Selected Characteristics of Atmospheric Precipitation on the Polish Coast of the Baltic Sea

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Abstract. The characteristics of extreme precipitation, including dominant trends, were analyzed for eight stations located on the Polish coast of the Baltic Sea for the period 1951-2010. Maximum 1-day and 5-day precipitation totals, events exceeding the 90th and 95th percentile calculated for the period 1961-1990 applied as indices enabling the assessment of the frequency of wet conditions. Annual trends were calculated using the standard linear regression method, while the fit of the model was assessed with the t-test at the 95% confidence level. Annual precipitation reaches values from 775 mm on the east coast to 683 mm on the central coast and shows positive trends on six out of eight analyzed stations, from 0.8 mm year\(^{-1}\) in Swibno to 2.5 mm year\(^{-1}\) in Dziwnow. The maximum 1-day precipitation totals range between 58.7 mm on the western coast to 105.0 mm on the central coast and show statistically significant trends (0.1 - 0.2 mm year\(^{-1}\)) in this area. There are, on average, six to seven 5-day rainfall periods recorded annually in the investigated area. The annual number of 5-day precipitation periods shows positive statistically significant trends in the central and eastern part of the South Baltic coast (0.2-0.3 per 10 years). The median of the maximum 5-day precipitation totals ranges from 21.6 mm in Swinoujscie to 78.6 mm in Ustka. Trends in changes in maximum 5-day rainfall totals reach the level of 0.1-0.2 mm year\(^{-1}\) and are statistically significant in stations from Swinoujscie to Ustka and in Gdynia. The values of the 90th percentile of 1-day precipitation total are equal to 8-10 mm. Annually, there are about 16-18 days with such precipitation recorded in the area under investigation. The trends are positive (0.1-1.0 day per 10 years) on the central coast. The values of the 95th percentile of 1-day precipitation totals reach 11.5-14.0 mm. Annually, there are about 8-9 days with such precipitation recorded in the area under investigation. The trends are positive (0.3-0.4 days per 10 years) on the western and central coast.

1. Introduction

The length of the Polish Baltic coast is 601 km [1]. In this zone of interaction of the marine and terrestrial environment, geomorphological and hydrological phenomena occur very dynamically, 100 km of abrasive – accumulative coast is strongly threatened by sea erosion [2]. As a result of modern climate changes, the level of the Baltic Sea is systematically rising [3, 4], which may cause, over several decades, an increase in the rate of high coast abrasion and flooding of lowland and depression areas. At the same time, the incidence of storm surges will increase. The fifth IPCC Annual Report [5] indicates an increase in the probability of extreme precipitation in Europe. Intense short-term rainfall with high intensity, moderate rainfall lasting several days or prolonged wet conditions lasting several to over a dozen weeks have an impact on the development of slope processes on the cliffs [6]. Knowing the frequency of occurrence of extreme precipitation phenomena may, therefore, be of great importance in the study of the functioning of coastal geoekosystems.
The work aimed to characterize extreme precipitation along the Polish Baltic coast in the period 1951-2010. The variability of extreme precipitation has been presented on the background of the mean annual precipitation totals. The source material for this study was the daily sums of precipitation from eight meteorological stations (figure 1). The data are available at the Historical Database of the Polish Institute of Meteorology and Water Management. Due to the lack of measurement data, precipitation analysis for stations: Swinoujscie, Kolobrzeg, and Ustka was based on the research period covering the years 1956-2010.

Five indices of extreme precipitation that enable the assessment of intensity and frequency of extremely wet conditions were analysed. Maximum 1-day precipitation total (R1d), maximum 5-day precipitation total (R5d) together with the number of 5-day precipitation periods (R5NoP), and the number of events exceeding the 1961-1990 90th and 95th percentile of daily precipitation total (90pNoD and 95pNoD, respectively) were applied to characterize extreme precipitation. To characterize extreme precipitation maximum 1-day precipitation total (R1d) were applied by [7, 8, 9, 10] and may be a good indicator of extreme precipitation in coastal regions of north Poland as such events caused serious damage in cities located in this area [11, 12]. According to [13] maximum 5-day precipitation total (R5d) appropriately characterizes the cases of extreme precipitation. Events exceeding the 1961-1990 95th (p95) percentile of daily precipitation total was applied by [8] to determine the threshold values for extreme precipitation events on the Polish Baltic coast as well as by [14] and [15] to analyse extreme precipitation in Poland and Germany. Annual trends were calculated using standard linear regression method, while the fit of the model was assessed with the F-test at the 95% confidence level [16].

