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THE RELATIONSHIP BETWEEN TEMPERATURE, CLOUDINESS AND PRECIPITATION AT THE TIME OF RAPID GROWTH OF THE CRACOW AGGLOMERATION

Abstract: The paper presents attempts to identify a relationship between temperature, cloudiness and precipitation in Cracow in the period 1951-2000. The data include mean monthly and annual temperature, the number of days with the maximum temperature greater than 10°C and 25°C, annual and daily precipitation, the type of precipitation, as well as the overall cloudiness and the type of clouds. Close attention was paid to anomalous values. Since 1960s, the cloudiness and precipitation had followed a corresponding pattern as a result of the change of the cloudiness structure, probably caused by the increasing air temperature.

Keywords: air temperature, cloudiness, precipitation, anomaly, urban climate, Cracow

1. Introduction

At the onset of the 21st century, more than 80% of Europeans live around towns and cities. The omnipresent urbanisation continues to claim new land and together with the industrial development it causes considerable change to the environment leading to the changes in natural climate. It is therefore increasingly important to understand urban climate and the relationships between its components.

The increase of air temperature, one of the earliest-diagnosed features of urban climate, is among its most typical and best researched evidences. The warmer urban air spurns convection processes and, consequently, increases the occurrence of the cumulus-type clouds. The developing Cu and Cb clouds yield intense occasional rainfall, rainstorms and hailstorms.

Lewińska (2000), using European examples, argued that urban areas are a typified by such features as increased precipitation (by 10-30% on average), the occurrence of very intense rainfalls including rainstorms (increase by 10-47%) and hailstorms (by up to 90%), increased precipitation in the city centres, as well as occasional snowfalls around large steelworks and cogeneration power plants.

After the Second World War, Cracow experienced a rapid territorial and demographic expansion. During 1946-1990, the city grew from 165.3 to 326.8 km^2 (by 97.7%) and its population rose from 299 400 to 750 500 (by 150.7%). The greatest growth rate was recorded in housing (by 345.3%), as large housing estates were built in two housing belts at the northern and southern edge of the city (Mydel 1994). The construction of a huge steelworks and building the new town of Nowa Huta (at present: one of Cracow's districts) resulted in a period of the fastest population growth during 1950s.

The impact of the increasing urbanisation on the city's climate was confirmed when an urban heat island (UHI), a resultant of all anthropogenic influences on natural environment, was identified over Cracow (Obrębska-Starklowa et al. 1997). Urban heat islands develop as heat accumulates over urban areas and their intensity is proportional to the size of a city. In Cracow, the estimated mean UHI intensity in the city centre is 1.2°C but varies from day to day from 5 to 7°C (Obrębska-Starklowa et al. 1997). The annual pattern shows the UHI intensity to be stronger during the cold half-year (1.0-1.6 °C), and weaker during the warm half-year seasons (0.5-0.8 °C). Spatially, the Cracow UHI followed the city's expansion. In 1950, the island only covered the densest developed central quarter (Śródmieście) (Lewińska et al. 1990). Over the following ten years, it expanded and another one developed above of Nowa Huta. The two heat islands merged in the 1960s, as urban development gradually closed the gap between the old city and Nowa Huta. The large new UHI was three times larger than the one from the 1950s, but varied in its UHI intensity.

This paper aims to identify the relationships linking air temperature, cloudiness and precipitation in Cracow during the period of the city's most rapid growth, i.e. after 1950. The team also focussed on those extreme phenomena in air temperature, precipitation and cloudiness, which had been regarded by numerous climate researchers as evidence of a climate change (Obrębska-Starkel, Starkel 1991), and had been on the increase recently, probably due to the global warming effect.

2. Source data and methodology

The study was based on daily climatological observations made at the climatoligical station of the Jagiellonian University, Cracow, Department of Climatology of Institute of Geography and Spatial Management during the years 1951-2000. The station is located in the city centre at the Botanic Garden (φ =50°04' N, λ = 19°58' E, h= 220 m a.s.l.).

