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Precipitation changes on the Polish coast of the Baltic Sea (1954–2003) due to changes in intensity of westerlies over Europe

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ABSTRACT: The present study investigated changes in precipitation totals, frequency of days with precipitation, and relationships between precipitation totals in individual seasons at several weather stations on the Polish coast of the Baltic Sea. From 1954 to 2003, precipitation totals were almost invariant, except for a significant positive trend in March precipitation totals in Szczecin, Koszalin, Łeba, and Elbląg. Much more extensive were the changes in the frequency of wet days. Time-series analysis of the precipitation frequency demonstrated an increasing annual wet-day total on the eastern part of the coast (Hel, Gdynia, and Elbląg). The increase occurred at the highest rate in Elbląg. A significant upward trend was observed at almost all weather stations in June, and also in Elbląg in January, March, and October, and in Koszalin in February. Atmospheric circulation is a major factor influencing both short- and long-term fluctuations in precipitation. Therefore, we also analysed the links between changes in the frequency of wet days and changes in large-scale atmospheric circulation (the intensity of westerlies in particular). These relationships were explored by comparing the frequency of precipitation events in periods with differing intensity of westerlies. The present study demonstrated that the direction of air-mass advections have a stronger effect on the number of days with precipitation than on precipitations totals. More intense western advection causes more frequent precipitation, especially in the eastern part of the study area.

KEY WORDS: Precipitation totals · Frequency of wet days · Trends · Polish coast

1. INTRODUCTION

Trends in pluvial conditions in Poland in the second half of the 20th century have been addressed in several studies. Both annual and seasonal precipitation totals have shown multi-directional fluctuations and variations rather than a significant trend (Żmudzka 2002). However, analysis of a long time series (1891 to 2000) detected an increase in annual precipitation totals in northern Poland (Zawora & Ziernicka 2003). On the coast of the Gulf of Gdansk, both positive and negative trends were found in yearly and half-yearly (warm and cold half-years) precipitation totals at individual stations (Miętus & Filipiak 2002, Miętus et al. 2003). In most cases, however, the trends were not statistically significant. Kirschenstein (2004) showed alternation of increases and decreases in the annual, half-yearly, and seasonal precipitation totals. Precipitation sums were observed to increase, primarily in winter and spring (Kożuchowski 2004a, Miętus et al. 2005), and particularly in March (Degirmendžić et al. 2004, Kożuchowski 2004a), the increase constituting a component of the progressing pluvial oceanity of the climate in Poland (Kożuchowski et al. 2000).

Changes were also revealed in the precipitation frequency (number of wet days). Niedźwiedź (2000) reported an increase in the annual number of wet days in the second half of the 20th century in Polish lowland averages (based on data from the 14 most suitable stations). On the other hand, Przybylak et al. (2007), who

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used NCEP/NCAR reanalysis grid data sets, showed a downward trend in spatially averaged annual mean numbers of days with precipitation. Miętus & Filipiak (2002), on the other hand, showed a systematic increase in the number of days with precipitation at half of the stations located in the coastal zone of the Gulf of Gdansk, but found no significant changes at the remaining stations in the area.

As atmospheric circulation is the main factor controlling pluvial conditions (Ustrnul & Czekierda 2000), several studies have investigated relationships between precipitation changes and atmospheric circulation. Precipitation, particularly in winter, was shown to be very strongly and positively influenced by cyclonic circulation (Niedźwiedź et al. 1994). In addition, directions of air-mass advection affect sums of precipitation (Kirschenstein 2002, Malinowska 2006), although on a scale smaller than that of the baric system (cyclonic or anticyclonic). Western circulation was demonstrated to have the strongest positive influence on precipitation (Twardosz & Niedźwiedź 2001, Degirmendžić et al. 2004, Kożuchowski 2004b), although the effect is not entirely clear-cut: during spring-summer, the increase in precipitation totals was associated with a stronger intensity of the southern air-mass advection, while from June to November, the precipitation sums were negatively correlated with the western component of the circulation. The eastern and northeastern cyclonic circulation was associated with heavy precipitation totals in the northwestern part of Poland (Kirschenstein 2002, 2004). In the south of Poland, the most intense precipitation occurs during days with a northeastern cyclonic circulation (Twardosz & Niedźwiedź 2001).

