Geographia Polonica
2017, Volume 90, Issue 1, pp. 5-20
https://doi.org/10.7163/GPol.0075

INSTITUTE OF GEOGRAPHY AND SPATIAL ORGANIZATION
POLISH ACADEMY OF SCIENCES
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MEDITERRANEAN CYCLONES, THE ATMOSPHERIC MOISTURE CONTENT AND PRECIPITATION IN POLAND

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Abstract

The article describes changes in the frequency and activity of cyclones moving from the Mediterranean Sea basin to the area of Central and Eastern Europe in the period 1958-2008. Furthermore, long-term trends in the amount of precipitation in Poland are analyzed, as well as the moisture content in the atmosphere over Poland related to the activity of Mediterranean cyclones. A relationship was observed between the amount of precipitation, the precipitable water in the atmosphere over Poland and the cyclone trajectories. In the analyzed period, the number of Mediterranean cyclones reaching Central and Eastern Europe decreased. Moreover, signs of decreasing activity of these cyclones were also noted. The average moisture content in the atmosphere over Poland also showed a downward trend. The precipitation totals associated with the activity of Mediterranean cyclones became lower, while the intensity of precipitation did not change significantly. Mediterranean cyclones are associated with high moisture content in the atmosphere. This surplus amounts to an average of nearly 15%, and in periods with the highest precipitation it reaches ca. 40%. The maximum daily precipitation reaches nearly 8 times the value of the current moisture content in the atmosphere.

Key words

Mediterranean cyclones • cyclone trajectories • precipitation • precipitable water • long-term trends • Poland

Introduction

The cyclonic systems migrating to Central and Eastern Europe[1] from over the Mediterranean Sea (MEC – Mediterranean European Cyclones) appear in this area ca. 7 times a year. Only their certain proportion (around 23% of the 351 identified cases of Mediterranean cyclones between 1958 and 2008) arrive onto Central and Eastern Europe along the Vb track, identified by van Bebber in 1891 and extending from the south to the north on the eastern side of the Polish borders. Moreover, MEC travel along trajectories extending from the south to the north through the territory of Poland (34%), as well as to the west of the country's borders (8%), and the quasi-latitudinal track located south of the territory of Poland (26%). The latter track draws the lows eastward. About 10% of cyclones travel the 'retrogressive track' from the Black Sea north-westward and westward, approaching the borders of Poland (Degirmendžić & Kożuchowski 2014).

According to Bielec-Bąkowska (2010), more than 10% of deep cyclones occurring over Poland are represented by low pressure systems moving from over the Mediterranean Sea along the T7 track, which corresponds to the Vb track. About 14% of strong advections bring air masses from Italy, the Adriatic and the Balkan Peninsula to Poland (Degirmendžić & Kożuchowski 2006).

Mediterranean cyclones represent a certain peculiarity among the circulation factors shaping the climate of Poland (Kożuchowski 2003; Bartoszek 2006). They appear infrequently, but have a considerable impact on the income portion of water balance. Their relatively high incidence in spring reduces to some extent the moisture deficits of the season. Some precipitation episodes arising in connection with Mediterranean cyclones, especially in summer, are exceptionally abundant and are responsible for high daily precipitation totals, rarely observed in Poland, significantly exceeding the level of 100 mm day^{-1}; those were, among others, the daily totals of 21 August 1972 in Bielsko-Biała (147 mm), of 30 July 1977 on Śnieżka Mt. (150 mm), of 8 July 1997 on Hala Gąsienicowa (Tatra Mts) (223 mm) and of 20 July 2001 in Jelenia Góra (119 mm).

Mediterranean cyclones carry northwards the moisture resulting from high evaporation rate over the basin of the Mediterranean Sea. As a result of the transformation of air masses and due to precipitation occurring on the advection track, the moisture content in the air coming to Poland from the Mediterranean Sea (or the Black Sea) decreases. According to Suligowski (2004), the 'Mediterranean' air over Poland contains only 41-88% of the initial reserve of moisture formed in the source area.

In the western sectors of MEC cyclones, a circulation develops, encountering the orographic barriers of the Western Carpathians, the Sudeten Mountains and the Alps, which contributes to the formation of high precipitation in the region. At the dissipation stage, the lows over Central Europe transform often into quasi-stationary systems, and the related precipitation becomes long-lasting (Bartoszek 2006). Therefore, 2- to 5-day precipitation totals reach extremely high levels, often exceeding the monthly mean precipitation total. A significant example was the precipitation on Śnieżka Mt. of 31 July 1977, almost equal to the average July precipitation total, and on 1 August 1977, with a volume close to the average August total (Otop 2004). Long-term high-intensity precipitation causes the overflowing of rivers and flooding. Daily precipitation amounts of >30, >50 and >90 mm are identified by the IMGW (the Institute of Meteorology and Water Management) with successive degrees of flood risk.

Every fourth Mediterranean cyclone brings to Poland a daily precipitation of >50 mm (Bartoszek 2006). Morozowska (1987) as well as Bogdanowicz and Stachy (1998, 2002) report that 88% of severe flooding in Poland is connected with the activity of lows situated on van Bebber's (1891) Vb track. The authors

[1] The area herein conventionally called Central and Eastern Europe is situated between the parallels passing through Trieste (45° 39′ N) and Gotland (58° 11′ N) and between the meridians passing through Dortmund (7° 32′ E) and Odessa (30° 44′ E).

of the work on extreme meteorological phenomena in Poland (Buchert et al. 2013) state that 75% of dangerously high precipitation in Poland is caused by Vb-cyclones. The highest likelihood of heavy precipitation associated with the activity of Vb-events includes the area of Poland stretching from the Silesian and Żywiecki Beskid Mountains through the Krakowsko-Częstochowska Upland and the Lubelska Upland up to the Bug river (Lorenc 2012).