The data analysed included mean monthly and annual air temperature; the number of days with maximum air temperature above 10 °C and above 25 °C; daily and annual totals of precipitation and the type of precipitation; cloudiness and genera cloud at three observation times.

The monthly and annual temperature and precipitation values, normal and anomalous, were determined according to the method proposed by U. Kossowska-Cezak (2000/2001). The classification adopted was based on standard deviation (σ) from the long-term mean value so that each range for both normal and the remaining values had the size of one standard deviation. This means that the range of normal values was determined by the long-term (50 years) value ±0.5σ, and all other value ranges started with the deviation equal to 1.5σ. Thus, the mean monthly and annual temperature and precipitation values above 1.5σ were regarded as positive anomalies and those below –1.5σ, as a negative anomalies.

3. Temperature, precipitation and cloudiness

Figure 1 shows the values of the discussed climate elements during the period 1951-2000 (Fig. 1). The annual mean cloudiness (Fig. 1a) decreased (by ca. 10%) between 1951 and the early 1980s, and then has slightly increased. The highest mean annual cloudiness (78%) was recorded in 1952 and the lowest one (56%) was recorded in 1982. Precipitation revealed alternating growing and diminishing trends (Fig. 1b). There was a clear precipitation maximum (nearly 1000 mm) recorded in 1966. The lowest precipitation (448 mm) was recorded in 1993. The 1960s recorded considerable above-average precipitation. After a number of precipitation-deficit years, precipitation has been showing a growing trend since 1995. At the end of 1990s, the frequency of extreme precipitation events increased, including the catastrophic rainfalls in September 1996, July 1997 and April 1998 (Twardosz 1999).

Since 1960s, there has been a significant coincidence in the cloudiness and total precipitation (correlation coefficient 0.600, significant at 0.05 level). This was linked to a change in the cloudiness structure in Cracow, probably caused by the temperature increase. During the first half of the 20th century, the St and Ns clouds played a key role in the overall cloudiness in Cracow (up to 30%) (Matuszko 2001), but then the frequency of the convection clouds increased.

While there was no clearly identifiable trend in either cloudiness or total annual precipitation, the air temperature revealed a growing trend (Fig. 1c). The period 1951-2000 was 0.7°C warmer as compared to the first half of the 20th century. Since 1983, there were as many as seven years with the value temperature greater than 10°C, and in 2000 the mean annual temperature reached 11.0°C. It was the highest mean annual temperature in the records of the Cracow Climatological Station, i.e. since 1792.

The winter temperature was the greatest contributor to the overall annual temperature increase (Trepińska 1997, 2000). The number of days with the maximum air temperature >10°C (t_{max}>10°C) in December, January and February has been rising since the beginning of the 20th century. During the second half of the 20th century, the number of days with t_{max}>10°C in each of those winter months was 50% greater than during the first half of the century. Over the entire period, the greatest increase in the number of days with t_{max}>10°C was recorded in February (2.4 days in 100 years), and the smallest increase in January (1.4 days in 100 years). It is however worth noting, that as many as 84% of the January days with t_{max}>10°C occurred during the 20th century and 46.9% during the latest 20 years (1981-2000). In the January of 1992, there were 11 such days and during the January of 1990, the second ranked January in the period, there were six such days (Fig. 2). Again, these were the highest numbers in the history of the Cracow weather records.

The considerable increase of air temperature, particularly strong in the winter season, had an unquestionable influence on the other meteorological elements.

