Oceanological and Hydrobiological Studies

International Journal of Oceanography and Hydrobiology

Volume 45, Issue 3, September 2016
pages (405-423)

ISSN 1730-413X
eISSN 1897-3191

Selected extreme weather events on the Polish coast of the Baltic Sea in the period 2001-2014

by

Janusz Filipiak*, Mirosława Malinowska

DOI: **10.1515/ohs-2016-0036**
Category: **Original research paper**
Received: **September 25, 2015**
Accepted: **January 25, 2016**

Department of Meteorology and Climatology, Institute of Geography, University of Gdańsk, ul. Bażyńskiego 4, 80-952 Gdańsk, Poland

Abstract

The article examines the spatial and temporal variability in selected extreme meteorological phenomena on the Polish coast of the Baltic Sea. Data from the 2001-2014 period related to a few meteorological and oceanographic elements were used to calculate indices of extreme weather events. The amount of intensive and widespread precipitation events in the 21st century corresponds well with the long-term means and is stable over a long period. The number of 50-60 frost days recorded per year has been systematically decreasing for several decades. Only a few deep cyclones occur per year and year-to-year variations of their number and magnitude corresponds to the overall long-term insignificant changes in the cyclone activity in the North Atlantic and the European region. The mean annual number of days with strong winds reaches nearly 8 cases per year. About 6 storm surges per year are recorded and this value has been slowly increasing in the long-term perspective. The rare occurrence of sea ice in 2001-2014 is a continuation of the reduction in the phenomenon observed in the 20th century. The passage of deep cyclones resulting in strong winds, storm surges and waves constitutes the most dangerous hazard to the coast.

Key words: climate change, coastal zones, extreme weather event indices

* Corresponding author: *filipiak@ug.edu.pl*

DE GRUYTER

The *Oceanological and Hydrobiological Studies* is online at oandhs.ocean.ug.edu.pl

Introduction

The IPCC 5th Assessment Report of Working Group I clearly stated in 2013 that the increase in global air temperature reached 0.85°C since 1880. Each of the decades in the 1981-2010 period has been continuously warmer than any preceding decade since the instrumental global temperature became available (IPCC 2013) and the period 2001-2010 with the mean air temperature estimated at 14.47°C is considered to be the warmest decade during the last 160 years (WMO 2013). 9 years of this decade were among the 10 warmest years on record. Furthermore, the subsequent years 2011-2014 were also characterized by exceptionally high global air temperature values and 2014 with the average temperature of 14.57°C was the warmest year in the history of observations. The scale of regional and local warming in Europe is even greater. The linear trend of the annual mean temperature in the 1871-2011 period is equal to 0.08°C per decade in the southern part of the Baltic Sea basin and up to 0.11°C in the northern part (BACC II 2015). The year 2014 was the hottest year on record in 19 European countries and according to WMO's statement (http://public.wmo.int/en/media/news/2015-second-hottest-year-record-europe), the year 2015 was the second warmest year on record in Europe.

The changing climate is manifested not only by the change in the mean air temperature. Temperature anomalies are associated with abnormal pluvial and wind conditions. In 2003 and 2005, Central and Western Europe (respectively) were affected by extremely dry conditions, whereas large parts of Europe in 2007 recorded exceptionally heavy precipitation. The year 2010 was the wettest year on record globally, also in Europe – the central and eastern parts of the continent were affected by major flooding. 4 particularly severe and high-impact cyclones hit Europe since the beginning of the 21st century: Kyrill (January 2007), Klaus (January 2009), Xynthia (February 2010, considered the worst storm of the decade) and Xavier (December 2013), affecting several countries across Western and Central Europe and bringing substantial economic and environmental losses.

There is a considerable number of papers on extreme meteorological, hydrological and climatic events in Poland. The major risks associated with weather-related hazards in Poland result from severe precipitation and extreme wind speed events (Lorenc et al. 2012). Poland is exposed to late spring and summer heavy rainfalls and floods, which are the most destructive disasters in this part of Europe. The northern part of the country is particularly affected by storm conditions associated with the passage of deep and intense cyclones over the Baltic Sea (Ustrnul et al. 2009). Although the global warming involves a dramatic increase in the risk of hazards caused by the occurrence of extreme weather events, the problem of weather extremes is no longer a subject of research, but also a problem of social, ecological and economic effect on many sectors of economy. Their exceptional course and intensity represents a growing threat to the natural environment as well as economic and social activity of man. Recent trends in extreme events are consistent with the expected impact of climate change.

Due to the complex nature, sometimes it is not possible to distinguish the impact of meteorological factors from the effects of their occurrence. As both represent a threat to the coastal area, the authors decided to characterize these extreme meteorological phenomena occurring on the Polish coast of the Baltic Sea, which through their nature or effects may affect the existing landforms leading to significant changes in this fragile region. The objective of this paper is to characterize the spatial and temporal risks associated with meteorological conditions that may potentially affect the southern coast of the Baltic Sea in its Polish part.

Data and methods

The IPCC defines an extreme weather or climate event as a value of a particular variable, which is above or below a threshold value near the upper or lower ends of the range of observed values of the variable (IPCC 2012). Given the nature of some atmospheric phenomena, the causality factor for such high-impact weather events can be determined, as well as its practical applicability.

Even though the definition is clear, it is very difficult to establish universal criteria to classify the extremes on global or even regional scales. Several years ago, the Expert Team on Climate Change Detection Monitoring and Indices (ETCCDI) together with the Task Team on the Definition of Weather and Climate Extreme Events (both established by the WMO Commission on Climatology) have addressed the issue of developing common methodologies and standards for defining extreme weather and climate events and assessing their contribution to climate change. During the last several years, the ETCCDI has developed a set of indices referring to extreme air temperature and precipitation phenomena (Klein Tank et al. 2009). Since the Joint WMO and IOC Commission for Oceanography and Marine Meteorology is also involved in the ETCCDI activities, it aims to develop a set of impact-relevant marine climate extreme indices for coastal and open-ocean areas (Wang et al. 2014).