The considerable amounts of precipitation associated with MEC cyclones are directly linked to the circulation conditions ensuring the constant inflow of moisture into the warm air masses in source region and allowing the condensation of water vapour and the formation of precipitation over a destination area. The continuous supply of moisture is particularly important because, as pointed out by Świątek (2013a), precipitation greatly exceeds water vapour and water content in the atmosphere: the so-called precipitable water (PW) column[2] is smaller than the amount of precipitation. Sobik and Błaś (2010) showed that the highest precipitation is produced when there are a strong convergence and high wind speeds above the planetary boundary layer. Such conditions prevail in an active low which does not move too fast.

The formation of high intensity precipitation is conditioned by a considerable moisture content in the atmosphere, but in the first place by the circulation system which ensures the supply of moisture and the condensation of water vapour. The functioning of this system is characterized by the so-called efficiency ratio, defined as the ratio of the precipitation total to the height of precipitable water column in the atmosphere; according to Suligowski (2004, 2013), with the highest precipitation (near Kielce) this ratio reaches a value of 3.23.

Ulbrich et al. (2003), who analyzed the conditions associated with floods in the Elbe basin in 2002, found that the factors activating Mediterranean cyclones were as follows: a trough on the 300 hPa isobaric surface over western Europe, a strong divergence near the tropopause and significant thermal contrasts of the air masses participating in the meridional exchange. Świątek (2013a), using the example of two episodes of torrential precipitation in Southern Poland related to the activity of Mediterranean cyclones in 1997 and 2010, showed the convergent flow of polar-marine, polar-continental and subtropical air masses over Poland flowing from different directions at the respective heights of 500 m, 2000 m and 4000 m above sea level. Convergence in the lower troposphere and the related macro-scale convection are, according to Sobik and Błaś (2010), the direct causes of heavy precipitation accompanying the lows wandering or stagnating over Poland and the neighbouring areas. In the convergence zone, a quasi-stationary cold front separates the warm tropical air masses flowing from the Mediterranean Sea from cold polar air situated on the western side of the low and forming the so-called 'cold drop' over Western Europe. In connection with the existing thermal contrasts, the atmosphere is strongly baroclinic, which is conducive to cyclone activity.

A similar picture was previously obtained by Ziemiański (2002), who presented a model of baroclinic instability reflecting the development of cells of descending air in the atmosphere above the 'cold drop' and ascending air in the warm sector of the cyclone, located next to each other (at a distance of the order of a thousand kilometers).

The annual average precipitation total in lowland Poland (605 mm) includes 55 mm (9.1%) of precipitation of Mediterranean origin, i.e. precipitation associated with the activity of Mediterranean cyclones, hereinafter also referred to in short as MCP (Mediterranean Cyclonal Precipitation). In the mountains and in their foreland, the average MCP total

[2] We use the term 'moisture content in the atmosphere' as a synonym for the term 'precipitable water content'. Both the terms mean 'the mass of water contained in a column of air above a unit surface area regardless of a state of water' (Wibig & Siedlecki 2007). 1 kg of precipitable water per a 1 m^2 area corresponds to a height of 1 mm of water in the atmosphere. Suligowski (2004) calls the mass of water in the column of the atmosphere with a unit cross-section the 'potential precipitation'.

is 112 mm (11% of the annual total of all precipitation). For the whole country, this share is 9.6%, which means that on average more than 66 mm of precipitation of Mediterranean origin falls on the territory of Poland annually. The largest shares of MCP in the annual total precipitation are characteristic of south-western Poland (12-14%) and the eastern part of the country, including the Lublin region (11%) (Degirmendžić & Kożuchowski 2015).

This study aims to determine long-term trends in the changes of frequency and selected characteristics of the dynamics of Mediterranean cyclones, the associated precipitation and moisture content in the atmosphere over Poland. The paper answers the question about trends in the occurrence of MEC cyclones and MCP precipitation in relation to the changes in total precipitation sums in Poland and in precipitable water (PW) in the atmosphere over Poland. Particular emphasis is put on testing the thesis that MCP events are associated with high moisture content in the atmosphere.

The results of the statistical analyses performed may constitute a contribution to the verification of the hypothesis of an increasing intensity of extreme hydro-meteorological phenomena which accompany the contemporary climate changes. Mediterranean cyclones undoubtedly create favourable conditions in Poland for such extreme phenomena as widespread and torrential precipitation, as well as overflowing rivers and floods.

Data and methods of their analysis

The study uses the database of cyclones over the Northern Hemisphere, created by Serreze (2009). The list includes low pressure systems developing over the Northern Hemisphere in the period between 1 January 1958 and 31 December 2008.

Of all the cyclones, those were selected for the purposes of this study which at any stage of cyclone development had their centres located within the basin of the Mediterranean Sea, the Black Sea or the Sea of Azov, and at a later stage of development they were no farther than 350 km from the Polish borders – as a result at least part of the country's territory is affected by cyclonic circulation.

351 Mediterranean cyclones (MEC) were selected, which were then grouped according to criteria including cyclogenesis and cyclolysis sites as well as cyclone trajectory. The following four classes of MEC cyclones were distinguished:

E – the eastern class of cyclones whose trajectory runs east of Poland, resembling van Bebber's Vb track;

C – the central class of cyclones with trajectories passing through the territory of Poland;

W – the western class of cyclones moving along the track west of Poland;

S – the southern class of cyclones moving from the west to the east along the track south of Poland.

In this study, the sporadically occurring cyclones travelling along the retrogressive track from the Black Sea are omitted.

The averaged positions of cyclone trajectories were mapped out within the distinguished MEC classes (Fig. 1). The average trajectories extend through the points of the highest cyclone frequency. The points of mean trajectory were depicted with a spatial resolution of $1° \times 1°$. It was found that the trajectories of the class W and class C cyclones are divided in a considerable area, creating separate branches – eastern and western – classified respectively as the WE, WW and CE and CW types of trajectories. A more detailed description of the methodology for determining the classes of MEC cyclones and their trajectories are presented in the articles by Degirmendžić and Kożuchowski (2014, 2015).