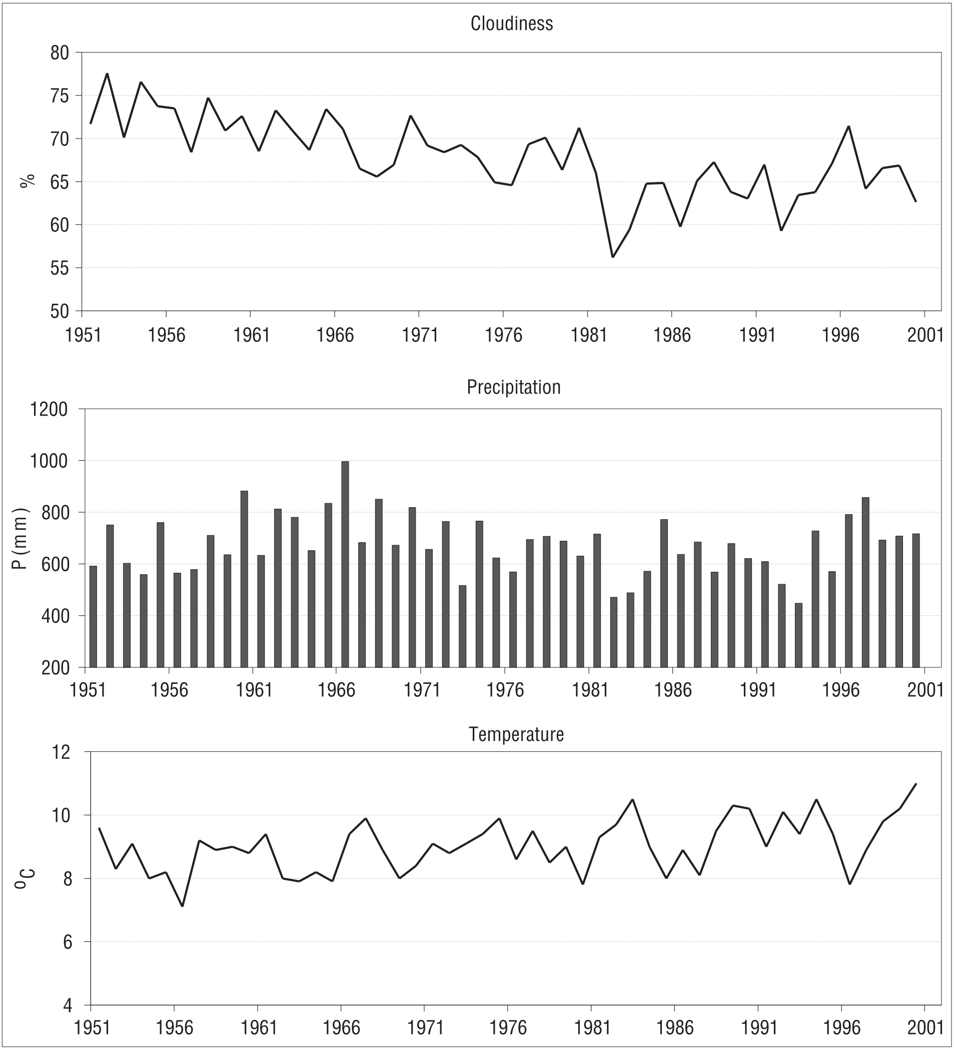

Fig. 1. Annual mean air temperature, cloudiness and precipitation totals in Cracow during the period 1951-2000

Ryc. 1. Przebieg rocznych wartości: średniej temperatury powietrza, wielkości zachmurzenia i sum opadów atmosferycznych w Krakowie w latach 1951-2000

For example, there was a decrease in the number of January days with snowfall towards the end of 1980s (Fig. 3). Also, during 1951-2000, there was a consistent increase in the occurrence of convection clouds during the cold half of the year (November-April) (Fig. 4), clearly coinciding with the growing frequency of very mild winter seasons (Piotrowicz 2000). During the same period, there was an increased occurrence in

