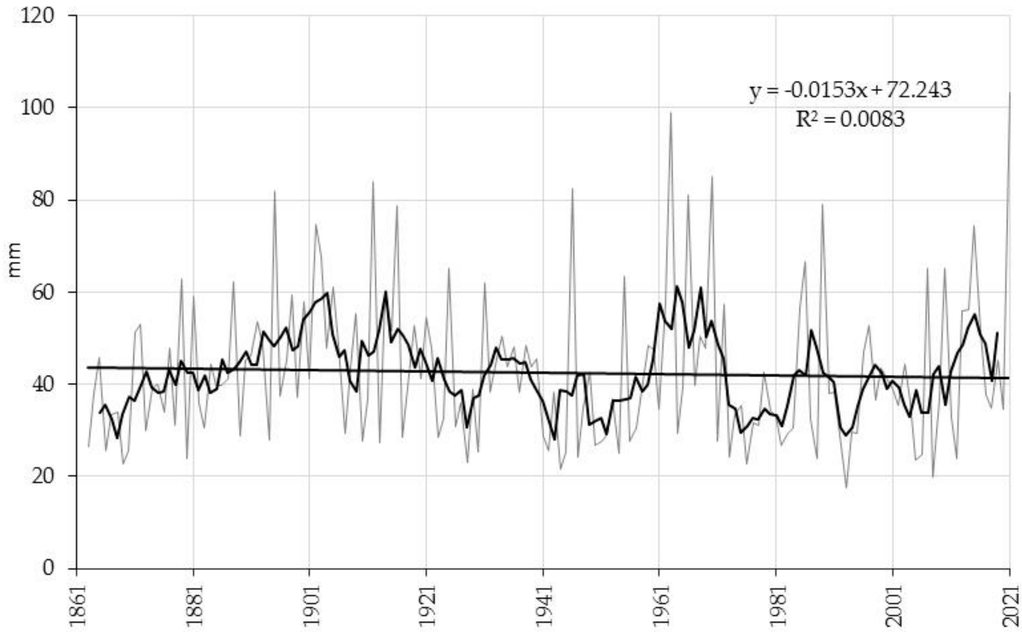

Figure 4. Evolution of annual maximum daily precipitation (AMDP) and values smoothed by 5-year consecutive averages, and the trend line (1863–2021).

The 159-year period investigated saw 2 months without precipitation, namely October 1951 and November 2011 (Table 1). Average MMDP totals in excess of 20 mm occur in Kraków from May to August, with the maximum average MMDP of 28.0 mm in July. In the winter months, they are less than 10 mm. The highest MMDP totals of all the months exceed 20 mm, which renders them qualifiable as very heavy precipitation. In the summer months, they are about 3–4 times higher than in winter (Table 1; Figure 5). Notably, the annual maximum daily precipitation (AMDP) does not necessarily have to also be the absolute highest daily total precipitation in a given month (MMDP). The highest daily total in a given month over the study period does not need to be the highest total in the year; it may also happen that the highest daily total in a dry year may be lower than the second or third highest in a wet year. As shown earlier, the lowest total in the series of annual maximum daily precipitation was 17.5 mm. The share of the maximum daily precipitation (MMDP) in the monthly total exceeds 30% in all months (Table 1). The record-high daily precipitation from April 1916 (78.8 mm) and from September 1963 (99 mm) accounted for over 50% of the total precipitation of the respective months.