The analysis of atmospheric precipitation is based on the daily precipitation totals obtained from 66 stations evenly distributed in the area of Poland in the period 1958-2008. The precipitation data were provided by the IMGW. The totals were assigned to the presence of MEC on the selected trajectories of their movement over Central and Eastern Europe.

The daily mean areal totals of MCP precipitation in Poland (from 66 stations) were

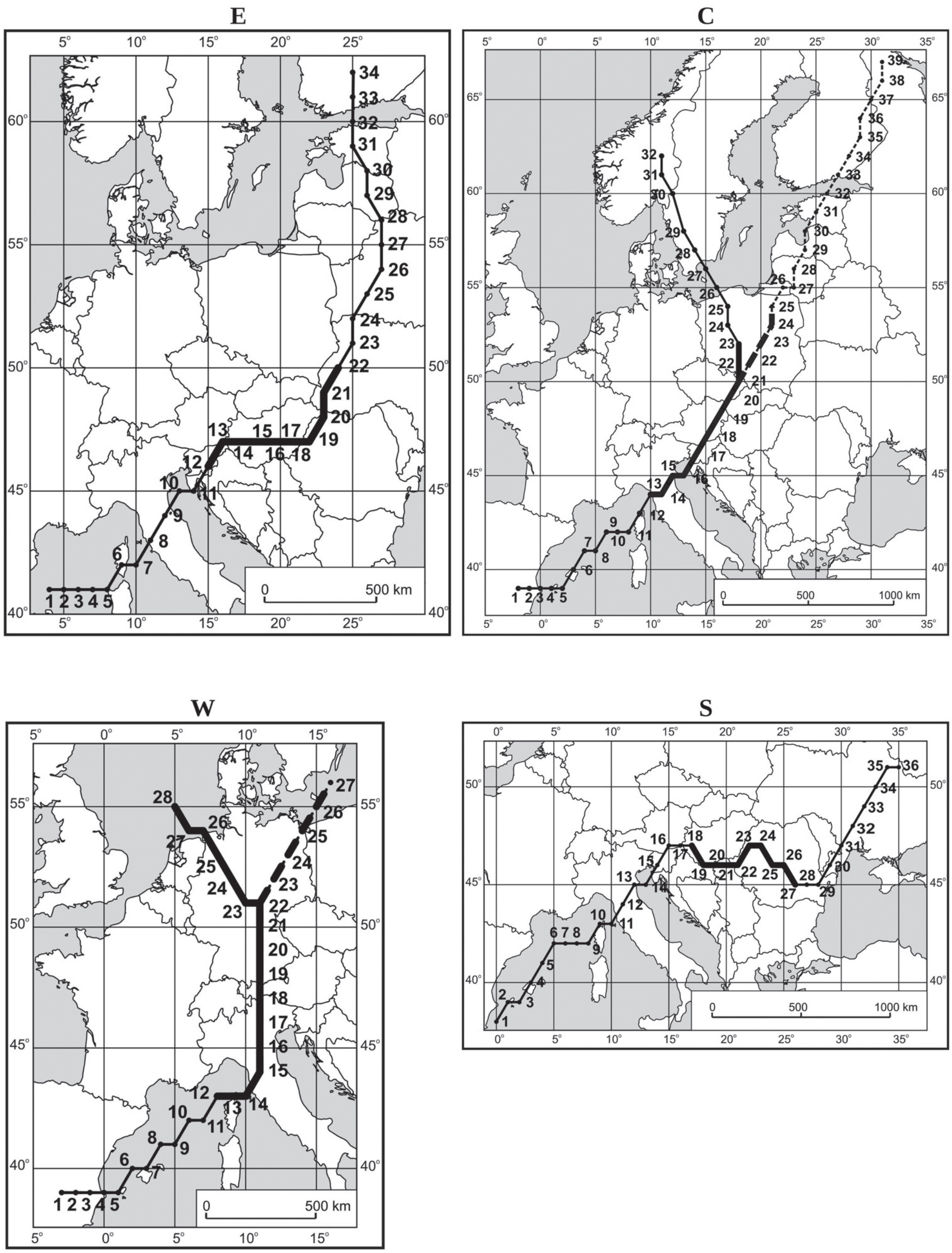

Figure 1. Average position of Mediterranean cyclone (MEC) tracks moving over Central and Eastern Europe: E – eastern track, C – central track (with CW and CE branches), W – western track (with WW and WE branches), S – southern track. The dashed line indicates the eastern branches of trajectory. Precipitation-efficient sections are in bold. Points along the trajectory are numbered according to the direction of movement of cyclones
Source of contour map: GoldenSoftware MapViever 7 Samples Files.

determined based on the values of the days when MEC cyclones were situated at the so-called precipitation-efficient section of a trajectory (E, C, W, or S, see Fig. 1). A precipitation-efficient section is the part of a trajectory which meets the following two criteria: (1) the mean areal precipitation in Poland, connected with MEC systems situated close to a given point of trajectory (within a radius of 250 km), exceeds the value averaged for the entire trajectory (all points of the trajectory); and (2) the maximum precipitation, selected from 66 stations in Poland, exceeds the value averaged for the entire trajectory (a more extensive description of the procedure for determining MCP precipitation and the precipitation-efficient section of the MEC trajectories can be found in the above-cited papers by the authors).

The long-term changes of MEC cyclones in the period 1958-2008 are described on the basis of their annual and seasonal incidence and the mean annual and seasonal values of the maximum vorticity (local pressure Laplacian), the minimum 6-hourly pressure tendency (maximum deepening) and the minimum pressure in the centre of each MEC cyclone. The maximum vorticity, maximum deepening rate and the minimum pressure were selected for each MEC system from 6-hourly measurements making up the cyclone life cycle. Thus, in addition to the frequency of cyclones, the characteristics of changes in cyclone dynamics over a multi-year period were obtained.