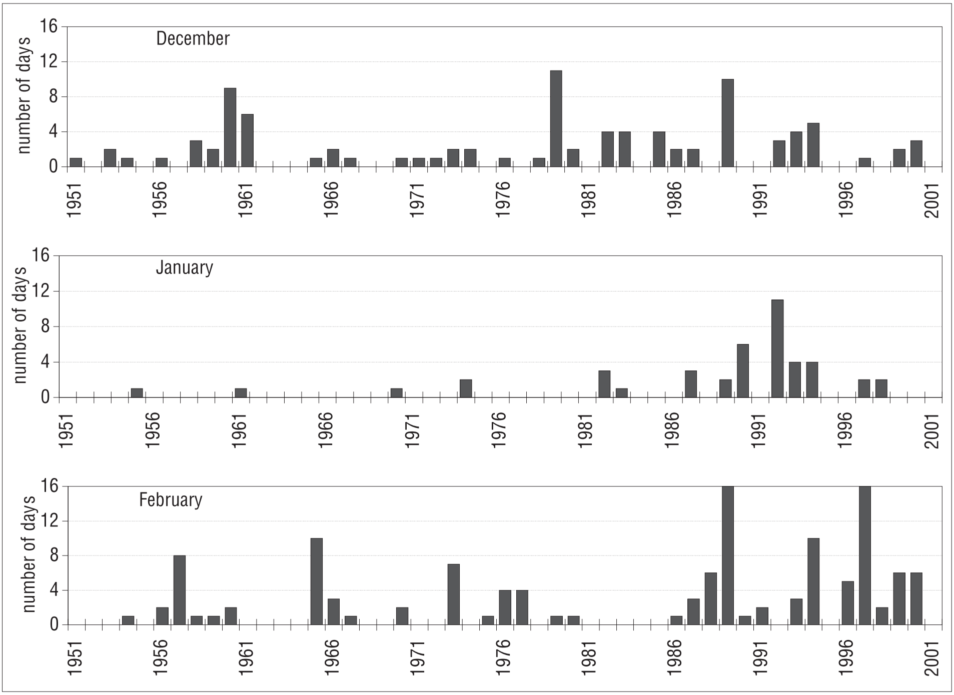

Fig. 2. The number of days with maximum air temperature above 10°C (t_{max}>10°C) in December, January and February in Cracow during the period 1951-2000

Ryc. 2. Przebieg liczby dni z temperaturą maksymalną powietrza powyżej 10°C (t_{max}>10°C) w grudniu, styczniu i lutym w Krakowie w latach 1951-2000

thunderstorms. Since 1983 on, there has been at least one rainstorm event in every cold half (Fig. 5). The increased thunderstorm/rainstorm activity began at the turn of 1980s and 1990s.

In the light of the latest research mean summer temperature either remains constant or shows a downward trend, thus contradicting the global warming theory in a way (Trepińska 1997, 2000). In Cracow, however, the warm half-year displayed a growing number of days with the maximum temperature above 25°C throughout the 20th century (Fig. 6). This means that the temperature of summer increases. Such days were began to occur earlier on, in April, which could explain the increasing number of days with the Cb cloud and rainstorms during that month.

4. Monthly and annual anomalies of temperature and precipitation vs. cloudiness

Considering the anomaly criterion adopted in this research, in the period 1951-2000 the more years with positive temperature and precipitation anomalies prevailed (Tab. 1). There were four exceptionally hot years (1983, 1989, 1993 and