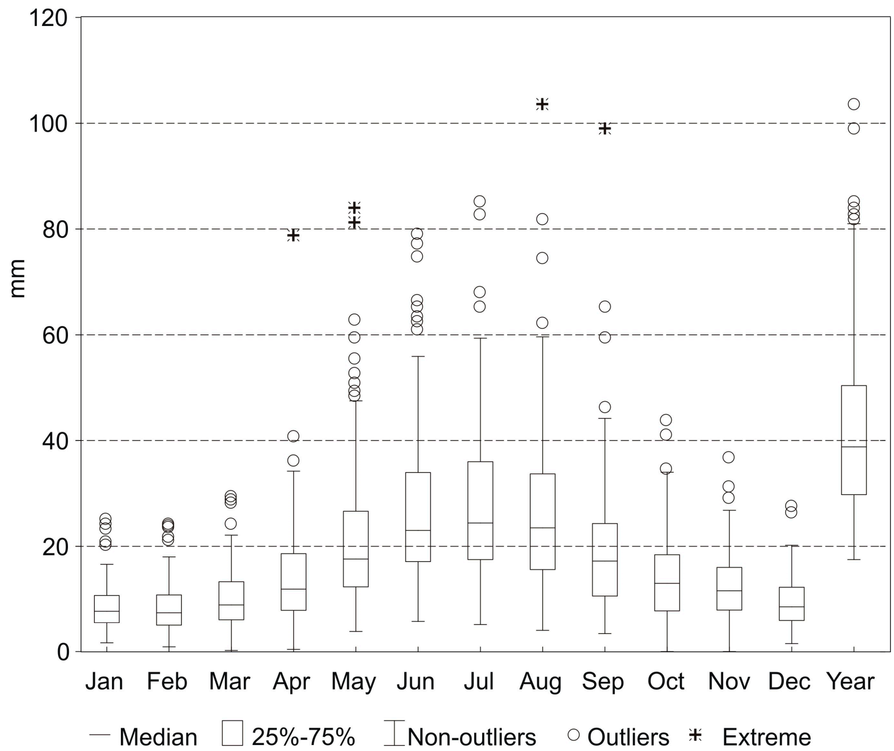

Figure 5. Statistical characteristics of maximum daily precipitation (MMDP) by month (1863–2021).

The statistical characteristics of precipitation are presented in a box-and-whisker plot (AMDP, MMDP) in Figure 5. In the case of AMDP, only outliers (nine values), i.e., values that are above 1.5 IQR (25–75%), are plotted. The MMDP series incorporates five extreme values (above the third interquartile range).

3.2. Effect of Atmospheric Circulation on the Occurrence of Precipitation Maxima (AMDP)

In a temperate climate, atmospheric circulation plays a prominent role in the formation of precipitation. In order to determine the effect of circulation on the frequency and magnitude of maximum daily precipitation (AMDP) in Kraków, use was made of the calendar of circulation types over southern Poland prepared by Niedźwiedź [23,35] from the years 1874–2021. It was developed on the basis of surface pressure charts for Europe from 00 and 12 UTC. In preparing the calendar, Niedźwiedź also referred to 700 hPa level pressure charts. The key elements of the types of circulation distinguished by the author include the direction of advection or its absence and the type of pressure system. The calendar defines 20 types of circulation, 16 of which are types describing the advection of air over the area concerned. These are described with a code denoting the direction of air advection and the associated type of pressure system (‘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 four types are advectionless situations or situations with various directions of advection. They are as follows: Ca—central anticyclonic situation, Ka—anticyclonic wedge, Cc—central cyclonic situation, Bc—cyclonic trough. Situations that escape the classification are marked with an X. Each daily precipitation maximum (AMDP) from the period 1874–2021 (148 daily totals) was assigned the relevant type of circulation. Given the seasonality of circulation processes, the characteristics of the frequency of such precipitation values in the 20 types of circulation was classified not only for the year as a whole, but despite their small number, also for the seasons (Table 2), with the exception of winter when such precipitation did not occur.

Table 2. Frequency (%) of maximum daily precipitation (AMDP) in types of circulation (1874–2021). N—number of days with maximum precipitation.

Type of Circulation		Spring (N = 25)	Summer (N = 103)	Autumn (N = 20)	Year (N = 148)
1	Na	4.0	-	-	0.7
2	NEa	8.0	-	-	1.3
3	Ea	-	1.9	-	1.3
4	SEa	-	-	5.0	0.7
5	Sa	-	1.9	-	1.3
6	SWa	-	-	-	-
7	Wa	-	1.9	-	1.3
8	NWa	-	1.0	-	0.7
9	Ca	-	-	-	-
10	Ka	-	3.8	-	2.7
11	Nc	32.0	12.3	10.0	15.0
12	NEc	12.0	9.5	10.0	10.2
13	Ec	4.0	9.5	20.0	10.2
14	SEc	4.0	5.7	5.0	4.8
15	Sc	4.0	1.9	-	2.0
16	SWc	-	4.8	-	3.4
17	Wc	4.0	3.8	5.0	4.1
18	NWc	-	3.8	-	2.7
19	Cc	-	5.7	5.0	4.8
20	Bc	28.0	30.5	40.0	31.3
21	X	-	1.9	-	1.5
1–21	Sum	100	100	100	100
1–10	a	12.0	10.6	5.0	10.1
11–20	c	88.0	87.6	95.0	88.4