Trends in MCP precipitation were determined on the basis of mean precipitation totals on the days of the occurrence of MEC cyclones at the precipitation-efficient sections of their trajectories. Moreover, the precipitation intensity was analysed, i.e. the mean totals per rainy day. The same characteristics were used in trend analysis of total precipitation in the area of Poland, as well as in the lowland and mountainous parts of the country.

Precipitable water (PW) content in the atmosphere over Poland was determined based on the data from the NCEP/NCAR Reanalysis database (Kalnay et al. 1996). The mean values of PW in the territory of Poland were calculated from six grid points with the coordinates 15°E, 17.5°E, 20°E and 22.5°E on the 52.5°N parallel, and 20°E and 22.5°E at 50° N latitude. The mean daily values of PW for each day of the year were determined, and next the relative deviations of PW from the long-term mean value of PW on the days with the occurrence of MCP precipitation (Δ) were calculated. The Δ deviations allow an assessment of the precipitable water changes in the atmosphere, regardless of the annual cycle of PW.

The coefficients of linear trends for the annual mean and seasonal mean (months DJF, MAM, JJA, SON) values were calculated, comprising a total of 17 characteristics of MEC, MCP and total precipitation in Poland, as well as precipitable water in the atmosphere (PW). The significance of the observed trends was checked using the Mann-Kendall test and assuming the significance level $\alpha = 0.05$

Furthermore, the mean values of PW were calculated for the days with MEC cyclones situated at rain-efficient segments of their trajectory, the intensity of MCP precipitation as well as the quotients of daily MCP (DP – Daily Precipitation) amounts and the corresponding precipitable water (PW) content. The quotients DP/PW are equivalent to the efficiency ratio of the precipitation-efficient system which was studied by Suligowski (2004, 2013).[3] The mean moisture content in the atmosphere over Poland during the occurrence of the highest daily precipitation of Mediterranean origin (MCP > 90 mm day^{-1}) was also presented.

Results and discussion

Long-term trends

The number of Mediterranean cyclones reaching Central and Eastern Europe was decreasing in the period 1958-2008; the annual number of MEC shows a significant downward trend (Fig. 2). The frequency of these cyclones

[3] The PW values ('potential precipitation') determined by this Author on the basis of ground-based measurements of atmospheric humidity are slightly higher than the 'precipitable water column' values used in this study, while the efficiency ratios are correspondingly lower.

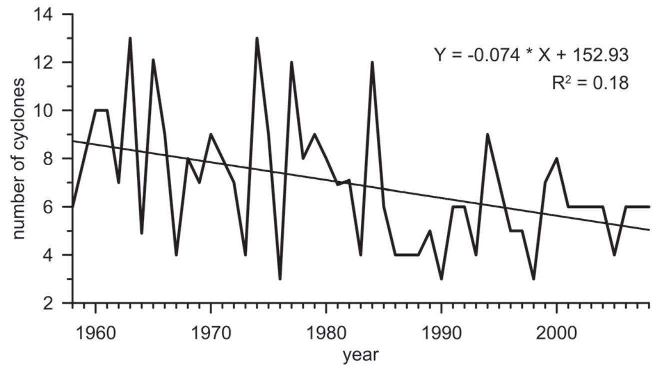

Figure 2. Annual numbers of Mediterranean cyclones (MEC) over Central and Eastern Europe in the years 1958-2008 and the linear trend of changes in the number of MEC

dropped by more than half of its mean value (6.88 cyclones per year, Tab. 1). Negative, but non-significant trends in the frequency of *MEC* cyclones in all seasons of the year are observed.

The annual numbers of *MEC* exhibit considerable variability; in some years only 3 cyclones were recorded (e.g. in 1976, 1990, 1998), in others – mainly in the first half of the analyzed period (the years 1963, 1975) - as many as 13 MEC cyclones. A low incidence of MEC systems in Central and Eastern Europe was characteristic of the 1980s. At that time, the presence of cyclones over the Bay of Genoa, the main area of Mediterranean cyclogenesis, was also extremely low (Bartholy et al. 2009), and deep cyclones travelling along the T7 track (equivalent to the Vb track) did not occur at all during the years 1980-1987 (quoted after Bielec-Bąkowska 2010).

Trends in MEC central pressure are vague and seasonally differentiated. Only the positive trend in the winter season turns out to be significant. A weak, insignificant positive trend is also observed in spring and in annual values; however, in summer and autumn MEC cyclones were deepening in the analysed period. The trend of pressure tendency shows insignificant changes. A relatively high, although also insignificant, negative trend coefficient occurs in autumn, which shows that in this time of year the dynamics of cyclones slightly increased. In autumn, MEC vorticity also increased. It can be assumed that the autumn cyclones became more active, and their number decreased insignificantly, while the winter cyclones became less frequent and their activity weakened (Tab. 1).

The mean annual precipitation of Mediterranean origin in the territory of Poland over the analyzed multi-year period decreased significantly, as did the incidence of MEC cyclones. Furthermore, MCP precipitation also significantly decreased in winter, which can be associated with the decreasing depth of MEC cyclones in this season (Tab. 1). MCP decreased particularly clearly in the mountains; precipitation in spring, autumn and winter, as well as the annual MCP totals, showed significant decreasing trends. In the lowlands, these changes proved to be insignificant, except for MCP precipitation in winter which decreased significantly, in line with the decreasing frequency and depth of MEC cyclones.

A comparison of MCP precipitation against total precipitation in Poland (Fig. 3), as well as the trend coefficients of MCP and total precipitation indicate a decreasing share of MCP in total precipitation in Poland. The trends in annual totals are similar, although MCP precipitation accounts for only ca. 10% of total precipitation. The downward trend of MCP is significant, while total precipitation decreased non-significantly, and in autumn and winter it showed a weak upward trend (Tab. 1).