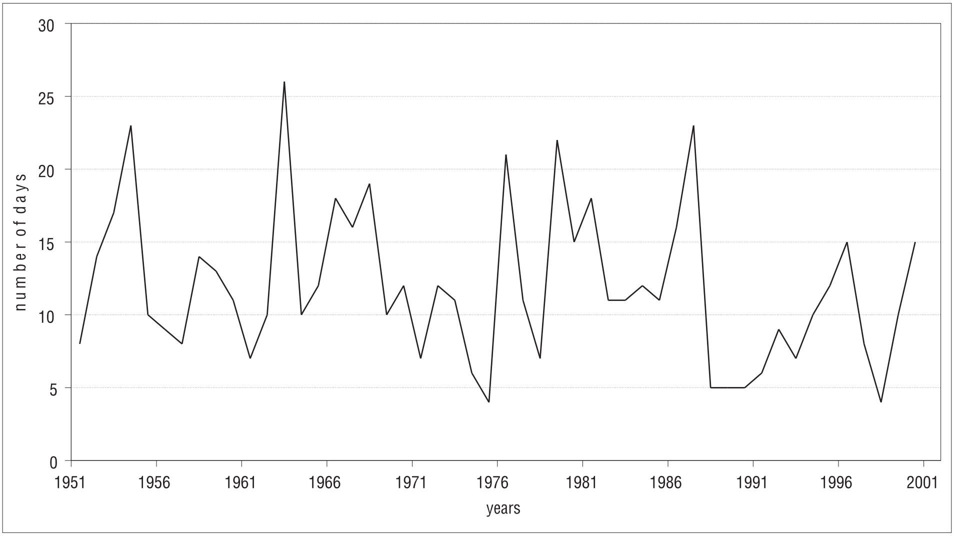

Fig. 3. The number of days with snowfall in January in Cracow during the period 1951-2000

Ryc. 3. Przebieg liczby dni z opadem śniegu w styczniu w Krakowie w latach 1951-2000

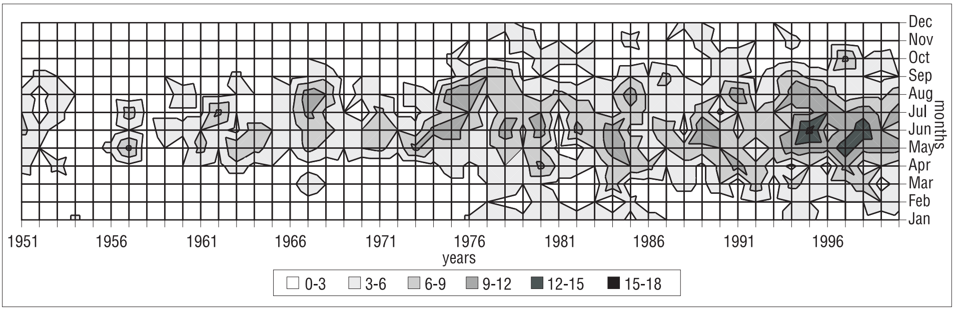

Fig. 4.Number of cases of Cb cloud in Cracow during the period 1951-2000

Ryc. 4. Liczba przypadków chmury Cb w Krakowie w latach 1951-2000

2000), and just two exceptionally cold ones (1956 and 1996). In the case of precipitation there were four years with particularly high anomalous values and two with extreme low precipitation. Contrary to the temperature anomalies, the wet years concentrated mostly in 1960s (1960, 1966, 1968) plus 1997, while the dry years1982 and 1983.

The year of 1982 was at the same time anomalously dry and had the lowest annual cloudiness (56%) during the whole fifty-year period. During that year, March recorded the cloudiness was particulary low (45%) and the precipitation was below the norm (7.6 mm), this year had also a very high number of cloudless days (21). Apart for the anomalously dry March, August and September recorded anomalously.

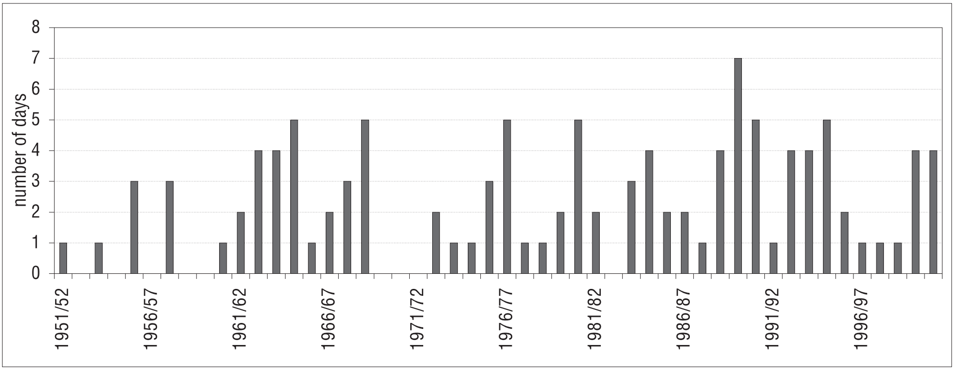

Fig. 5. The number of days with thunderstorm in the cold half-year (November-April) in Cracow during the period 1951/1952-1999/2000