The present study is a contribution to the discussion of the changes in pluvial conditions on the Polish Baltic coast and the circulation-related underlying causes of these changes. The aim was to characterize trends in the quantity and frequency of precipitation, and to describe — in a novel way — the effects of changes in the intensity of westerlies on changes in precipitation totals and frequency. Another aim was to describe changes in the degree of continentality of the Polish coastal zone.

2. DATA AND METHODS

The data set used consisted of daily precipitation totals from 1954 to 2003, recorded at weather stations in Szczecin, Świnoujście, Koszalin, Łeba, Hel, Gdynia, and Elbląg (Fig. 1). The data were retrieved from published (as annual summaries up to 1981) and unpublished materials of the Institute of Meteorology and Water Management. The weather stations are distributed more or less equidistantly along the Polish coast. The stations include 2 that are away from the coast (Szczecin and Elbląg) but that remain under the influence of the Baltic Sea because of the area's hypography and hydrology.

Homogeneity of the data series was determined by means of the standard normal homogenity test (SNHT) (Alexanderson 1986). Monthly precipitation totals in Gdynia and Łeba were found to be inhomogeneous (owing to relocation of the stations), and therefore appropriate correction factors had to be computed. Monthly precipitation totals were multiplied by the correction factors after 1966 (Gdynia) and 1972 (Łeba), when the data series lost their homogeneity.

The number of days with a measurable magnitude of precipitation (≥0.1 mm), in the present paper referred to as 'days with precipitation' or 'wet days', was based on series of daily precipitation totals.

Linear trends of sums and numbers of days with precipitation were analyzed. Correlation coefficients were tested for significance at the 0.05 level.

The circulation controls of precipitation changes were explored by comparing precipitation totals and numbers of days with precipitation over periods defined by individual forms of macrocirculation. Significant differences between the quantity and frequency of precipitation in the periods analyzed would be taken as evidence of the precipitation changes occurring as a result of changes in atmospheric circulation. The periods mentioned, known also as 'circulation epochs',