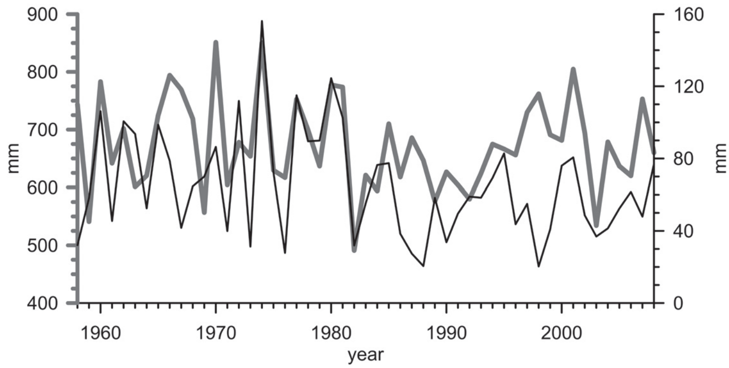

Figure 3. Annual total precipitation sums in Poland (grey bold line, left axis) and annual totals of precipitation of the Mediterranean origin (MCP) (right axis) in the years 1958-2008

Table 1. Mean values and coefficients of linear trends (a/50 years) of parameters of Mediterranean cyclones (MEC), precipitation totals and precipitation intensity in Poland and precipitable water in the atmosphere over Poland. Significant coefficients ($p < 0.05$) are in bold

Parameters	Annual mean	Trend coefficients (a/50 years)				
		year	spring	summer	autumn	winter
MEC Cyclones						
Number of systems	6.88	**-3.70**	-1.32	-0.43	-0.80	-1.13
Minimum central pressure [hPa]	997.50	0.15	0.05	-0.55	-3.45	**6.30**
Maximum deepening rate [hPa $(6h)^{-1}$]	-2.85	0.05	0.30	0.00	-0.75	0.00
Pressure Laplacian [mPa km^{-2}]	17.40	0.80	1.70	2.55	4.45	-4.00
Precipitation totals [mm]						
Mean total precipitation in Poland	686.8	-28.3	-1.8	-29.3	2.6	3.7
MCP precipitation in Poland	66.2	**-27.9**	-9.0	1.4	-13.0	**-7.8**
Mean total precipitation in the mountains	1019.5	-57.2	-1.7	-57.2	29.1	-12.1
MCP precipitation in the mountains	112.4	**-62.1**	**-20.4**	-11.4	**-16.9**	**-14.5**
Mean total precipitation in lowland Poland	605.2	-21.7	1.4	-22.8	-3.2	7.3
MCP precipitation in lowland Poland	54.9	-20.1	-6.5	4.4	-12.0	**-6.3**
Precipitation intensity [mm day^{-1}]						
Mean intensity of total precipitation in Poland	4.1	-0.29	0.01	**-0.82**	-0.10	-0.09
MCP precipitation intensity in Poland	5.8	0.78	0.52	2.35	-1.08	0.22
Mean intensity of total precipitation in the mountains	5.3	**-0.49**	-0.36	-1.05	0.16	-0.47
MCP precipitation intensity in the mountains	8.0	-0.82	-0.76	0.80	-2.62	-0.97
Mean intensity of total precipitation in lowland Poland	3.7	-0.24	0.10	**-0.73**	-0.19	0.00
MCP precipitation intensity in lowland Poland	5.1	1.19	0.79	**3.68**	-0.60	0.33
Precipitable water [mm]						
Mean precipitable water in the atmosphere over Poland	15.9	**-1.47**	**-1.36**	-1.29	**-2.38**	-0.79

Based on the results of various analyses, it can be assumed that precipitation in Poland has not shown any significant changes since the mid-twentieth century. According to Miętus (Projekt Klimat 2009), the mean areal precipitation in Poland in the years 1961-2009 "exhibits a slight downward trend". Marosz et al. (2011) detected decreasing trends of annual precipitation in most parts of Poland which are especially strong in Lower Silesia where in the years 1961-2008 precipitation decreased by more than 100 mm. Czarnecka and Nidzgorska-Lencewicz (2012) did not identify any significant changes in seasonal and annual precipitation in Poland in the years 1951-2010. Only "a slight tendency of an increase in the precipitation in spring and autumn and a decreasing share of summer precipitation in the annual total precipitation" was observed.

The trends in changes of precipitation of Mediterranean origin stand out against this background. It follows that precipitation of other origin ('not Mediterranean') increased. This is confirmed by the growing trend of the number of days with precipitation observed in "almost the entire country" (Marosz et al. 2011). This trend affects the change of the intensity of total precipitation which is thereby decreasing. It is significant in the summer season, and in the mountains it is characteristic of the annual mean precipitation intensity (Tab. 1). The precipitation intensity decreased both in the mountains, which was observed by Żmudzka (2010) and based on the example of data from Kasprowy Wierch Mt. (1966-2006), and in the south-western part of Poland "where a marked increase in the number of days with precipitation is accompanied by a decrease in precipitation (...)" (Marosz et al. 2011). Wibig's (2009) study showed that since the mid-twentieth century in Poland the incidence of precipitation with low daily totals had increased, while a decreasing trend was characteristic of high precipitation (at the level of the 5^{th}, 10^{th} and 25^{th} percentiles), as well as of the maximum daily totals. The conclusion about the precipitation maxima decreasing over the period 1951-2006 was also presented by Łupikasza (2010) who additionally demonstrated that the majority of these trends had been stable over that multi-year period. Contrary to the conclusion about the decreasing intensity of precipitation are opinions pointing to an increasing number of days with high amounts of precipitation. Lorenc (Projekt Klimat 2010) stated, *inter alia,* that at the turn of the twenty first century in Poland the frequency of days with precipitation >10 mm (an increase of 4 days/10 years), days with precipitation >30 mm (an increase of 3 days/10 years) and precipitation of over 50 mm (an increase of 2 days/10 years) increased. According to Lorenc and Olecka (2006), the entire period from 1971 to 2002 was characterized by a growing trend in the frequency of days with precipitation of >10, >20 and >30 mm, and periods without precipitation shortened during that time.