Ryc. 5. Przebieg liczby dni z burzą w półroczu chłodnym (listopad-kwiecień) w Krakowie w latach 1951/52-1999/00

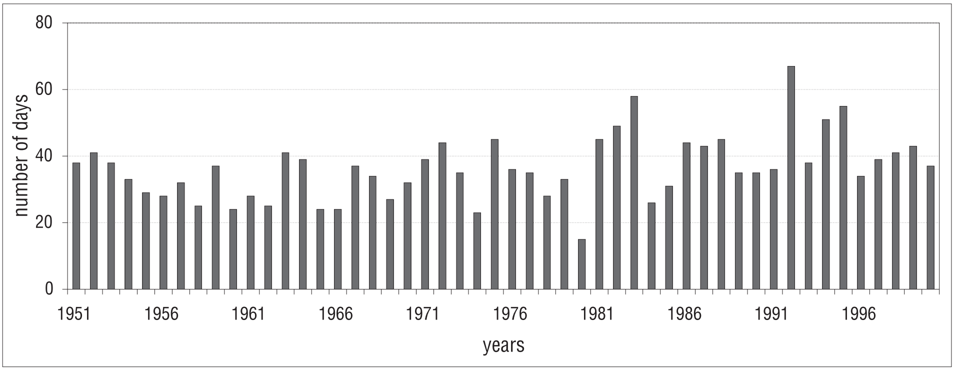

Fig. 6. The number of days with maximum air temperature above 25°C (t_{max}>25°C) in summer (June-August) in Cracow during the period 1951-2000

Ryc. 6. Przebieg liczby dni z temperaturą maksymalną powietrza powyżej 25°C (t_{max}>25°C) w lecie (czerwiec-sierpień) w Krakowie w latach 1951-2000

During the examined year period, the annual temperature and precipitation anomalies coincided just once in 1983. Extremely high temperatures were recorded in January, April and May with no anomalies in any other month. It is interesting that in a year with anomalously low precipitation, no anomalously low precipitation was recorded in any month and there was even a surplus precipitation in March.

A detailed investigation into the relationship between temperature and precipitation, carried out using anomalous values above and below 1.5ó revealed that the denominator of anomalies coincided in just two months during the period:

– negative; in October 1951, i.e. it was an anomalously cold and dry month; and

Tab. 1. The occurrence of the positive (+), negative (-) and normal values (n) of the average monthly and annual air temperature (t) and monthly and annual totals of precipitation (o) in Cracow, 1951-2000

Tab. 1. Występowanie anomalii dodatnich (+) i ujemnych (-) oraz wartości normalnych (n) średniej miesięcznej i rocznej temperatury powietrza (t) oraz sum miesięcznych i rocznych opadów atmosferycznych (o) w Krakowie w latach 1951-2000