Based on the results of the analyses presented in the available literature, the authors developed some additional severe weather indices supporting and supplementing the indicators proposed by WMO. Thus the core set of indices referring to air temperature, precipitation, wind speed and direction, and characterizing frequency, amplitude and duration of extremes was established and then supplemented with additional indices describing some selected effects of meteorological elements.

The meteorological and oceanographic data used in the analysis were obtained from the verified database of the Polish Institute of Meteorology and Water Management – National Research Institute (IMGW-PIB) and they include the observational material for the period of 2001-2014 derived from the synoptic stations located on the Polish coast of the Baltic Sea (Fig. 1). All the stations, except Łeba and Elbląg, are located not further than a few hundred meters from the sea shore. In the case of Łeba, this distance increases to 2.5 km, Elbląg is located in the lower part of the slope of the lakeland extending eastward above the flat delta of the Vistula River.

As the studied period 2001-2014 is too short to derive any trends, it was necessary to compare the extracted indices with long-term data. Such comparisons were established by using long-term mean values of the studied indices presented in the available publications and reports. In a few selected cases, however, it was not possible to compare the results of our analysis with the long-term variability in the studied parameters due to the lack of literature.

Data on daily precipitation totals were used to calculate indices referring to extreme precipitation events. There are 2 types of precipitation events, the occurrence of which may trigger various environmental processes (sometimes even of destructive nature) in coastal areas: heavy precipitation and widespread precipitation. The heavy precipitation (in the form of rain) is of local nature, but its instantaneous intensity may exceed 1 mm min^{-1} (torrential rain). The daily amount of precipitation may reach 50 mm or more. Great amounts of rainfall water contribute to the water level rising in rivers, which can lead to the floods. The most popular and frequently used in Poland classification of daily precipitation totals, introduced by Olechnowicz-Bobrowska (1970), distinguishes heavy precipitation totals exceeding 20 mm per day and very intensive totals which exceed 30 mm per day. As the daily precipitation totals ≥ 30 mm are extremely rare at the Polish coast of the Baltic Sea (Ustrnul & Czekierda 2009), this paper considers only the daily precipitation amount ≥ 20 mm (R_{20mm}) as heavy precipitation. Additionally, the annual maximum 1-day precipitation totals were also identified (R_{x1d}).

The stabilization of cyclonic activity lasting for several days associated with the positive NAO phase enables the advection of humid maritime air masses, which may cause high amounts of continuous precipitation, recognized as being crucial for the coastal zone. Such widespread rainfall, usually occurring at a regional scale, can last for a few days. The cumulative sum of such precipitation may reach 100-150 mm or more. The great saturation of soil with water may facilitate the development of mass movement processes on slopes of high coasts. The results of such precipitation events may also be visible in hydrological and environmental dimensions. The index of widespread precipitation (R_{x5d}) refers to the precipitation totals, which were recorded over 5 consecutive days with atmospheric precipitation. In the situation when such a phenomenon lasted longer than 5 days, only a period of 5 consecutive

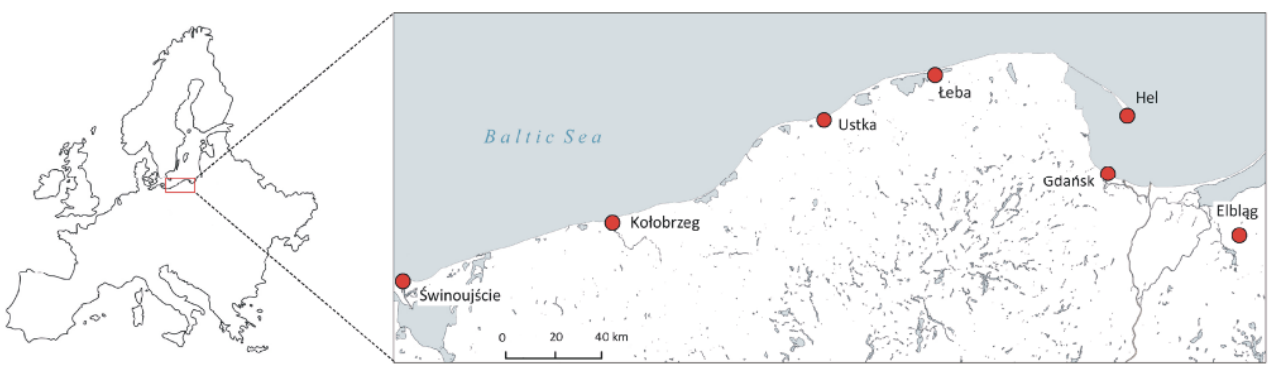

Figure 1

Location of the area and meteorological stations analyzed in the paper days with the highest total precipitation amounts was taken into consideration. The annual number and the mean monthly course of such weather events were calculated.

To avoid ambiguity, which could arise when 2 or more widespread precipitation events (one after another) merge into one longer-lasting event, also the duration was analyzed. In such cases, the whole duration of a particular widespread precipitation event was not limited to 5 consecutive days, but it included all days with the phenomena recorded.

Daily maximum and minimum air temperature data were used to calculate the frost day (*FD*) index. A frost day is a day when the minimum temperature drops below or reaches 0°C, while the daily maximum air temperature exceeds 0°C. This means that the 0°C threshold during a given day is exceeded. Such an analysis can be an important indicator of the rate of changes in thermal conditions in a given region and can be used in assessing the stability of the coastal ground structure, and may also be useful for experts implementing some infrastructure projects or those involved in the industry and transportation issues.