The results of the aforementioned analyses are not fully comparable, if only because of different series of precipitation measurements used therein, while at the same time trends in the incidence of high or low precipitation do not determine the trend of the averaged daily total, called the intensity of precipitation.

The precipitation intensity associated with Mediterranean cyclones showed a long-term rising trend. The trend is positive (with the exception of autumn and the mountains where a decrease predominates), and in the case of rainfall occurring during the summer season in the lowland part of Poland it is significant, in contrast to a declining trend in the intensity of total precipitation (Tab. 1). In Fig. 4, the predominance of MCP precipitation intensity over the intensity of total precipitation in Poland (whose long-term averages are, respectively, 5.8 and 4.1 mm day^{-1}), increasing since the 1980s, can be seen. Despite the decreasing MCP precipitation totals, its intensity (average precipitation per rainy day) increased as a result of a significant decrease in the frequency of MEC cyclones and, at the same time, of days with MCP precipitation.

Long-term mean of precipitable water over Poland (PW) is 15.93 mm. It is characterized by a distinct annual cycle with a summer

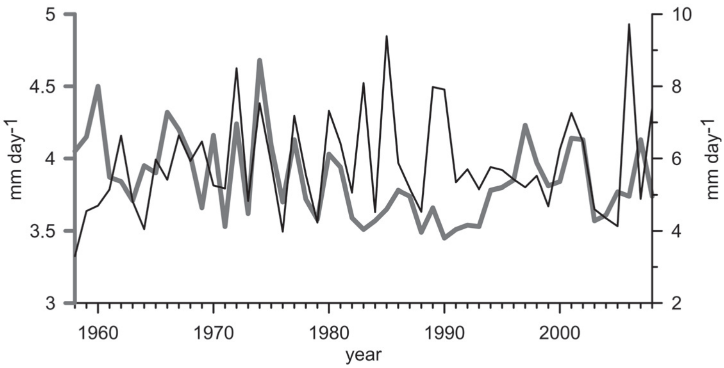

Figure 4. Annual average of total precipitation intensity in Poland (grey bold line, left axis) and annual average intensity of precipitation of the Mediterranean origin (MCP) (right axis) in the years 1958-2008

maximum (the highest long-term daily average is 26.43 mm) and a minimum in winter (the lowest daily average is 8.53 mm). The extreme values of PW are in the range 1.86 < PW < 40.97 mm. In annual course moisture content in the atmosphere and the intensity of precipitation in Poland are closely correlated (the correlation coefficient is 0.97).

Moisture content in the atmosphere over Poland is characterized by a downward trend (Fig. 5). In the period 1958-2008, the average annual values of PW decreased by almost 10% and it was a statistically significant change (Tab. 1). Likewise, the mean seasonal PW values in spring and autumn decreased significantly. The mean annual PW values were particularly low in the 1990s (Fig. 5). The coincidence of this depression of PW with the occurrence of significant climate warming (the unusually warm period between 1989 and 1995) is noticeable. However, in the first place, the long-term (1958-2008) trends in moisture content in the atmosphere over Poland and in the number of Mediterranean cyclones are congruent (Figs. 2 and 5).

The decreasing trends in PW values in the years 1958-2008 generally confirm the conclusions concerning the trends in the content of precipitable water over Europe, investigated by Wibig and Siedlecki (2007). The authors suggest that precipitable water in the atmosphere over the continents is affected both by the moisture flux from the surface and the advection of moisture dependent on the atmospheric circulation (Wibig 2008). In Europe, there are areas with diverse PW trends;

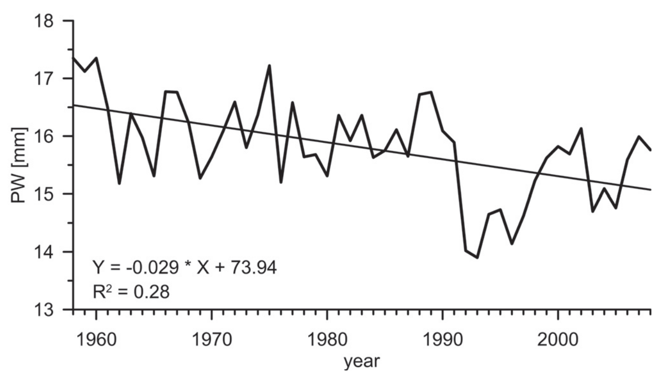

Figure 5. Annual average precipitable water in the atmosphere over Poland (PW) in the years 1958-2008 and the linear trend of PW changes

growing trends were observed, among others, in the east and the north of the continent, while decreasing trends mainly in the south of Europe.

Precipitable water in the atmosphere and precipitation versus MEC trajectories

Mediterranean cyclones affecting the territory of Poland bring an increase in precipitable water content in the atmosphere, which, moreover, is differentiated according to the position and the trajectory of a cyclone. In the period 1958-2008, 563 days were recorded on which Mediterranean cyclones were situated in the so-called precipitation-efficient sections of their trajectories. The relative frequency of these days is only ca. 3%. The most common were the cyclones moving along the central C track (almost 46% of all MEC), cyclones on the western W track occurred least frequently (10%) (Tab. 2).

The calculated average values of PW on the days with MEC and a comparison of these values with the long-term daily mean PW[4] (i.e. determination of relative deviations 'Δ' from the mean value of specified days in the year) allow to evaluate the average 'climatic' effect of the circulation controlled by Mediterranean cyclones on the moisture content in the atmosphere over Poland. Table 2 contains the results of these evaluations which show that the precipitable water over Poland during the occurrence of MEC cyclones in the precipitation-efficient sections of their trajectories is by 14.5% higher than the long-term daily mean of PW. For the cyclones moving along the W track and causing southern advection in Poland, it is by 21.6% higher, and when cyclones travel the E track and advection from the north prevails, the moisture content is only about 4.5% higher than the average.