Table 3 is a compilation of the cases of maximum rainfall assigned to the categories recognised as flood-inducing, i.e., with totals in excess of 70 mm [30]. Most precipitation maxima (88%) occur on days with cyclonic circulation; in autumn, there was only one instance of precipitation maximum on a day with anticyclonic circulation. This means that the character of circulation—cyclonic or anticyclonic—has a stronger effect on the occurrence of heavy precipitation than the direction of advection. This follows from the fact that the presence of vertical air movements, which increase the likelihood of occurrence of heavy precipitation, depends on the character of circulation. The greatest precipitation in anticyclonic circulation (Ka) reached 61 mm (2 June 1905), i.e., about 60% of the daily precipitation total in Kraków on 9 September 1963. The number of circulation types that entail precipitation varies depending on the season. In summer, precipitation occurs in more types than in the transitional seasons, since the long day creates favourable thermal conditions for the development of strong convection. Among the 20 types of circulation, those that are most conducive to precipitation, especially that of flood-inducing proportions (Tables 2 and 3), are the cyclonic types: cyclonic trough (Bc) and three types of advection—from the north (Nc), north-east (NEc) and east (Ec). However, the share of precipitation in these types of circulation varies from one season to another. In spring, 60% of the precipitation maxima occurred with the presence of the Nc and Bc types (32% and 28%, respectively). In summer and autumn, the maxima are by far the most frequent with the presence of type Bc (30.5% and 40%, respectively), although in summer, maxima are also frequent with the presence of the Nc type, and in the autumn with the Ec type. The three types of cyclonic circulation that not only trigger extremely high precipitation in Kraków, but also across the whole of southern Poland (Nc, NEc and Bc), are associated, inter alia, with cyclones moving from the Adriatic Sea in a north-easterly direction, usually across Hungary and the Carpathians, onto southern Poland and Ukraine, following the cyclone trajectory known as the Vb track [36]. Although they rarely reach southern Poland, such cyclones cause intensive, prolonged precipitation enhanced by orographic conditions [37].

The circulatory conditions described above entail catastrophic floods [38], such as the region-wide flood that hit southern Poland in May 2010 [39,40]. At the time, most of the precipitation and the greatest precipitation totals were recorded on days with a northerly cyclonic circulation and in the presence of a cyclonic trough [41].

Table 3. Daily precipitation ≥ 70 mm in Kraków (1863–2021).

Precipitation (mm)	Date of Occuration	Type of Circulation	Type of Precipitation
103.4	5 August 2021	Cc	Rain
99.0	9 September 1963	Ec	Thunderstorm with hail (hailstorm)
85.2	18 July 1970	Nc	Rain
83.9	25 May 1912	NEc	Thunderstorm with hail (hailstorm)
82.6	8 July 1946	Ec	Thunderstorm with rain
81.8	25 August 1895	X	Thunderstorm with rain
81.0	29 May 1966	Nc	Rain
79.0	24 June 1989	Bc	Thunderstorm with hail (hailstorm)
78.8	16 April 1916	Nc	Rain with snow (mixed precipitation)
77.1	23 June 1946	Bc	Thunderstorm with rain
74.8	19 June 1902	Nc	Rain
74.4	16 August 2015	SEc	Thunderstorm with rain

It follows from an analysis of the synoptic conditions on 9 September 1963 that, at that time, southern Poland was within the range of a low-pressure centre that was travelling, together with a system of atmospheric fronts from the Hungarian Plain to Belarus. Up until noon, Kraków was within the warm section of the cyclone, amidst humid and warm air coming from the Black Sea (Figure 6). South of Kraków, over the Carpathian Mountains, an area of cold atmospheric front formed which was moving north-east. According to Lewińska [34], the line of the front was moving over Kraków between 15.30 and 16.00 CET (14.30–15.00 UTC). The air in the warm section of the cyclone displayed low instability (CAPE of approx. 600 J/kg), but under the influence of conducive kinematic conditions, Cb clouds formed with heavy rainfall and thunderstorms featuring hail. Strong thunderstorms swept across southern Poland, with the area of Kraków seeing some of the heaviest [34]. Cold fronts typically move rapidly, which is why the precipitation zone is rather narrow and the rainfall lasts for a short time, no longer than 30–60 min.