Years	Months																								Year	
	Jan		Feb		Mar		Apr		May		Jun		Jul		Aug		Sep		Oct		Nov		Dec			
	t	o	t	o	t	o	t	o	t	o	t	o	t	o	t	o	t	o	t	o	t	o	t	o	t	o
1951	n	n	n	n	n	n	n			+	n		n	n				n	-	-	+	n				
1952			n	+	-							n								+		+	n			
1953	n	+	n	n	n		n	n	n	n		n		n		n	n	n	n		n		n		n	
1954	-	n	-		n		-	+	n			n		n	n				n		n			+		
1955	n	n	n	n		n	-	n		n		+	n	n	n		n	n	n		n					
1956	n		-	n		n			n				n			n	n		n	n	-		n	n	-	
1957	n			n	n		n	n	-				n			n		n	n		n		n		n	
1958	n	n			-	+	-	n	+				n		n		n	n		n	n	n			n	n
1959	n		n			n	n	n	n						n							n	n		n	
1960	n	n	n	n	n	n		n			n	n		+		+		n		n		n			n	+
1961				n		n	+	-							n	n			+		n		-	+	n	n
1962		n	n			n		+	-	+	-		-		n			n			n	+	-			
1963	-		-	n			n		n	n	n	n		n		n		+	n		+	n	-			
1964				n	-	+	n		n		+	n	n			n	n	n	n		n	+	n	n		n
1965	n	+		n	n	n			-	+	n				-						-			n		
1966		n		+	n	n			n	+	n		n				n		+		n		n	n	n	+
1967	n	n		n		n	n	n	n	n	n	n			n	n	+		+	n	n	n	n	+		n
1968	n	n	n	n	n					+				n			n		n	n		n	-		n	+
1969		n	n	n		n						n	n	n			n		n	n		n	-	n		n
1970						n	n	n		n	n		n	+	n							n	n			
1971	n		n	n			n	n				+	n	n				n	n		n	n			n	n
1972			n				n	+	n	n		n						n	-			n	n	-	n	
1973	n	n		n	n	-	n		n			n	n	n	n		n	n				n	n	n	n	

Years	Months																								Year	
	Jan		Feb		Mar		Apr		May		Jun		Jul		Aug		Sep		Oct		Nov		Dec			
	t	o	t	o	t	o	t	o	t	o	t	o	t	o	t	o	t	o	t	o	t	o	t	o	t	o
1974		n		n		-	n			n	-					n	n	n	-	+	n			n	n	
1975	+		n				n	n			n	+		n			+	n	n				n			n
1976	n	+		-		n	n		n	n	n				-		n	n	n	n			n		n	
1977	n			+				n	n					n				n					n			n
1978			n					n				n							n	n	n	n		n		n
1979		+		n		n				n	+	n			n	n				n	n	n	+		n	n
1980			n	n					-	n				n		n	n		n	+		n	n			n
1981	n	n	n							n			n	n	n			n	n		n					n
1982		n	n			-					n			n	+		+		n					+		-
1983	+		n	n		+	+		+										n	n			n		+	-
1984		n	n		n		n		n			n	-	n	n		n		+		n		n		n	
1985	-		-	n	n	n	n	n		n	-		n	n	n	+	n		n	n		n		n		
1986	n		-	n	n						n			n	n	n			n			-	n	+	n	n
1987	-		n		-	n	n	n			n	n			-	n			n	n		n	n			n
1988					n		n			n	n				n	n	n	n	n		-					
1989		-						+	n		-	+	n		n	n	n	n		n	n				+	n
1990			+	n	+		n			n	n				n		-	+	n			+	n			n
1991				n			n	n	-		n				n			n	n		n	n		n	n	
1992	n	n		n	n	n	n	n	n		+	-		n	+	-	n	n			n	n	n			
1993			n	n	n	n	n		+		n			n	n		n	n		n	-	n			n	-
1994	+		n			+		+	n	n	n		+			n		+						n	+	n
1995	n	n		n	n	n	n		n	n	n	n	+				n				-		-	n	n	
1996		n			-		n	n		+				n	n	+	-	+	n			n	-		-	
1997				n	n		-			n	n	n		+	n		n	n			n		n	n	n	+
1998		n		n	n	n	+	+				n	n	n	n	n	n	n	n	+	-					n
1999		n	n	+				n	n		n	+		n	n		+	n	n				n	n		n
2000	n	n		n		+	+		+	n		n		+					+		+	n		n	+	n

– positive; in April 1998, i.e. this was an anomalously hot and humid month.

In most other months with anomalous temperature and precipitation at the same time a negative temperature anomaly was accompanied by a positive precipitation anomaly. Exceptions were provided by June and July of 1992, when a positive temperature anomaly was accompanied by a negative precipitation anomaly. That was also a year with very low mean annual cloudiness (59%).