The average precipitable water content during the occurrence of MEC is higher than its long-term average, but individual values of PW on the days with MEC exhibit a significant variability – the highest and the lowest values are close to the PW extremes in Poland: on the days with *MEC*, the reported PW values varied from 3.8 to 36.6 mm (Tab. 2). This variability can be explained by the characteristic features of the MEC circulation systems, and in particular by the convergence of different air masses – the humid 'Mediterranean'

Table 2. Precipitable water (PW) in the atmosphere over Poland on the days with MEC in precipitation-efficient sections of the W, C, S, E trajectories, and its long-term (1958-2008) mean values

MEC trajectories	Frequency			PW			
	n	F1	F2	Minimum	Maximum	Average	Δ_{AVE}
W	58	0.31	10.3	6.4	31.1	19.5	0.216
C	258	1.39	45.8	5.3	36.4	19.4	0.197
S	126	0.68	22.4	4.8	36.6	17.0	0.096
E	121	0.65	21.5	3.8	32.0	16.0	0.045
Σ MEC	563	3.02	100	3.8	36.6	18.1	0.145
Total	18 615 (365 days × 51 years)	100	-	1.9	41.0	15.9	0.000

Δ_{AVE} – average relative deviation of PW, n – number of days on which MEC were in precipitation-efficient sections of trajectory, F1 – incidence in %, F2 – incidence in % of days with *MCP* precipitation

[4] The average daily values of PW in the multi-year period were calculated according to the following scheme – if a *MEC* occurred e.g. on 01.07.1977, then the average of the days 01.07 in all the 51 years (1958-2008) was calculated; the same was done for each day with a MEC.

air and the drier air flowing from the north or from the east. The differentiation of PW depending on the trajectory of MEC confirms this conclusion.

Table 3. Average intensity of MCP precipitation (DP) and average precipitable water (PW) over Poland depending on the MEC tracks, average intensity of total precipitation in Poland (DP-PL), long-term average of precipitable water in Poland (PW-PL) and the ratios DP/PW

MEC trajectory	DP* [mm day^{-1}]	PW* [mm]	DP/PW
W	2.2	19.5	0.11
C	5.6	19.4	0.29
S	3.3	17.0	0.19
E	5.9	16.0	0.37
Σ MEC	5.8	18.1	0.32
PL	4.1	15.9	0.26

* values are averaged on the days with MEC cyclones situated at precipitation-efficient sections of a given trajectory

The average intensity of MCP precipitation is higher than the intensity of total precipitation in Poland and amounts to 5.8 mm day^{-1}, which represents 32% of the average moisture content in the atmosphere on the days with MEC cyclones. This percentage is higher than that characterizing the intensity of total precipitation in Poland and the mean precipitable water (26%) (Tab. 3).

Cyclones moving along E track are characterized by the greatest intensity of precipitation (5.9 mm day^{-1}) at the lowest precipitable water content (16 mm): the ratio DP/PW reaches 0.37. The C trajectory represents a ratio of 0.29. The small intensity of Mediterranean precipitation and the low ratios DP/PW are associated with the W and S trajectories. The ratios DP/PW are in these cases lower than the average for Poland (0.26) and are equal to 0.11 and 0.19 respectively (Tab. 3).

The differentiation of the DP/PW ratios is affected by the directions of advection over Poland, associated with the MEC trajectories: if it is the northern advection (E trajectory), the ratio reaches 0.37, with the southern advection (W trajectory) it is only 0.11, although the value of PW at the same time is high (Tab. 3). Also, the rule is observed according to which the heaviest precipitation occurs to the east (or on the left side, looking in the direction of the movement of low pressure systems) of the position of cyclones and also their trajectories (Wrona 2008; Sobik & Błaś 2010; Świątek 2013b).

Extreme precipitation and precipitable water in the atmosphere

On the basis of mean values it can be considered that precipitation 'consumes' only part of the reserve of atmospheric moisture. However, given the maximum precipitation totals, it can be seen that the amount of daily precipitation, including MCP precipitation, can exceed several times the current precipitable water content in the atmosphere. This is a result of moisture advection in a circulation system conducive to the condensation of water vapour.

Table 4 summarizes the values of daily precipitation totals, the precipitable water content in the atmosphere, its deviation from the multi-year average, and the ratio DP/PW representing 13 cases of daily MCP totals exceeding 90 mm. It was rainfall ranging from 99 mm day^{-1} (Kraków, 9 September 1963) to 234 mm day^{-1} (Hala Gąsienicowa, 8 July 1997). In addition, the same characteristics are summarized for extremely high precipitation in Poland exceeding 200 mm day^{-1}, including the 'record' of daily rainfall, i.e. the up to 300 mm precipitation of 30 June 1973 on Hala Gąsienicowa (Tatra Mts).

Extremely high MCP occurred on the days when precipitable water in the atmosphere over Poland was at a level of 23.5 to 35.3 mm; on average, the level was close to 30 mm, which is twice the average multi-year value. However, there were situations when high precipitation was accompanied by a moisture content slightly lower than the daily average ($\Delta < 0$). The maximum MCP was 3-8 times higher than precipitable water value ($3.24 < DP/PW < 7.88$, Tab. 4). Extreme

Table 4. The intensity of the highest daily precipitation (DP) and the corresponding precipitable water content in the atmosphere (PW), relative deviations of PW from the multi-year average (Δ) and the DP/PW ratios.