On another occasion, on 5 August 2021, Poland was under the influence of a low with a system of atmospheric fronts moving from south to north along the eastern border of the country. Polar sea air, temporarily warmer and wetter in the warm section of the cyclone, was flowing in from the south of Europe. As the cyclone was developing at the surface, the upper atmosphere saw a deepening of the upper trough and an increase in the advection of cold at the rear of the trough. Over southern Poland, the cyclone reached the occluding stage and was also observable in the upper layers of the atmosphere, both at the 850 hPa and 500 hPa geopotential fields (Figure 7). The influx of a very warm and humid air mass and the slow movement of weather fronts gave rise to intense, continuous rainfall.

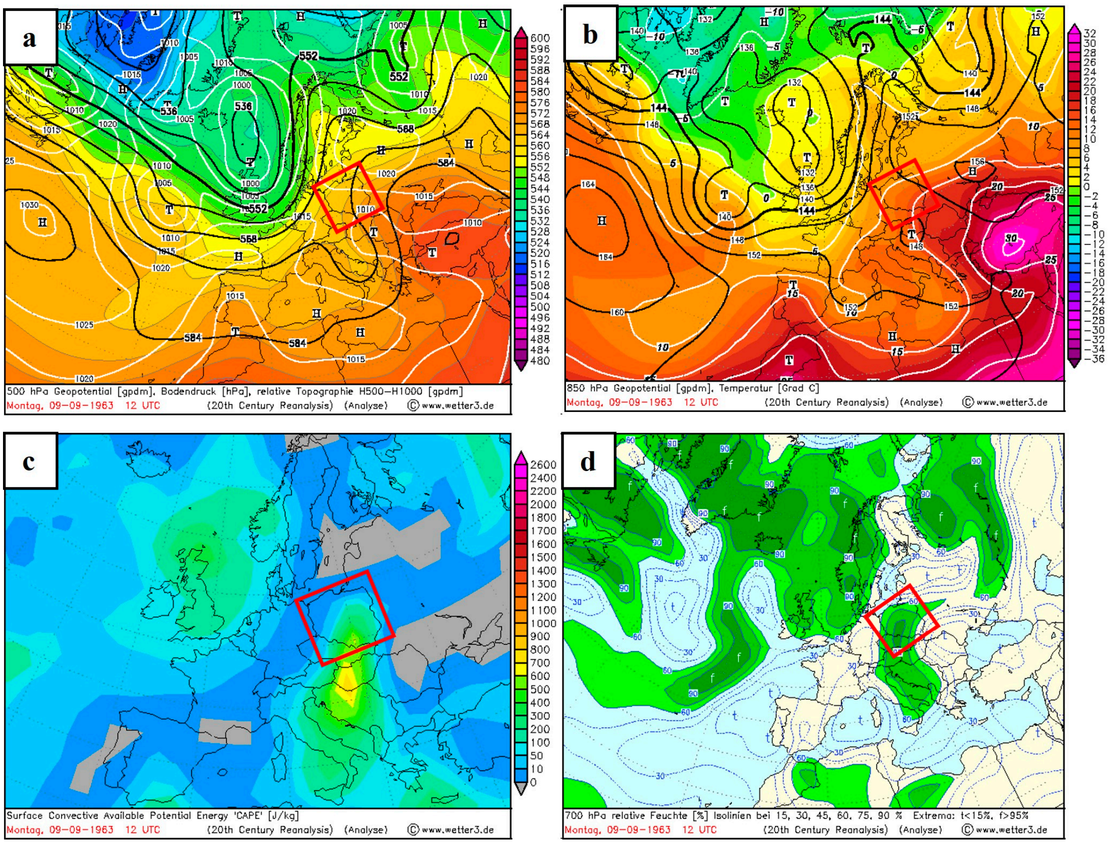

Figure 6. Absolute topography at 500 hp (dmgp, black lines), ground-level pressure (hPa, white lines) and relative topography 500–1000 hp (dmgp, colours) (**a**), distribution of the geopotential field and air temperatures at the 850 hPa (**b**) pressure levels, CAPE [J/kg] (**c**) and distribution of relative air humidity [%] at 700 hPa (**d**) on 9 September 1963 (12 UTC) [31]. Red square frame: Area of Poland.