2. Analysis and Results

2.1. The annual precipitation totals
The mean annual precipitation totals at the Polish Baltic coast were characterized by a large spatial diversity in the second half of the twentieth century and the beginning of the 21st century. The lowest values were recorded in the eastern part of the research area, at stations in Gdynia (542.9 mm) and Swibno (557.2 mm), slightly higher, at about 560-570 mm, in the western part of the coast and the highest annual totals were recorded on the central coast, where they reached above 660 mm (table 1.) The analysis of the changes in annual precipitation totals showed that six out of eight stations showed statistically significant positive trends ranging from 0.71 mm-yr⁻¹ in Darlowo (central coast) to 2.54 mm-yr⁻¹ in Dziwnow. At two stations: Ustka and Gdynia, annual precipitation totals show a negative trend but not statistically significant.

| Table 1. The annual mean precipitation totals (mm) on the Polish coast of the Baltic Sea in the years 1951-2010, and the slope values (mm-yr⁻¹) from the fitted regression equations. Statistically significant values are shown in boldface |  |
The maximum 1-day precipitation (R1d) recorded on the southern coast of the Baltic Sea during the period under review were very diverse, ranging between 58.7 mm in Swinoujscie (August 29, 1969) to 105.0 mm in Darlowo (June 28, 1991) (table 2). The median values of the maximum daily sums of precipitation were very similar at the analyzed stations, ranging from 29.8 mm in Dziwnow to 33.9 mm in Hel. The spectrum of distribution of maximum daily rainfalls is therefore very diverse at individual stations. Analysis of changes in perennial maximum daily precipitation showed the existence of statistically significant positive trends on the central coast of Polish Baltic coast, starting from the Dziwnow station (0.18 mm yr\(^{-1}\)) to Hel (0.15 mm yr\(^{-1}\)), with the highest growth rate at Ustka station (0.22 mm yr\(^{-1}\)). The exception is the Darlowo station, where a statistically significant negative trend of the maximum daily precipitation is observed, at -0.11 mm yr\(^{-1}\). At the stations in Swinoujscie and Swibno, R1d trend changes are positive but not statistically significant. At the station in Gdynia, R1d change trends are negative but not statistically significant.

### Table 2. Maximum 1-day precipitation totals (1Rd) (mm) on the Polish coast of the Baltic Sea in the years 1951-2010, and the slope values (mm yr\(^{-1}\)) from the fitted regression equations.

| Station     | Swinoujscie\(^a\) | Dziwnow  | Kolobrzeg\(^a\) | Darlowo | Ustka\(^a\) | Hel     | Gdynia | Swibno |
|-------------|-------------------|----------|-----------------|---------|-------------|---------|--------|--------|
| Mean total  | 563.4             | 569.4    | 679.0           | 662.8   | 683.4       | 582.0   | 542.9  | 557.2  |
| Trend       | 0.85              | 2.54     | 1.92            | 0.71    | -0.91       | 1.10    | -0.01  | 0.84   |

\(^a\)1956-2010

2.3. The 5-day precipitation periods and maximum 5-day precipitation totals

On average, 6-7 5-day precipitation periods (R5NoP) are observed annually on the southern coast of the Baltic Sea. The spatial variability of this indicator is not large; it varies from 5.9 at the meteorological station in Gdynia to 7.3 in Ustka (table 3). The central coast from Kolobrzeg station to Hel station is characterized by a slightly higher average number of 5-day rainfall periods than the western and eastern parts of the area under investigation. Statistically significant changes in the annual number of five-day precipitation periods (R5NoP), from 0.15 mm-10yrs\(^{-1}\) to 0.34 mm-10yrs\(^{-1}\), characterize the eastern part of the research area from the station in Darlowo to the Swibno station.