There is a close relationship between the thermal conditions and the development of sea ice. Depending on the severity of winter and the duration of a period with air temperature continuously below 0°C, different stages of sea ice can be observed – initial ice (frazil ice, slush and shuga), fast ice and floating ice. Sea ice occurring every year in the Baltic Sea affects the functioning of the maritime economy causing difficulties in shipping and the operation of harbors. The impact of sea ice on the coast is varied. On the one hand, the floating ice erodes the coast, but on the other – the coast is protected by a fast-ice belt. A layer of ice, formed during severe winters, creates a natural barrier to the destructive force of waves and stabilizes the beaches. Therefore, the floating ice poses a greater threat to the coast than a fast-ice layer. Data on the sea ice forms were also obtained from IMGW-PIB stations: Świnoujście, Ustka and Hel. In the case of the first 2 stations, the development of sea ice was observed in the mouths (estuary sections) of the short coastal rivers – Świna and Słupia, respectively, and in the area of the open sea waters. In Hel, the development of ice was observed in the Gulf of Gdańsk as well as in the area of the open sea waters. The number of days with sea ice (I_s) was calculated during the particular winter seasons since 2000/2001 to 2013/2014.

When analyzing the indices related to the wind and its effects, we used 3-hour information on wind speed and direction as well as sea-level pressure (SLP). The effects on the coast are strongly associated with the occurrence of storm conditions, which in turn are related to the passage of deep and intense cyclones involving a fast and significant drop in the atmospheric pressure value and high speed of wind. Strong winds cause abrasion of sea cliffs and flat sandy coasts, which may even result in the retreat of the coast. The intensity of this process can be up to 1 m yr^{-1}, or even more. It is estimated that the average annual destruction of the entire Polish open sea coast can reach 0.4 m yr^{-1} (Jania & Zwoliński 2011). The passage of such a deep cyclone over the Baltic Sea poses a threat not only to the coastal zone, but also to objects located inland due to high wind speeds resulting from a large pressure gradient (Owczarek 2002).

The winds caused by a strong pressure gradient, characteristic of deep and intense cyclones with a speed exceeding 17 m s^{-1} (force of 8°B and more), are defined as gales. A straightforward investigation into the long-term variability of extreme winds may often be difficult due to inappropriate exposure of anemometers at numerous stations affecting the data homogeneity. Thus, the variability in the number of gale days (*GD*), i.e. days with a wind speed exceeding 17 m s^{-1}, is presented on the example of Ustka, having the best exposure of the anemometer, as it was estimated according to the rules established by WMO (WMO 2010).

In order to measure the cyclonic activity in the region of the Polish coast of the Baltic Sea, three indices based on the SLP data from the Hel station were used. The annual number of pressure observations below 980 hPa (N_{p980}) was considered relevant to describe the occurrence of single deep cyclones on the Polish coast. The intensity of particular cyclones was measured using the index of the annual number of absolute pressure tendencies exceeding 6 hPa/3 h ($\Delta p/\Delta t$). Contrary to the two previously mentioned indices allowing for particular cyclones as deep and severe meteorological phenomena, the intra-annual 1st percentile of the pressure dataset (P_{1p}) relates to the overall climatology of the background pressure field. It allows to detect general features of the regional sea-level pressure field, sometimes characterized by a great amount of cyclones, but not deep or vigorous enough to be presented by a value of indices associated with intense systems (Bärring & Fortuniak 2009).

Sometimes strong winds may result in storm surges, defined as an abnormal rise of the sea level along the coast, caused by the passage of a low pressure center (WMO & UNESCO 2012). According to the definition by WMO (WMO 1988), a storm surge occurs when the sea level rises above a level that would not have occurred if there were winds from other directions. In the case of the Polish coast, storm surges are associated mainly with north-westerly, northerly and north-easterly winds (Sztobryn & Stigge 2005). The impact of storm surges on the coast is manifested by destruction of the coastline, including high coasts, like cliffs, and low coasts as sandy beaches and dunes. The effects of storm surges may be observed in almost the entire area of the Polish coast of the Baltic Sea. In some specific synoptic situations, the delta of the Vistula River is exposed to this type of risks, which is not normally the case (Sztobryn et al. 2012a).

A particular type of storm surges does not have to occur along the whole coast. Occasionally, warning conditions are recorded on the western coast, while on the eastern coast the sea level is normal (Sztobryn & Stigge 2005). The highest storm surges along the western part of the coast of the southern Baltic Sea are observed when atmospheric depressions move from the Norwegian Sea to the south, while on the eastern coast – from the north-west to the south-east. Due to a considerable degree of bathymetric differentiation of the southern Baltic, the warning sea level varies between different stations: in Świnoujście – 560 cm, in Ustka – 570 cm and in Hel – 550 cm (Majewski et al. 1983). The annual number of storm surges (*SS*), defined as instances when the warning threshold value is exceeded by the sea level, was calculated for these 3 stations.

Borówka (1980, 2001) and Jania & Zwoliński (2011) referred to another dangerous effect of winds – long-lasting strong winds significantly transform sandy beaches by moving great volumes of their material. Borówka (1980, 2001) reported that winds exceeding 10 m s^{-1} (as measured at the height of 1 m above the ground) are most effective; they last up to several tens of hours and are characterized by only minor changes in their direction. Our study has tried to capture the situations when the wind speed was 10 m s^{-1} or more for at least 2 neighboring observations and wind direction did not change by more than 90° *(En)*. As the wind speed significantly increases with height, particularly over rough terrain, we performed a reduction of our wind speed data to 1 meter above the ground, in accordance with the procedure recommended by WMO (2014). Next, the annual number of such events and their duration *(Ed)* were determined. The strongest events, lasting continuously for at least 24 hours (*En1d*) were distinguished among such long-lasting events.