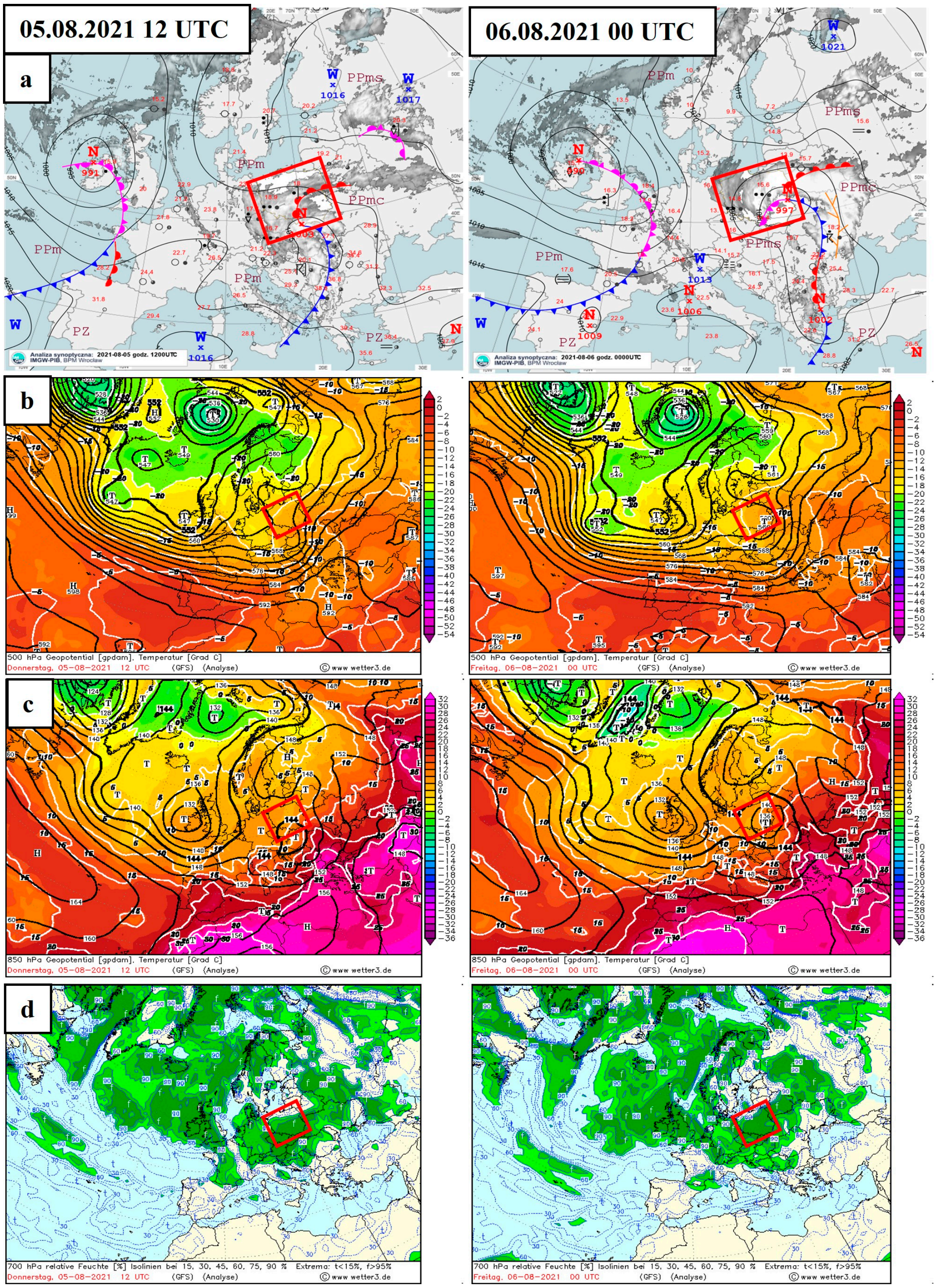

Figure 7. Surface synoptic map (IMGW-PIB) (**a**), distribution of the geopotential field and air temperatures at the isobaric levels of 500 hPa (**b**) and 850 hPa (**c**), distribution of relative air humidity [%] at 700 hPa (**d**) [31] on 5 August 2021 (12 UTC) and 6 August 2021 (00 UTC). Red square frame: Area of Poland.