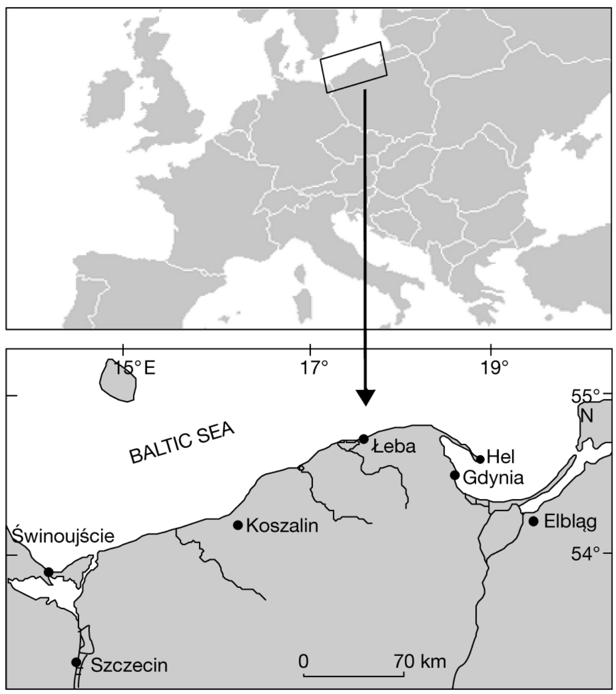

Fig. 1. Location of the weather stations on the Polish coast

were identified by Degirmendžić et al. (2000) based on 2 measures of zonal circulation intensity: the Zonal Index (ZI), defined as the difference in pressure between 35° N and 65° N, and the North Atlantic Oscillation index (NAO). ZI is a measure of the westerly flow on the hemispherical scale, while NAO allows average westerlies to be estimated according to zone, with respect to the Atlantic-European sector of the zone. Degirmendžić et al. (2000) defined circulation epochs based on the NAO index as presented by Jones et al. (1997). Degirmendžić et al. (2000) determined their epochs for the period 1901 to 1998 based on seasonal averages of ZI and NAO; as a result, each year was assigned 8 numerical values representing 8 variables. The Ward clustering method — applied to the 98 yr of the period analyzed (1901 to 1998), each described by the 8 variables — produced 4 groups of similar years. Inclusion of the time factor (the year expressed as its numerical value) as the ninth variable resulted in the years being grouped in temporal sequences corresponding to the epochs sought. The least intense zonal flow, accompanied by average meridional flow, was observed within the period 1957 to 1970; hence this period is referred to in the present paper as the 'neutral epoch'. A relatively strong eastern flow was observed in the period 1971 to 1986, and therefore this period is referred to as the 'eastern epoch'. As the period 1987 to 1998 was dominated by the strongest western circulation, it is termed the 'western epoch'.

The significance of differences between epochs in precipitation totals, and in the number of days with precipitation, was tested with the Student's *t*-test at $p = 0.05$.

Assessment of changes in the degree of pluvial continentality on the Polish coast was based on trends in the quotients of summer precipitation totals to winter ones, and the quotients of spring precipitation totals to autumn ones. A reduced prevalence of summer over winter precipitation totals was assumed to represent an increased maritime influence on pluvial conditions on the Polish seacoast. Enhanced climatic oceanity was assumed also to be evidenced by increased domination of autumn over spring precipitation sums.

Variability in the number of wet days was illustrated by cumulative relative anomalies of the number of days with precipitation, calculated according to the formula:

$$y_i = \sum_{i=1954}^{2003} \left(\frac{R_i}{\overline{R}} - 1 \right) \quad (1)$$

where: y is the cumulative relative anomaly, i is the succeeding year, R_i is the yearly number of days with precipitation and $\overline{R}$ is the multi-annual average number of days with precipitation.

3. RESULTS

3.1. Trends in precipitation

From 1954 to 2003, a significant increase in precipitation totals was recorded in March in Szczecin, Koszalin, Łeba, and Elbląg (Fig. 2). The strongest positive trend occurred in Elbląg and was related to both the frequency and intensity of precipitation increases in March (Kożuchowski 2004a). Although the magnitude of these increases (up to 31.49 mm in 50 yr of data from Koszalin), the determination coefficients remain low (e.g. 0.16 only in Koszalin). The monthly precipitation total increased significantly in Gdynia in May (25 mm during the period of study, with the determination coefficient as low as 0.09). Fig. 2 shows linear trends in the March monthly precipitation totals at the weather stations at which significant trends were observed. Although not significant at the $p < 0.05$ level, increases in monthly precipitation totals in March were also observed at other stations.

During the period of study, there was no evidence of changes in climatic oceanity of the Polish coast, as indicated by the lack of changes in the summer versus winter, and autumn versus spring precipitation sums. Analysis of between-season precipitation ratios revealed significant changes in the summer versus winter precipitation total in Elbląg only (Fig. 3). A decreasing trend in the ratio of summer to winter precipitation sums in Elbląg may be indicative of a small increase in the oceanity of pluvial conditions at that station. However, a decreasing trend in the ratio as well as a relatively sharp increasing trend of changes in winter, and a weak decreasing (non-significant) trend in summer, might have been equally random.

Time-series analysis of precipitation frequency showed an increasing yearly number of days with precipitation on the eastern part of the coast (Hel, Gdynia, and Elbląg) (Table 1). The highest rate of increase (>30 d during 50 yr) occurred in Elbląg. A significant upward trend was observed at nearly all weather stations in June (except Szczecin and Świnoujście), and additionally in Elbląg in January, March, and October, and in Koszalin in February.