During the research period, particularly high fluctuation of monthly values was recorded in 1952 and 1982. Temperature and precipitation values close to the average were very few. Additionally, 1952 was the year with the highest in cloudiness during the whole period (78%), with just three cloudless days and the overall highest monthly cloudiness value in February (98%). Three months of 1952, i.e. February, October and November, recorded anomalously high precipitation and March had anomalously low temperature.

Year 2000 also featured many anomalies with four hot months (April, May, October and November) and two wet months (March and July). Very low cloudiness was observed in May (46%) and very high in July (76%) when it was 15% higher than the long-term July mean (61%).

5. Conclusion

Along with the territorial, industrial and demographical growth Cracow experienced during the second half of the 20th century, climate which relationships between air temperature, precipitation and cloudiness, were observed. The years with positive anomalies in temperature and precipitation prevailed. In most cases, a negative temperature anomaly corresponded to a positive precipitation anomaly. Most of the years with excessive precipitation occurred in 1960s. The clearly observed increase in the mean annual temperature, particularly strong since the end of 1980s, had probably been spurned by both natural and anthropogenic factors. The warming of the Cracow climate contributed to the changed cloudness structure and had an influence on the scale and type of precipitation in the city.

The decreasing dry air humidity above the city caused the decreaseof low stratus-type clouds and fog frequency, which may have caused the reduced number of days with weak precipitation. The frequency of low convection clouds increased and the development of the Cu and then Cb often led to intensive occasional rainfall, rainstorms and hailstorms all of which have become more frequent during recent years.

It is worth noting the contribution of the winter season to the increase of the mean annual temperature. This was highlighted by the increasing occurrence of the number of days with Cb clouds and with thunderstorms during winter seasons.

The results obtained for Cracow study confirmed the research published in other European cities.

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Związki między temperaturą powietrza, zachmurzeniem i opadami atmosferycznymi w okresie intensywnego rozwoju aglomeracji krakowskiej

Streszczenie

W opracowaniu dokonano próby określenia relacji między temperaturą, zachmurzeniem i opadami atmosferycznymi w Krakowie w latach 1951-2000. Przeanalizowano wartości średnie miesięczne i roczne temperatury powietrza, liczbę dni z temperaturą maksymalną powyżej 10^{0}C i 25^{0}C, sumy roczne i dobowe opadów

atmosferycznych oraz rodzaje opadów, wielkość zachmurzenia i rodzaje chmur. Szczególną uwagę zwrócono na wartości anomalne, które wyznaczono w oparciu o wielkość (±0.5σ) odchylenia standardowego od średnich wieloletnich.

Wraz z dynamicznym rozwojem terytorialnym, przemysłowym i demograficznym Krakowa od 1951 roku zauważono istotne związki w przbiegu temperatury powietrza, opadów atmosferycznych i zachmurzenia. Warunki termiczne i opadowe charakteryzowała przewaga lat z dodatnimi anomaliami. Ujemnej anomalii termicznej najczęściej odpowiadała dodatnia anomalia opadowa. Nadmiary opadów koncentrowały się w latach sześćdzesiątych.

Obserwowany wyraźny wzrost średniej rocznej temperatury powietrza, szczególnie silnie zaznaczający się od końca lat osiemdziesiątych został wywołany prawdopodobnie zarówno czynnikami naturalnymi jak i antropogenicznymi. Ocieplenie klimatu Krakowa przyczyniło się do zmiany struktury zachmurzenia oraz miało wpływ na wielkość i rodzaj opadów atmosferycznych nad miastem. Wzrosła częstość występowania niskich chmur konwekcyjnych, prowadzących często do intensywnych opadów przelotnych, burz i gradobić.

Warto zaznaczyć,że na wzrost średniej rocznej temperatury powietrza największy wpływ ma temperatura miesięcy zimowych. Znamienny jest fakt, że w ostatnich latach także w tej porze roku zwiększyła się częstość występowania chmur Cb i liczby dni z burzą.

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