Results

Extreme events related to atmospheric precipitation

A considerable spatial pattern regarding the number of days with heavy precipitation can be observed on the Polish coast (Fig. 2). An average annual number of such days in 2001-2014 in the

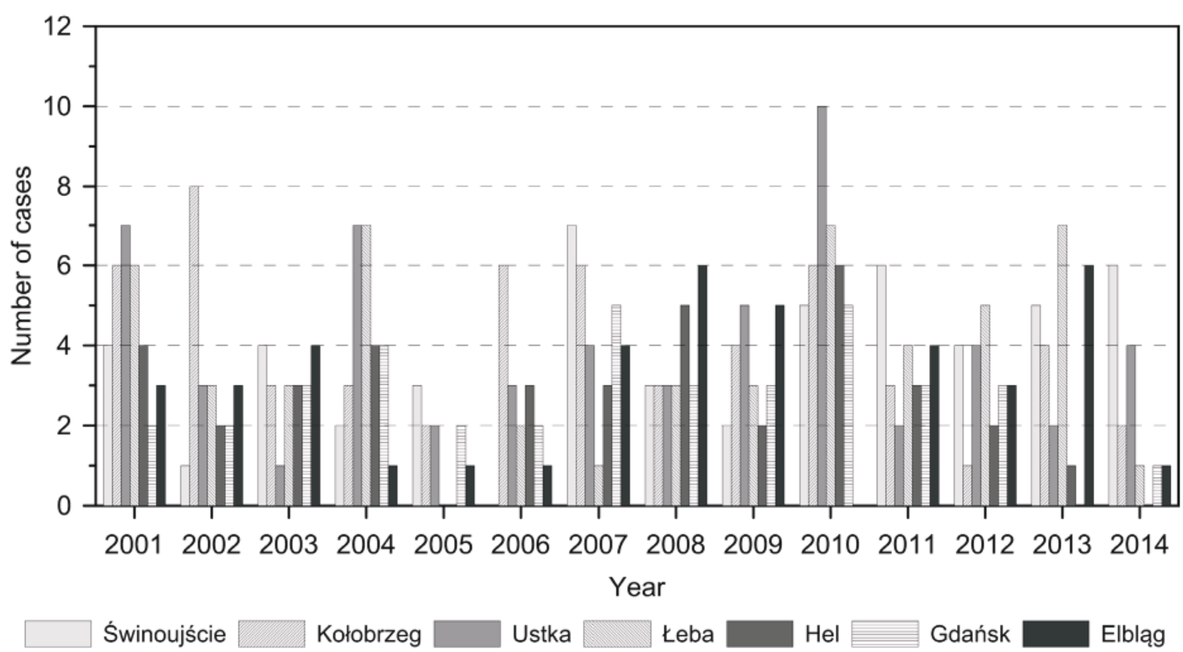

Figure 2

The annual number of days with heavy precipitation on the Polish coast of the Baltic Sea, 2001-2014 analyzed area ranged from about 3 at the stations located on the coast of the Gulf of Gdańsk (the eastern part of the analyzed coast: Gdańsk – 3.1 days, Elbląg – 2.9 days) to 4.3-4.5 in the central part of the open-sea coast (Ustka and Kołobrzeg, respectively) (Fig. 2). This gives a total of 50-55 days with heavy precipitation in the period of 2001-2014 in the central part of the open-sea coast, whereas at least 10 cases less were recorded at the other coastal stations within the analyzed 14 years.

Also the year-to-year fluctuations of the *R20mm* index are interesting (Fig. 2). The smallest number of heavy precipitation events occurred in 2005. No such weather phenomena were observed at the stations in Łeba and Hel, while only 1-3 cases were recorded at the other stations. No such day occurred in Świnoujście in 2006; at the same time, 6 such days were recorded in Kołobrzeg. The largest values of the *R20mm* index were determined in Ustka in 2010 (10 days with heavy precipitation) and in Kołobrzeg in 2002 (8 days).

Days with heavy precipitation occur mainly during the warm season, i.e. from May to October, when thermal convective processes occur even in the coastal strip, which is relatively colder than inland areas. Between July and September, daily precipitation events in the amount exceeding 20 mm may occur even once a month (Fig. 3). In May, June and October, such events are less frequent as heavy precipitation occurs usually once every 2 years. During the cold season (from November to April), extreme daily precipitation amounts are observed very rarely and they are mainly related to the cyclones from active atmospheric fronts (Ustrnul & Czekierda 2009).

The presented results correspond well to those obtained by Malinowska & Filipiak (2009) and Koźmiński & Michalska (2004), who analyzed the variability in precipitation totals on the Polish coast in the second half of the 20th century. According to the above authors, the mean annual number of days with heavy precipitation observed in the study area ranged from 2 to 4. The lack of any statistically significant changes in the annual number of such days was also reported by the above-mentioned authors in relation to longer periods. Ustrnul et al. (2014) confirmed the lack of long-term trends in daily precipitation totals in the period between 1951 and 2013 and estimated that the occurrence probability of daily heavy precipitation in the warmest months – July and August on the Polish coast of the Baltic Sea does not exceed 5%. However, Lorenc et al. (2012) identified positive tendencies in the annual number of daily precipitation events in the amount exceeding 10 mm in the western part of the Polish coast in the shorter period of 1971-2002.

The maximum daily precipitation totals on the Polish coast of the Baltic Sea ranged on average from 20 mm to about 40 mm (Fig. 4). The lowest maximum daily precipitation totals on the southern coast of the Baltic Sea occurred in 2005 when the value of *Rx1d*