3.2. Relationship between number of wet days and intensity of westerlies

The Student's *t*-test failed to detect significant differences in the annual and seasonal precipitation totals between individual epochs; the lack of significant differences is related to the lack of significant changes in precipitation sums, except for the precipitation totals in March. Consequently, the analyses presented in this

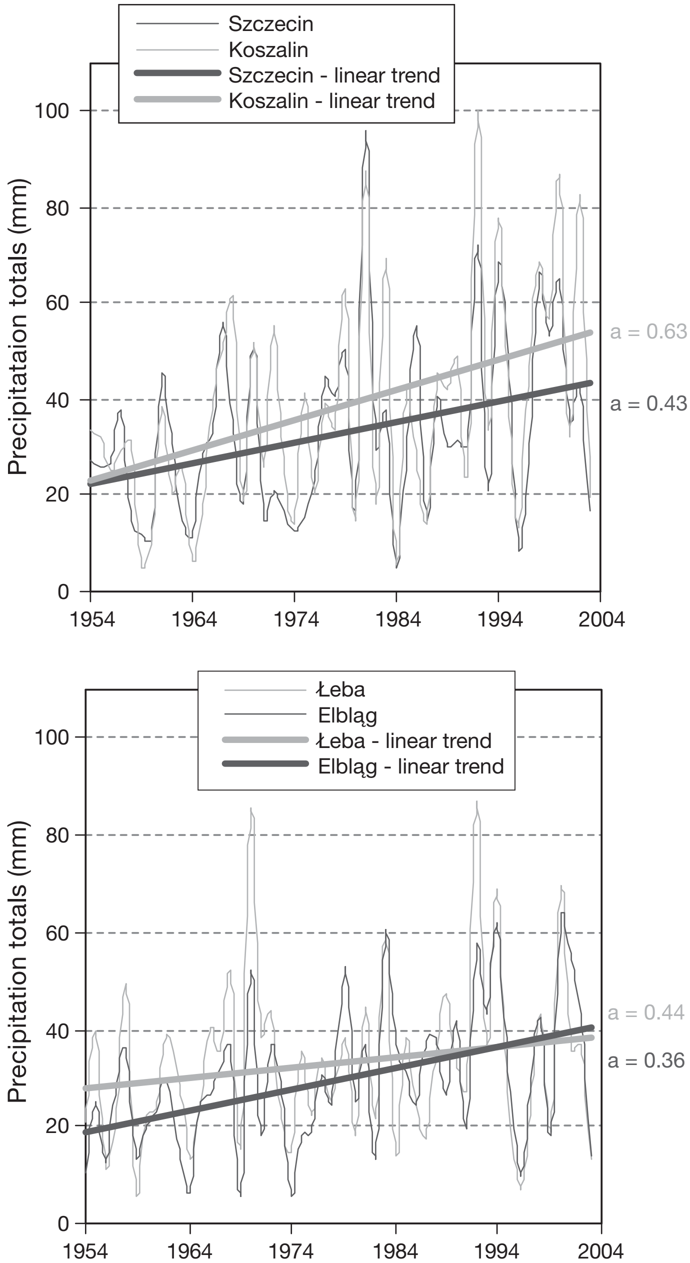

Fig. 2. Precipitation totals in March with linear trends and regression coefficients (a, to right of graphs) for Szczecin and Koszalin (upper panel) and Łeba and Elbląg (lower panel)

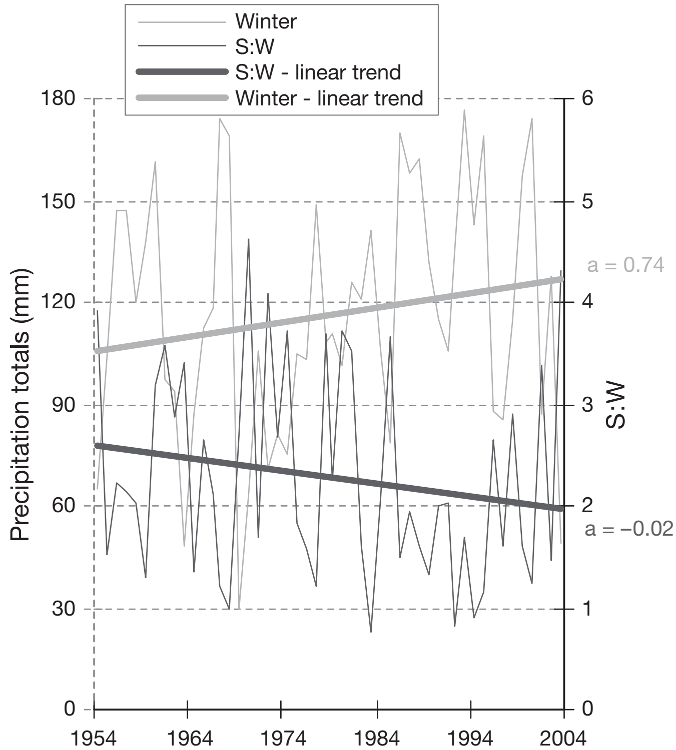

Fig. 3. Winter precipitation totals in Elbląg and the ratio of summer to winter precipitation total in Elbląg (S:W), with linear trends and regression coefficients (a, to right of graph)

section deal with the frequency of days with precipitation only.