Value	DP [mm day^{-1}]	PW [mm]	Δ	DP/PW
MCP_{MAX} > 90mm (n = 13)				
Minimum	99	23.50	-0.076	3.24
Average	143	29.81	0.187	4.88
Maximum	234	35.30	0.407	7.88
P_{MAX} > 200 mm (n = 9)				
Average	225	29.23	0.267	7.74
P_{EXTR}	300	30.56	0.304	9.82

MCP_{MAX} – maximum precipitation of the Mediterranean origin (*MCP*), P_{MAX} – highest precipitation in Poland, P_{EXTR} – maximum daily precipitation of 30.06.1973, n – number of cases

daily totals (DP > 200 mm) appeared when precipitable water in the atmosphere clearly exceeded the multi-year average, while precipitation exceeded the current PW value nearly 8 times, and in the case of the record rainfall of 30 June 1973 – nearly 10 times.

With an increase in the amount of rainfall extremes, the ratio DP/PW, which estimates the efficiency of precipitation forming processes, increases, too. There is also a rise in the Δ value – extremely high precipitation is generally accompanied by 'surplus' precipitable water. The increase in the amount of extreme precipitation (P_{MAX}) resulting from a growing surplus of moisture (Δ) can be described by the equation[5]

$$P_{MAX} = 34.3\,\Delta + 109$$

However, the dependence of the amount of precipitation on precipitable water is not significant; the variability of Δ explains only 2% of the variance of maximum precipitation, which can also occur even when there are 'shortages' of moisture in the atmosphere. The efficiency of the process transforming the atmospheric moisture into precipitation can vary greatly. Most of extremely high precipitation, however, occurs when surplus of precipitable water is high, reaching up to about 150% of its average content in the atmosphere (Fig. 6). This refers both to precipitation of the Mediterranean origin (MCP) and other precipitation.

Assuming the extreme values of PW and the ratio DP/PW, the possible maximum amount of precipitation (CMP – Credible Maximum Precipitation) can be assessed. If the "maximum efficiency of the system" in the case of MCP is 7.88 (Tab. 4) and the highest moisture content PW = 40.97 mm (Tab. 2), it means that daily CMP reaches 322.8 mm, whereas the extremely high value DP/PW = 9.82 of 30 June 1973 (Tab. 4) represents the possible maximum daily precipitation, reaching even up to 402 mm. These assessments are comparable to extreme precipitation amounts observed in the Czech Sudeten and considerably exceeding a total of 300 mm day^{-1} (e.g. 345 mm rainfall in Nova Louka on 30 July 1897, according to Niedźwiedź (2003)). Suligowski's (2004, 2013) assessments indicate that the possible maximum precipitation in the Kielce region can reach up to 227 mm day^{-1}. The measured amount of rainfall in Lubień on the upper Pilica river (211 mm on 8 June 1988 by Kłysik & Fortuniak 1993) and in the village Sienno near Kielce (219 mm on 19 May 1941, by Grela et al. 1999) are consistent with this assessment.

[5] The equation describes the link between 100 cases of highest daily precipitation totals P_{MAX} (regardless of their origin) observed in Poland in the years 1958-2008 and the moisture content in the atmosphere (Δ).

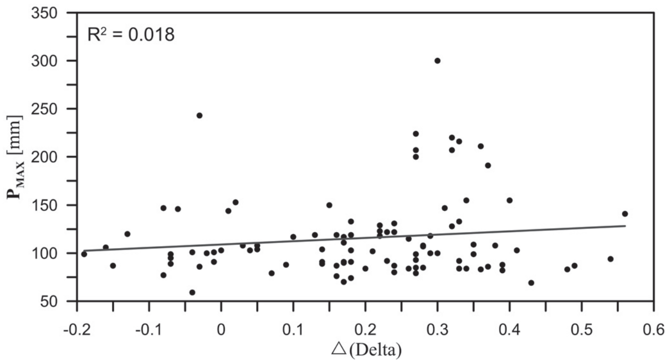

Figure 6. Maximum daily precipitation totals in Poland (P_{MAX}) depending on precipitable water in the atmosphere (Δ). 100 cases of maximum daily rainfall from the years 1958-2008 are included. Δ - relative deviation of precipitable water (PW) from long-term average of PW on the day with P_{MAX}

Conclusions

The results of the analyses performed lead to the conclusion that in the period 1958-2008, the number of cyclones arriving in Central and Eastern Europe from the Mediterranean Sea basin decreased. Some characteristics also point to the decreasing activity of these cyclones. The average precipitable water content in the atmosphere over Poland also showed a downward trend.

The precipitation totals associated with Mediterranean cyclones decreased, while the intensity of precipitation did not change significantly, and in the lowland parts of the country daily precipitation sums of the Mediterranean origin increased. These changes were different from the trends characterizing total precipitation sums and intensity in Poland.

Mediterranean cyclones are generally associated with a high content of precipitable water in the atmosphere. However, there are cases of MCP occurring at average or slightly less than average PW level. The mean Mediterranean precipitation intensity accounts for almost ⅓ of the average PW value. The highest daily rainfall, however, reaches a value almost 8 times higher than the current moisture content in the atmosphere. This means that the possible maximum MCP may reach above 322 mm day^{-1}.

A characteristic dependence of precipitation and the moisture content in the atmosphere on the trajectories followed by Mediterranean cyclones was observed. The western (W) track of cyclones is associated with the lowest precipitation intensity, occurring at relatively high precipitable water PW. The eastern (E) track, in turn, is distinguished by the highest intensity of precipitation and low precipitable water in the atmosphere, which means that the formation of MCP in the cyclones of this class is the most efficient.

The analysis presented in this paper, focusing on precipitation associated with the activity of Mediterranean cyclones, do not confirm the hypothesis of an increasing frequency of extreme hydro-meteorological events in Poland.

Acknowledgements

The studies were supported by the National Science Centre grant NCN N N306313739. The authors wish to thank Professor Joanna Wibig for providing a dataset on the precipitable water content in the atmosphere over Poland.

Editors' note:
Unless otherwise stated, the sources of tables and figures are the authors', on the basis of their own research.

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Article first received • September 2015
Article accepted • August 2016