4. Conclusions

Based on the 159-year series of precipitation data in Kraków, it can be seen that annual maximum daily precipitation (AMDP) occurs from March to November, but it is most frequent in July (27%). There are short-term fluctuations in the precipitation totals over the study period, but there is no identifiable statistically significant trend of changes in their volume. It is typical for precipitation totals to vary widely and only very large volume changes reach statistical significance levels. Contrary to what might be expected, there is no simple relationship between changes in precipitation and air temperature. Even though growth in temperature intensifies convection, research in Kraków [26] has found that this does not translate into higher amounts of precipitation. This may be attributed to the fact that in the Polish climate, the hottest years are also the driest ones, and dryness is not conducive to precipitation. The secular series of precipitation maxima used in this article necessarily provokes questions about urban influence on precipitation. In the second half of the 20th century, the city of Kraków substantially expanded both in territory and population. In the first place, the period saw far-reaching quantitative and qualitative change in industrialisation, which caused particulate and gaseous air pollution levels over Kraków to grow several times. Research by Polish climatologists, e.g., ref. [24], has demonstrated that human impact on daily precipitation levels is mainly manifested by the generation of drizzle-sized precipitation (up to 1 mm of the daily total), especially trace-level precipitation (0.0 mm). This effect is particularly strong in 1961–1995. Urban impact on precipitation is an interesting issue of practical relevance, but one typically researched in the context of short precipitation, i.e., that with a high time resolution, such as hourly precipitation. This study, however, demonstrates that this impact does not need to be identifiable at all in the daily maxima. Precipitation with a high daily total and the highest intensity—almost 99 mm in 60 min—was observed on 9 September 1963. The share of that precipitation in the monthly total amounted to 58.9%, and to 12.7% of the annual total. It occurred on a day with easterly cyclonic circulation. Meanwhile on 5 August 2021, a central cyclonic situation gave rise to intense rainfall that totalled more than 103 mm, which was the heaviest daily rainfall recorded in Kraków from the start of instrumental measurements, i.e., since 1863. Both on 9 September 1963 and on 5 August 2021, warm and humid air was flowing into southern Poland from the Black Sea and the cyclonic centre was passing a short distance away from Kraków. As is commonly known, the closer the fronts are to the centre, the more active and more developed are the vertical and horizontal cloud systems. The above means that precipitation zones closer to the centre of cyclones are wider and the precipitation itself is more intense.

The study period saw 12 cases of maximum precipitation that belong to the 'flood-inducing' categories (over 70 mm/day). These cases of heaviest precipitation occurred in cyclonic situations: Cc, Bc, Nc, NEc, Ec and SEc. Maximum precipitation (MMDP) exceeded 20 mm in all months, that is, it belonged to the very heavy category.

In addition to them being triggered by heavy rainfall, local floods and swollen rivers are encouraged by land development, which mainly concerns highly urbanised sectors of cities forming large areas of sealed surface. These increase runoff, and have low capacity for water to soak into the ground (infiltration). The heavy rainfall observed in urbanised areas in Kraków hampered city traffic with torrential streams flowing along the streets, carrying gravel and stones, and with trees falling onto overhead tram lines, damaging them. Ponding (lakes) formed in places. The rainfall events of September 1963 and August 2021 caused local flooding of residential buildings in the city, even of their upper floors, and interruption to vehicular and tram traffic, with the latter chiefly caused by falling trees.

Author Contributions: Conceptualization, R.T. and M.C.; methodology R.T., M.C. and I.G.; validation, R.T., M.C. and I.G.; formal analysis, R.T., M.C. and I.G.; investigation, R.T., M.C. and I.G.; resources, R.T., M.C. and I.G.; data curation, R.T., M.C. and I.G.; writing—original draft preparation, R.T., M.C. and I.G.; writing—review and editing, R.T. and M.C.; visualization, R.T., M.C. and I.G.; supervision, R.T. and M.C.; project administration, R.T. and M.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

Acknowledgments: We thank Paweł Pilch and Martin Cahn for reviewing the English.

Conflicts of Interest: The authors declare no conflict of interest.

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