In Gdynia and Elbląg, the mean number of days in the year with precipitation in the neutral epoch was significantly lower than during the western epoch (Fig. 4). The largest differences in the seasonal number of wet days were observed in autumn, when the weaker zonal circulation during the neutral epoch brought about less frequent rains. In autumn in Szczecin, Hel, Gdynia, the number of days with precipitation was significantly lower during the neutral epoch than in both the eastern and western epochs, while in winter this difference between epochs occurred in Elbląg only (Fig. 5).

The largest differences between the number of days with precipitation in individual epochs were found in autumn (and in winter in Elbląg), while significant changes in the number of days with precipitation were observed mainly in the summer month of June. This finding is related to various directions of trends observed in different summer months. In July and August, the number of days with precipitation decreased non-significantly (data not shown). Furthermore, the number of days with precipitation in the cold half-year was higher than in summer, and therefore the differences between those numbers were larger as well.

The curves produced by pooling cumulative relative anomalies in the number of wet days (Fig. 6) show an obvious relationship with large-scale circulation variability. During the neutral epoch, the curves display a drop, indicating negative deviations from the multiannual frequency average. During the eastern epoch, the curves show low values because posi-

Table 1. Linear trends in number of days with precipitation for those months and stations showing significant changes. Year: linear trends in number of days with precipitation per year in the period 1954 to 2003; a: regression coefficient. **Bold:** significant ($p < 0.05$)

	Szczecin		Świnoujście		Koszalin		Łeba		Hel		Gdynia		Elbląg	
	a	p	a	p	a	p	a	p	a	p	a	p	a	p
Jan	0.00	>0.1	–0.01	>0.1	0.02	>0.1	–0.01	>0.1	0.03	>0.1	0.03	>0.1	**0.11**	0.014
Feb	0.06	>0.1	0.04	>0.1	**0.09**	0.048	0.03	>0.1	0.02	>0.1	0.04	>0.1	0.05	>0.1
Mar	0.08	0.186	0.06	>0.1	0.06	>0.1	0.05	>0.1	0.07	0.086	0.08	0.063	**0.10**	0.034
Jun	0.06	>0.1	0.08	0.063	**0.09**	0.048	**0.10**	0.014	**0.12**	0.008	**0.11**	0.025	**0.09**	0.048
Oct	0.05	>0.1	0.03	>0.1	0.06	>0.1	0.06	>0.1	0.08	0.086	0.08	0.086	**0.11**	0.025
Year	0.16	>0.01	0.10	>0.01	0.35	0.086	0.17	>0.1	**0.39**	0.034	**0.40**	0.048	**0.60**	0.002

tive and negative deviations are balanced. As of the early 1980s, the curves gradually rise, evidencing higher frequencies of days with precipitation during the western epoch than in the whole 50 yr interval studied.

Changes in the frequency of wet days were greater in the eastern than in the western part of the coastal zone, with the largest changes observed in Elbląg (Table 1). Elbląg, too, displayed the strongest relationships of precipitation with circulation conditions. The strong effect of the direction of air-mass advection on precipitation in Elbląg is a result of that station's location on the western slope of the Elbląg Plateau, in the vicinity of a sill separating the Vistula River Plain and the Elbląg Plateau. Such a location is conducive, during the westerly flow, to orographic rainfalls similar to those in mountain areas (Trapp & Malinowska 2003), which would explain the exceptionally high frequency of precipitation during the western epoch.