### Table 3. The mean annual number of 5-day precipitation periods (R5NoP) on the Polish coast of the Baltic Sea in the years 1951-2010, and the slope values (mm-10yrs\(^{-1}\)) from the fitted regression equations. Statistically significant values are shown in boldface

| Station     | Swinoujscie\(^a\) | Dziwnow  | Kolobrzeg\(^a\) | Darlowo | Ustka\(^a\) | Hel     | Gdynia | Swibno |
|-------------|-------------------|----------|-----------------|---------|-------------|---------|--------|--------|
| R5NoP       | 31.0              | 29.8     | 34.4            | 33.2    | 31.1        | 33.9    | 31.8   | 33.8   |
| Median      | 0.33              | **0.18** | **0.09**        | **-0.11** | **0.22** | **0.15** | -0.04  | 0.04   |

\(^a\)1956-2010
A very large spatial diversity characterized the maximum 5-day precipitation (R5d), recorded in the analyzed area. The values of this indicator at the station in Hel reached 60.6 mm while at the station in Ustka as much as 235.2 mm (table 4). The median maximum day rainfall (R5d) was slightly more varied in the analyzed years compared to the maximum 1-day precipitation totals (R1d), taking the values 21-31 mm values on seven out of eight stations. The station in Ustka stood out from the other stations with the median of 5-day precipitation totals (R5d) reaching the value of 78.6 mm. The maximum 5-day precipitation totals (R5d) on the Polish coast of the Baltic Sea show a statistically significant positive trend, from 0.09 mm yr\(^{-1}\) at the station in Swinoujscie to 0.22 mm yr\(^{-1}\) at the Ustka station. The lack of a statistically significant trend is characteristic for stations in Hel and Świbno.

Table 4. Maximum 5-day precipitation totals (R5d) (mm) on the Polish coast of the Baltic Sea in the years 1951-2010, and the slope values (mm yr\(^{-1}\)) from the fitted regression equations. Statistically significant values are shown in boldface

| Station | Swinoujscie\(^a\) | Dziwnow | Kolobrzeg\(^a\) | Darlowo | Ustka\(^a\) | Hel | Gdynia | Świbno |
|---------|-----------------|---------|----------------|---------|------------|-----|--------|--------|
| R5d     | 81.8            | 76.0    | 72.6           | 104.9   | 235.2      | 60.6| 85.7   | 116.2  |
| Median value | 21.6            | 25.9    | 29.2           | 31.3    | 78.6       | 21.8| 24.5   | 24.8   |
| Trend   | **0.09**        | **0.12**| **0.16**       | **0.18**| **0.22**   | -0.04| **0.20**| -0.04  |

\(^{a}1951-2010\)

2.4. Number of days with precipitation above 90th quantile

The 90\(^{th}\) quantile values (90p) of daily precipitation totals at the analyzed stations vary from 7.90 mm in Gdynia to 9.80 mm in Darłowo (table 5). These values are slightly lower than the value of precipitation 10 mm day\(^{-1}\), considered by [8] as an extreme precipitation indicator. Annually, there are about 16 to 19 days with precipitation ≥90p (90pNoD) recorded at the Polish coast of the Baltic Sea. Interestingly, the lowest mean number of such days was noted at the station in Darłowo (16.2) and the highest in the station in Kolobrzeg (18.9). Both stations are separated by only 70 km, which may indicate a large influence of local factors on the characteristics of extreme rainfall in this area. 90pNoD trends of change in the analyzed period were very diverse, depending on the station. On the central coast, at the stations from Dziwnow to Darłowo, 90pNoD values show statistically significant trends ranging from 0.07 day yr\(^{-1}\) to 0.97 day yr\(^{-1}\). At stations in Ustka and Gdynia, where the trends of changes are also statistically significant, the number of days with precipitation ≥90p decreases.

Table 5. The 90\(^{th}\) quantile values (90p) of daily precipitation totals (mm), the average annual number of days with precipitation ≥90p (90pNoD) (day) on the Polish coast of the Baltic Sea in the years 1951-2010, and the slope values (day yr\(^{-1}\)) from the fitted regression equations. Statistically significant values are shown in boldface

| Station | Swinoujscie\(^a\) | Dziwnow | Kolobrzeg\(^a\) | Darlowo | Ustka\(^a\) | Hel | Gdynia | Świbno |
|---------|-----------------|---------|----------------|---------|------------|-----|--------|--------|
| 90p     | 8.20            | 8.20    | 9.20           | 9.80    | 9.70       | 8.40| 7.90   | 8.50   |

\(^{a}1956-2010\)
90pNoD 18.1 18.4 18.9 16.2 18.2 17.2 17.9 16.3
Trend 0.33 0.97 0.55 0.07 -0.06 0.59 -0.15 0.12

2.5. Number of days with precipitation above 95th quantile
The 95th quantile values (95p) of daily precipitation totals at stations located on the Polish coast of the Baltic Sea, showed value from 11.50 mm at the station in Dziwnow to 14.00 mm at the station in Kolobrzeg (table 6). On average, there were between 8.1 and 9.9 days with precipitation ≥95p recorded at the stations Swinno and Kolobrzeg, respectively. Statistically significant positive trends, ranging from 0.33 to 0.44 day per decade characterize the west part of the Polish Baltic Sea coast. The increase in the number of days with precipitation ≥95p is also characteristic at the Hel station.