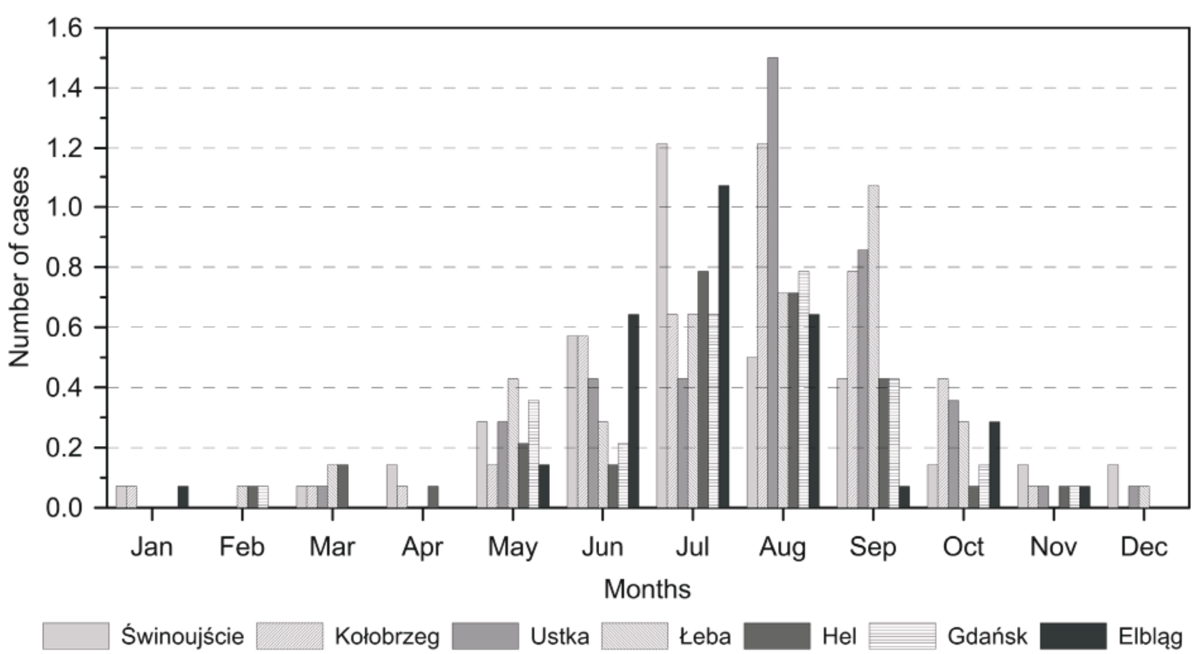

Figure 3

The annual course of the mean monthly number of days with heavy precipitation on the Polish coast of the Baltic Sea, 2001-2014

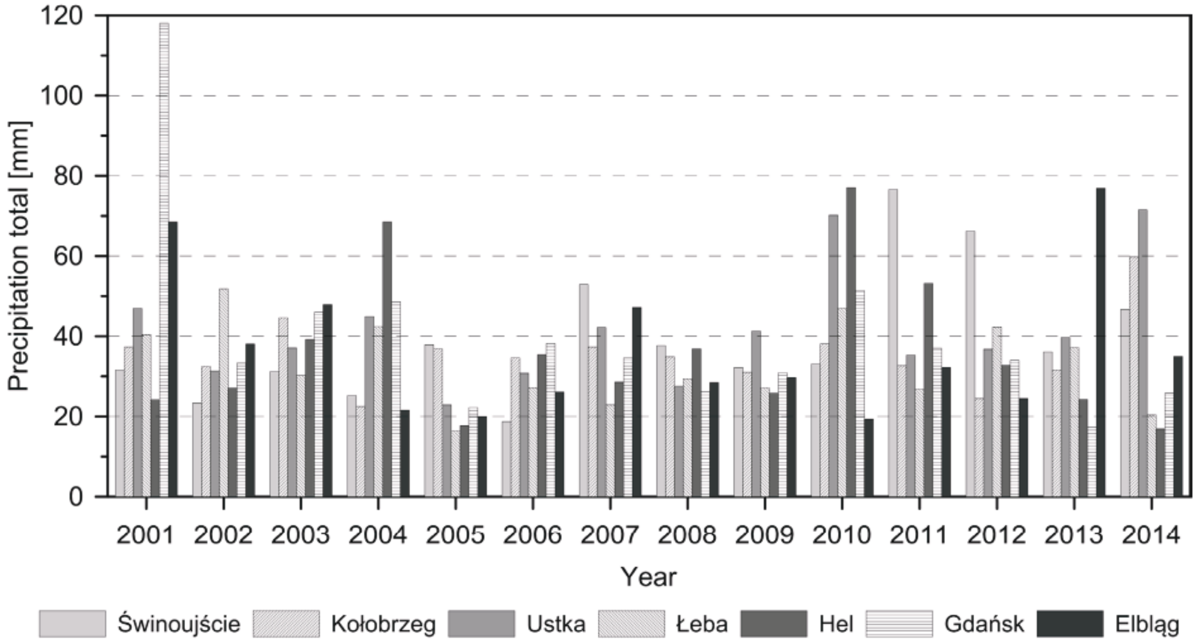

Figure 4

The annual maximum daily precipitation totals on the Polish coast of the Baltic Sea, 2001-2014

index reached only about 20 mm at most stations. The maximum daily rainfall of nearly 40 mm was recorded only in Świnoujście and Kołobrzeg. The absolute maximum daily precipitation totals in the investigated area in 2001-2014 did not exceed 80 mm, except 1 event – the rainfall that occurred in Gdańsk on the 9th July 2001 with the amount of 118.0 mm. It was an example of local torrential rain, relatively rare on the coast, more likely to be observed in the upland areas and mountains. Although it did not cause any considerable damage in the relief, the loss in the infrastructure of the city of Gdańsk was large (Miętus et al. 2003a). Furthermore, a few cases of the daily total precipitation exceeding 60 mm occurred in the considered area between 2001 and 2014. The precipitation of 68.5 mm was recorded in Elbląg in 2001 and in Hel in 2004. In 2010, the daily precipitation amount of 70.2 mm in Ustka and 77.1 mm in Hel was recorded. In 2011 and in 2012, daily totals of 76.6 mm and 66.2 mm (respectively) occurred in Świnoujście and in 2013, heavy precipitation of 76.9 mm was recorded in Elbląg. Finally, in 2014 the daily total of 71.5 mm was recorded in Ustka.