4. DISCUSSION AND CONCLUSIONS

Annual, seasonal, and monthly precipitation totals were almost invariable, except for the positive trend in March, and monthly precipitation sums along the Polish coast were lowest in March and February. Thus, an increase in precipitation sums in March (a month characterized by relatively low precipitation totals) would reduce the seasonal inhomogeneity in pluvial statistics. It could be taken as an indicator of pluvial oceanity. Relationships between the seasonal precipitation totals (except for probably random trends in Elbląg) demonstrated no trend in climatic oceanity on the Polish coast from 1954 to 2003.

The increase in precipitation totals in March was also observed in southern Sweden. Busuioc et al. (2001) associated the increase with intensification, since 1964, of the westward movement of air masses in March. Previously, as of the 1920s on, the early spring was dominated by the eastward movement, hindering

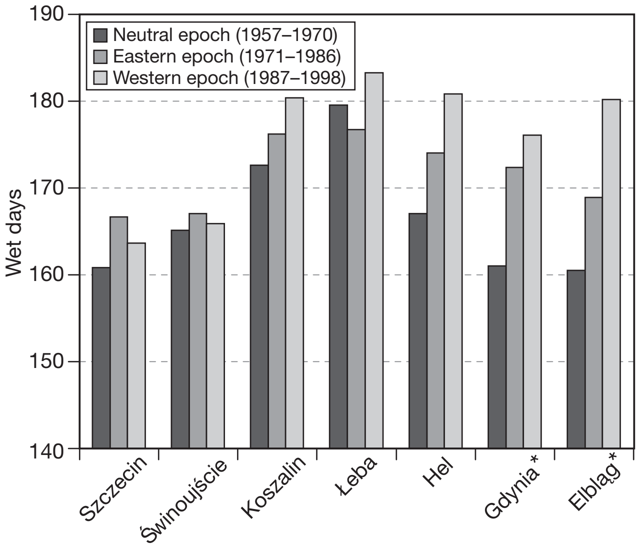

Fig. 4. Mean number of wet days per year for each station in individual circulation epochs. *Significant difference ($p < 0.05$) between neutral epoch and western epoch

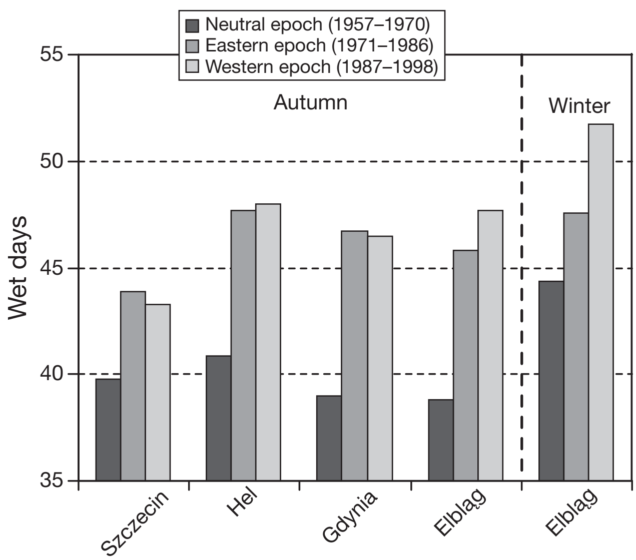

Fig. 5. Mean number of wet days in autumn and winter at stations where differences between epochs were significant ($p < 0.05$) for that season

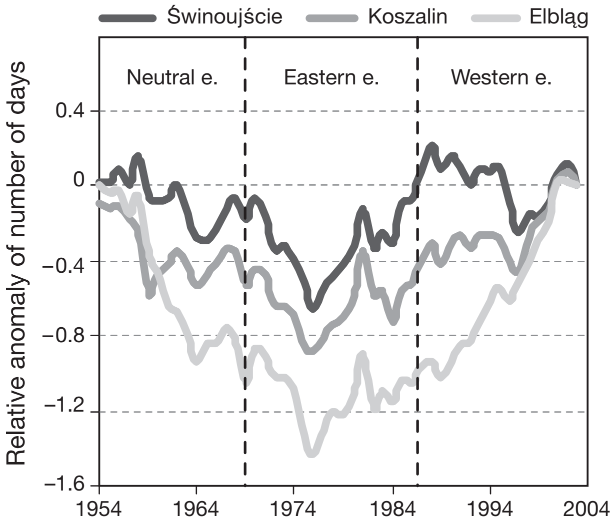

Fig. 6. Cumulative curves reflecting relative anomalies from the multiannual frequency average of the number of wet days at individual stations

precipitation. Degirmendžić et al. (2004) also associated the increase in precipitation sums in March in Poland with increased intensity of the westerly flow, and the progressing warming which jointly contributed to the increase in the atmospheric water vapor content.