Table 6. The 95th quantile values (95p) of daily precipitation totals (mm), the average annual number of days with precipitation ≥95p (95pNoD) (day) on the Polish coast of the Baltic Sea in the years 1951-2010, and the slope values (day⋅10yrs⁻¹) from the fitted regression equations. Statistically significant values are shown in boldface

| Station     | Swinoujscie | Dziwnow | Kolobrzeg | Darlowo | Ustka | Hel | Gdynia | Swibno |
|-------------|-------------|---------|-----------|---------|-------|-----|--------|--------|
| 95p         | 11.70       | 11.50   | 12.80     | 14.00   | 13.80 | 12.20| 12.60  | 12.70  |
| 95pNoD      | 9.1         | 9.2     | 9.9       | 8.2     | 9.3   | 8.8  | 8.4    | 8.1    |
| Trend       | 0.33        | 0.41    | 0.44      | 0.06    | -0.21 | 0.17 | -0.06  | 0.11   |

a1956-2010

3. Conclusion
The annual precipitation totals on the Polish coast of the Baltic Sea generally show a growing trend, statistically significant in 6 out of the 8 analyzed stations. The increase in the sum of annual precipitation in the South Baltic Bay Area, although not statistically significant, has been demonstrated by [7]. In contrast, a statistically significant increase in precipitation sums in Northern Europe, north of latitude 50, showed [9]. Thus, in general, it can be assumed that the annual sums of atmospheric precipitation in the analyzed area have an increasing tendency.

The median values of the maximum daily sums of precipitation (R1d) range from 29.8 mm to 33.9 mm with absolute maximum values reaching even 105mm. Trends in the changes of this characteristic are spatially diversified and statistically significant on the central coast, with the exception of the station in Darlowo. Similar results were obtained by [9], indicating an increase in the value of extreme 1-day precipitation in this part of Europe. According to [10], maximum daily precipitation in winter generally increases, but only in Kolobrzeg, the change is statistically significant. In warm seasons, dominate increases in 1-day precipitation maximum precipitation, however, they are statistically significant only in Swinoujscie.

The maximum 5-day precipitation totals (R5d) are characterized by a generally statistically significant positive trend of changes in the area being analyzed. The only exception is Gdynia station, where this trend is negative. The obtained results coincide with the results of the studies [9]. Also, the analysis carried out by [10] revealed that the 5-day precipitation sums show increases for many stations in Northern Poland, however not statistically significant.
The values of the 90th quantile of daily precipitation (p90) take values in the range from 8.2 - 9.8 mm and are slightly lower than 10 mm (one of the extreme precipitation indicators recommended by [13]). There is an increase in the number of days with such precipitation observed in the western part of the analyzed area, while in the central part the trends of changes have different signs, depending on the station. Some of these changes are statistically significant. The increase in the number of days with precipitation ≥ p90 in northern Poland in the period 1961-2008 was demonstrated by [7], although the pace of these changes was not statistically significant.

The values of the 95th quantile of the daily sums of precipitation (10-12 mm) are close to the threshold values determined by [8] for the occurrence of extreme climate events. However, the research [8] did not reveal any statistically significant trends in the changes of this indicator. The increase in the number of days with such precipitation, however, shows a long-term growing tendency, as shown by the results of the research [13].

The large spatial differentiation of the directions of changes not only of the sums of annual precipitation but also of various indicators of extreme precipitation is a typical feature, as shown in research [14, 15].

The presented spatial pattern of changes in precipitation leads to the conclusion that the areas located on the Polish Baltic coast, especially in the western and central parts of the Baltic Sea, receive increasing amount of atmospheric water, but are also more frequently exposed to extreme precipitation, which may have negative not only economic but also ecological consequences.

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