The frequency of such daily extreme rainfalls was changing within the last few decades in Northern Europe (Besselaar van der et al. 2013), but regional and local trends are inconsistent (Łupikasza et al. 2010). Ustrnul & Czekierda (2009) discussed extreme high daily precipitation totals over Poland and identified only 1 heavy rainfall exceeding 100 mm at the Polish coast of the Baltic Sea from 1951 to 2006. It occurred on the 24th of July 1988 when the total of 141 mm was recorded in Łeba. The same day, the daily precipitation total in Ustka reached 94.2 mm.

Values of the R_{x5d} index generally ranged from 30 to 60 mm (Fig. 5). However, much higher precipitation amounts were also recorded. In 2001, the maximum 5-day total precipitation exceeded 80 mm at the stations in Kołobrzeg and Ustka (88.8 mm and 87.6 mm, respectively). In 2003, the highest values of R_{x5d} were determined at the stations in Kołobrzeg (93.4 mm), Elbląg (82.9 mm) and Łeba (77.1 mm). In Ustka and Łeba, very high values of R_{x5d} were recorded in 2004 (110.4 mm and 76.4 mm, respectively). The year 2011 brought the highest value of R_{x5d} in Świnoujście (121.8 mm). In 2013, the maximum 5-day total precipitation occurred again at the station in Ustka (74.5 mm).

The annual number of widespread precipitation events on the Polish coast in 2001-2014 considerably varied in time and space. The number of cases ranged from 5 in Gdańsk in 2003 to 17 at the station in Świnoujście in 2002 (Fig. 6). The widespread precipitation events were least frequent in 2003 and 2013 – generally, the number of such events did not exceed 10 cases. The number of the described phenomena increased in 2004-2007; the annual number of cases at particular stations varied between 10 and 16.

Between 2 and 4 heavy widespread precipitation events, with 5-day totals exceeding at least 30 mm, were observed every year at the stations of the

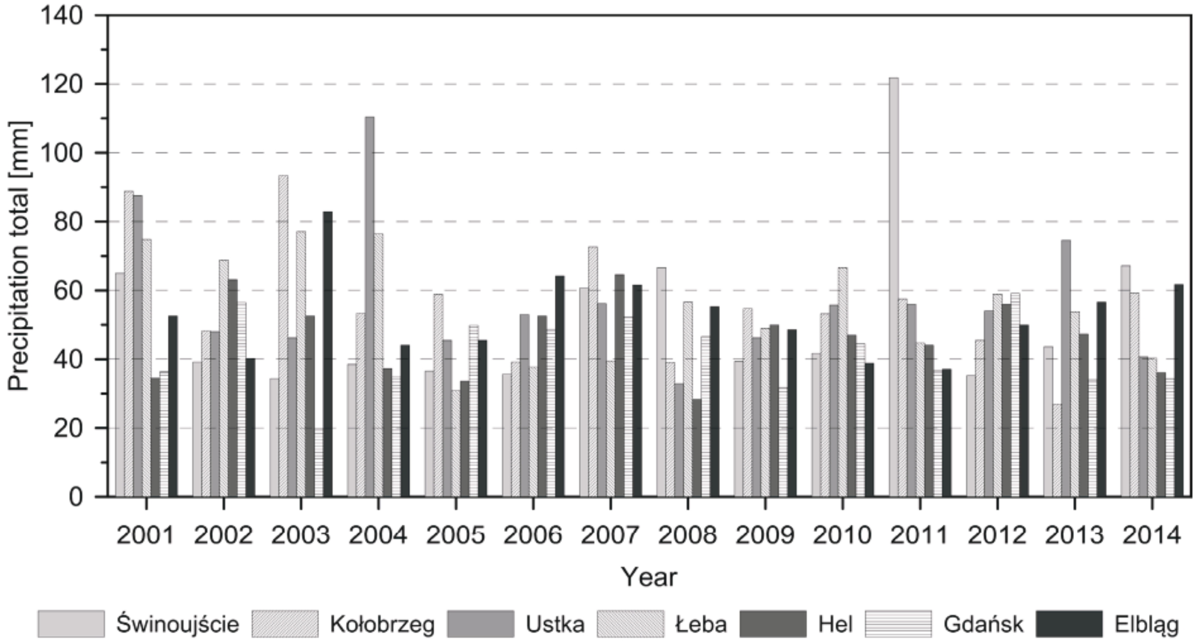

Figure 5

The annual maximum cumulative 5-day widespread precipitation totals on the Polish coast of the Baltic Sea, 2001-2014

Polish Baltic coast. Sometimes this number was larger at particular locations, e.g. 9 cases were registered in Kołobrzeg in 2002 and 7 cases in Elbląg in 2004. At some stations such events did not occur at all, e.g. Gdańsk in 2003, Hel in 2008 or Kołobrzeg in 2013. To sum up, the largest number of the heavy widespread precipitation events in 2001-2014 was observed in Łeba (50 cases) and Elbląg (49 cases). Such events were the least frequent in Gdańsk (24 cases) and in Świnoujście (27 cases).