The changes in the number of wet days were stronger than trends in precipitation totals. The present study showed an increase in the annual wet-day frequency at several weather stations as well as in the frequency of precipitation in June (Table 1). Räisänen & Joelsson (2001), in their attempt to model changes of wet-day frequency in Europe, placed the southern Baltic Sea and northern Poland on the boundary between areas characterized by increased number of days with precipitation (north and northwestern Europe) and areas where the number of such days decreases (the southern and southwestern parts of the continent). Given the results of the present study, the eastern part of the Polish Baltic coast should be placed in the first group, although the change trends are minor.

Furthermore, the present study demonstrated that westerlies have a stronger effect on precipitation frequency than on precipitation sums. The frequency of precipitation during the domination of western circulation (1987 to 1998) was higher than average, particularly in autumn and winter. The less-intense zonal air-mass advection (1957 to 1971) was accompanied by less-frequent precipitation.

The relationship between pluvial conditions on the Polish coast and the trends in the intensity of westerlies were not overly strong, in contrast to a very strong positive influence reported from the northern part of Europe (e.g. Busuioc et al. 2001) and a negative effect in southern Europe (e.g. Tomozeiu et al. 2005) and Turkey (Türkeş & Erlat 2005). This is associated with the change in the axial direction of the maximum humidity transport across the Atlantic and Europe during periods of high NAO indices. The atmospheric humidity is then transported further north and east over northern Europe and Scandinavia, while the humidity transport over the Mediterranean Sea, southern Europe, and part of central Europe (Hurrell 1995, Kapala et al. 1998) is restricted. Because of the intermediate location of the southern Baltic coast between the 2 zones, the NAO intensity effect on precipitation in the area is weaker than that in other parts of Europe.

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LITERATURE CITED

Alexanderson H (1986) A homogeneity test to precipitation data. J Clim 6:661–675

Busuioc A, Chen D, Hellström C (2001) Temporal and spatial variability of precipitation in Sweden and its link with the large-scale atmospheric circulation. Tellus 53A:348–367

Degirmendžić J, Kożuchowski K, Wibig J (2000) Epoki cyrkulacyjne XX wieku i zmienność typów cyrkulacji atmosferycznej w Polsce. Przegląd Geofizyczny 3–4:221–238 (in Polish with English abstract)

Degirmendžić J, Kożuchowski K, Żmudzka E (2004) Changes of air temperature and precipitation in Poland in the period 1951–2000 and their relationship to atmospheric circulation. Int J Climatol 24:291–310

Hurrell JW (1995) Decadal trends in the North Atlantic Oscillation: regional temperatures and precipitation. Science 269:676–679

Jones PD, Jonsson T, Wheeler D (1997) Extension to the North Atlantic Oscillation using early instrumental pressure observations from Gibraltar and south-west Iceland. Int J Climatol 17:1433–1450

Kapala A, Mächel H, Flohn H (1998) Behavior of the centre of action above Atlantic since 1881. I. associations with regional climate anomalies. Int J Climatol 18:23–36

Kirschenstein M (2002) Cyrkulacyjne uwarunkowania opadów w północno-zachodniej Polsce. Przegląd Geofizyczny 1–2: 45–59 (in Polish with English abstract)

Kirschenstein M (2004) Rola cyrkulacji atmosferycznej w kształtowaniu opadów w północno-zachodniej Polsce (The role of the atmospheric circulation in forming precipitation in the north-west Poland). Pomorska Akademia Pedagogiczna, Słupsk

Kożuchowski K (2004a) Zmienność opadów atmosferycznych w Polsce w XX i XXI wieku. In: Kożuchowski K (ed) Skala, uwarunkowania i perspektywy współczesnych zmian klimatycznych w Polsce. Biblioteka Publishers, Łódz, p 47–58 (in Polish with English abstract)

Kożuchowski K (2004b) Cyrkulacja atmosferyczna nad Polską i jej wpływ na warunki klimatyczne. In: Kożuchowski K (ed) Skala, uwarunkowania i perspektywy współczasnych zmian klimatycznych w Polsce. Biblioteka Publishers, Łódz, p 69–88 (in Polish with English abstract)

Kożuchowski K, Degirmendžić J, Fortuniak K, Wibig J (2000) Trends to changes in seasonal aspects of climate in Poland. Geogr Pol 73:7–24

Malinowska M (2006) Makroskalowe uwarunkowania opadu atmosferycznego na Żuławach Wiślanych. Wiadomości IMGW 1:25–48 (in Polish with English abstract)

Miętus M, Filipiak J (2002) Struktura czasowo-przestrzennej zmienności warunków opadowych w rejonie Zatoki Gdanskiej. Materiały Badawcze IMGW, ser. Meteorologia 34, Institute of Meteorology and Water Management (IMGW), Warsaw (in Polish with English abstract)

Miętus M, Filipiak J, Owczarek M (2003) Czasowo-przestrzenna struktura opadów w rejonie Zatoki Gdanskiej i jej możliwe zmiany w skali XXI wieku (The temporal and spatial variability of pluvial conditions in the area of the coast of the Gulf of Gdansk and expected changes in XXI century). In: Cyberski J (ed) Powódź w Gdańsku 2001. Gdańskie Towarzystwo Naukowe, Gdańsk, p 35–56

Miętus M, Filipiak J, Owczarek M, Jakusik E (2005) Zmienność warunków opadowych polskiego wybrzeża Morza Bałtyckiego w świetle kwantylowej klasyfikacji opadowej. Materiały Badawcze IMGW, ser. Meteorologia 37 (IMGW), Warsaw (in Polish with English abstract)

Niedźwiedź T (2000) The dynamics to selected extreme climatic events in Poland. Geogr Pol 73:25–39

Niedźwiedź T, Ustrnul Z, Cebulak E, Limanówka D (1994) Long-term climate variations in southern Poland due to atmospheric circulation variability. In: Heino R (ed) Proc Eur Workshop 'Climate variations in Europe'. Kirkkonymmi, 15–18 May 1994. Academy of Finland 3/94:263–277

Przybylak R, Vízi Z, Araźny A, Klejna M, Maszewski R, Uscka-Kowalkowska J (2007) Poland's climate extreme index. 1951-2005. Geogr Pol 80:47–58

Räisänen J, Joelsson R (2001) Changes in average and extreme precipitation in two regional climate model experiments. Tellus 53A:547–566

Tomozeiu R, Stefan S, Busuioc A (2005) Winter precipitation variability and large-scale circulation patterns in Romania. Theor Appl Climatol 81:193–201

Trapp JA, Malinowska M (2003) Atmospheric conditions of water exchange on the Vistula River Plain. Wiadomości IMGW 2:13–25

Türkeş M, Erlat E (2005) Climatological responses of winter precipitation in Turkey to variability of the North Atlantic Oscillation during the period 1930-2001. Theor Appl Climatol 81:45–69

Twardosz R, Niedźwiedź T (2001) Influence of synoptic situations on the precipitation in Kraków (Poland). Int J Climatol 21:467–481

Ustrnul Z, Czekierda D (2000) Cyrkulacyjne uwarunkowania opadów atmosferycznych w Polsce. Wiadomości IMGW 2:3–21 (in Polish with English abstract)

Zawora T, Ziernicka A (2003) Precipitation variability in time in Poland in the light of multi-annual mean values (1891–2000). In: Pyka J, Dubicka M, Szczepankiewicz-Szmyrka A, Sobik M, Błaś M (eds) Man and climate in the 20th century. Studia Geograficzne 75:123–128

Żmudzka E (2002) O zmiennosci opadów atmosferycznych na obszarze Polski nizinnej w drugiej połowie XX wieku. Wiadomości IMGW 4:23–37 (in Polish with English abstract)

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