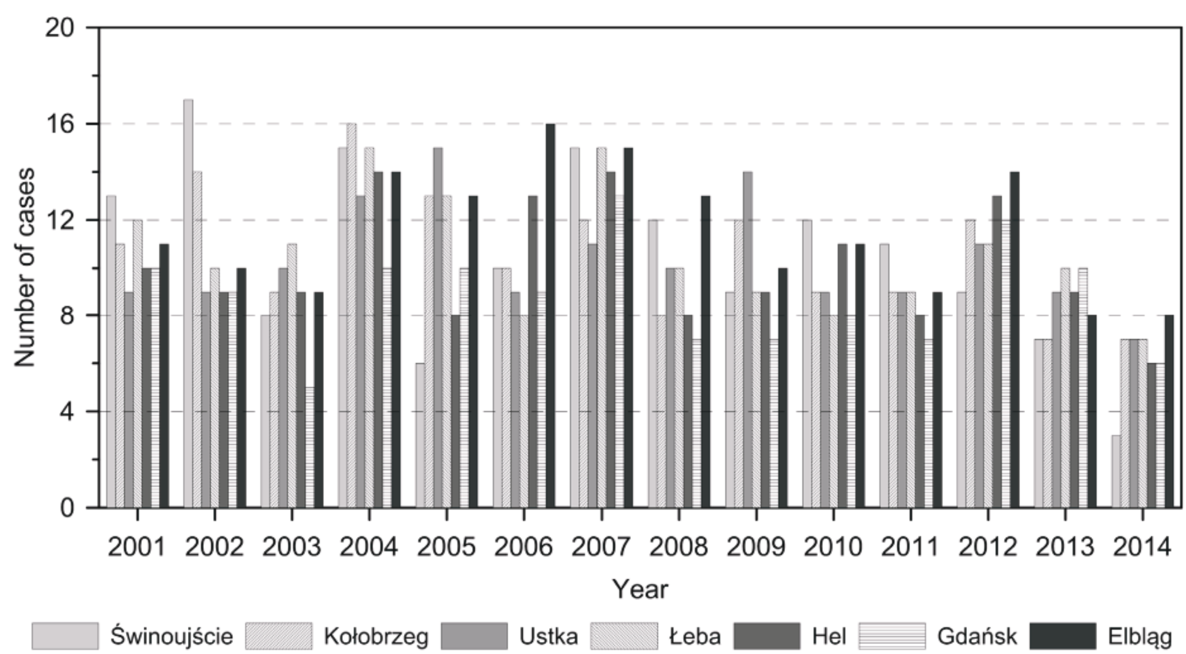

Figure 6

The annual number of widespread precipitation events on the Polish coast of the Baltic Sea, 2001-2014

The total duration of widespread precipitation events ranged on average between 50 and 80 days per year, depending on the station. The total annual duration of the analyzed cases was the longest at the stations located on the open-sea coast as well as in Elbląg and the shortest in Gdańsk. In 2003 and 2013, the total duration of all widespread precipitations was about 40-60 days; even less in Gdańsk – in 2003, the value of this index did not exceed 30 days. The longest total duration of widespread precipitation events was recorded at the analyzed stations in 2004 and 2012 – over 100 days in 2004 at most stations with the maximum (120 days) in Elbląg.

The widespread precipitation events are most frequent in the cold season, i.e. from October to March (Fig. 7). Their total cumulative number on the Polish coast in 2001-2014 was more than 10 cases per month and sometimes even more, depending on the station. The analyzed weather phenomena were particularly frequent in January when 18-19 events of widespread precipitation were recorded along the Polish coast, with the maximum (22) in Elbląg. The total number of the analyzed events in the warm months was much lower – it ranged from 4-10 in April and May to 5-13 in August and September. In July, the summer maximum was observed when the total number of widespread precipitation events in 2001-2014 ranged from 11 in Gdańsk to 14 in Ustka, Łeba and Hel, which means that approximately 1 widespread precipitation event occurred in July every year. The origin of such precipitation is slightly different during warm and cold seasons. In warm months, the relatively thick, instable layer in the troposphere, the high surface air temperature and relative humidity, and the sufficient instability energy determining the development of intensive convective processes influence the occurrence of frequent local intensive rains, whereas the widespread precipitation events in the cold season are mostly associated with the passage of cyclones and relevant advection of moist polar maritime air masses from the Atlantic Ocean. The heaviest widespread precipitation events with 5-day totals exceeding at least 30 mm are most frequent in the warmest months (summer and autumn, i.e. from June to October). They are hardly ever observed in spring when the sea waters and the coast are commonly too cold for the formation of strong convection.

The widespread precipitation events are not only more common in the cold season, but their average duration is also longer than in the warm season. The analysis of the annual course of the total number of days with the widespread precipitation events on the Polish coast of the Baltic Sea (Fig. 8) reveals that the longest widespread precipitation events occurred in November, December and January. In each of these months, a total number of days with the considered events was at least 100, thus about 8-10 days of widespread precipitation occur on average every year

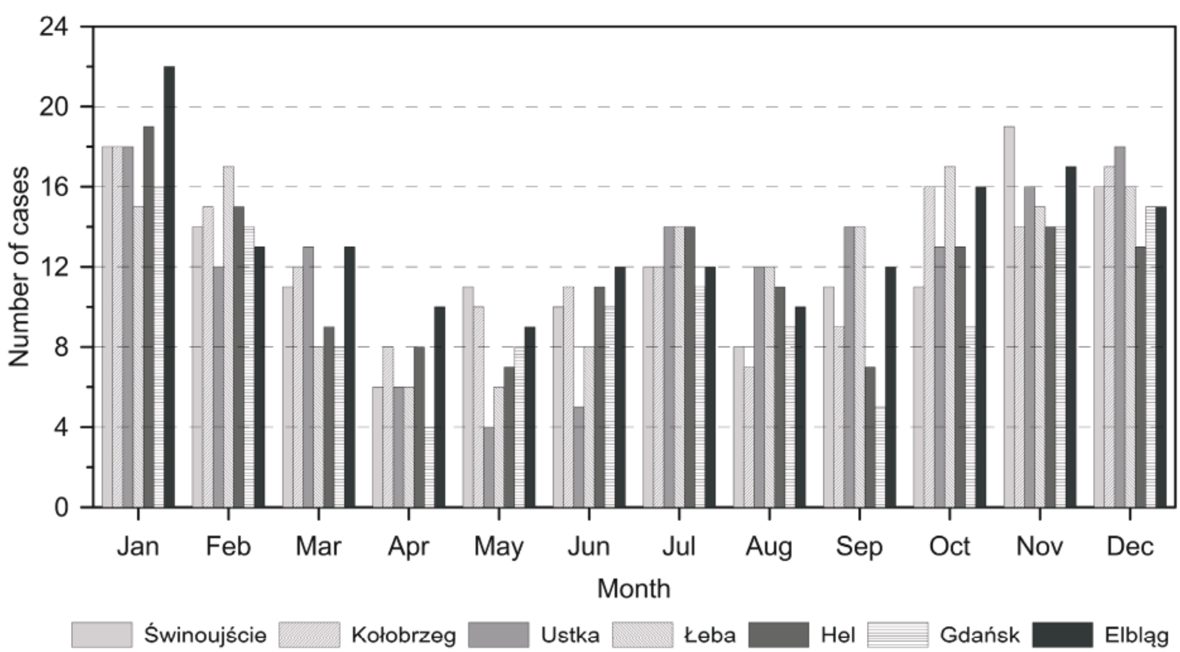

Figure 7

The annual course of the monthly number of widespread precipitation events on the Polish coast of the Baltic Sea, cumulative values for the period 2001-2014

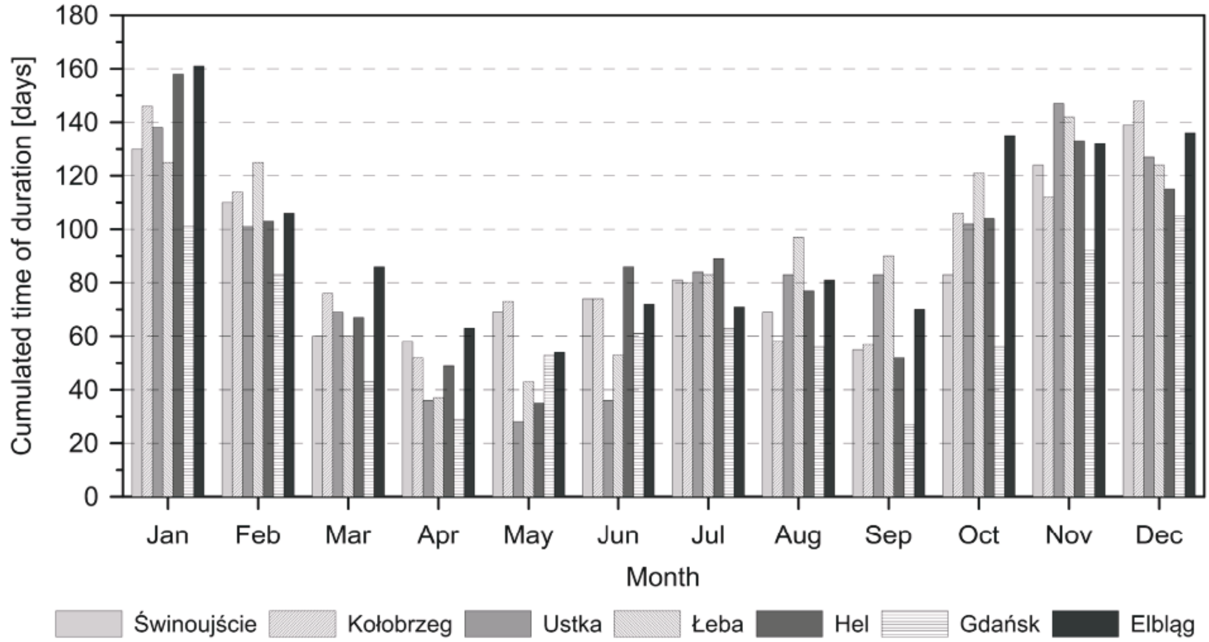

Figure 8

The annual course of the monthly duration of widespread precipitation on the Polish coast of the Baltic Sea, cumulative values for the period 2001-2014

during each of the above-mentioned months. In the cases of Ustka and Łeba, the total duration of these phenomena in November was higher than the value calculated for January. The smallest value of the index was determined in April and May.

Besselaar van der et al. (2013) and Łupikasza et al. (2010) found that the positive trends in the widespread precipitation amounts may be expected in Northern Europe. The widespread precipitation events are not only more common in the cold season, but their average duration is also longer than in the warm season, and the highest probability of these events is in winter and spring. The risk of local flood associated with the risk of widespread precipitation in Poland was highlighted by Lorenc and Olecka (2006). According to the results of their analysis, the coastal stations were characterized by positive trends in such events in 1971-2002, however, the tendency considerably declined after 1990. Malinowska and Filipiak (2009) analyzed the temporal variability in widespread precipitation events of totals exceeding 50 mm in the period 1951-2008 at the coast of the Gulf of Gdańsk (at the stations in Gdynia and Gdańsk-Świbno). Although such rainfalls may occur even every 2 or 3 years in this region, the positive tendencies are not statistically significant.

Extreme events related to air temperature

Spatial distribution of the mean annual number of the 0°C threshold-crossings on the Polish coast significantly varies. In the western part of the coast, more than 50 crossings per year have been observed in the 21st century (52 in Świnoujście and 57 in Kołobrzeg), less in the eastern part, e.g. on average 48 (Gdańsk), and even less in Hel. At the coldest stations of the coast – Elbląg and Łeba, daily air temperature exceeds the freezing point almost 60 times per year. The number of frost days has been systematically decreasing at the selected stations during the analyzed period (Fig. 9).

The annual number of FD corresponds with the occurrence of cold months (Fig. 10). Generally, the season of frost days begins in October. In September, the frost days occur only at the most eastward station. The last crossings of the 0°C threshold on the Polish coast are recorded in May. February and March are the months with the highest mean monthly number of frost days, ranging from 11 to 14 at particular stations. In December and January, such days are less frequent than in the 2 above-mentioned months.

The systematic decrease in the mean annual number of the 0°C threshold-crossings observed in the 21st century on the Polish coast can be considered as a continuation of the negative, statistically significant trend in the number of frost days, observed on the coast of the Gulf of Gdańsk in 1951-1998 by Miętus &

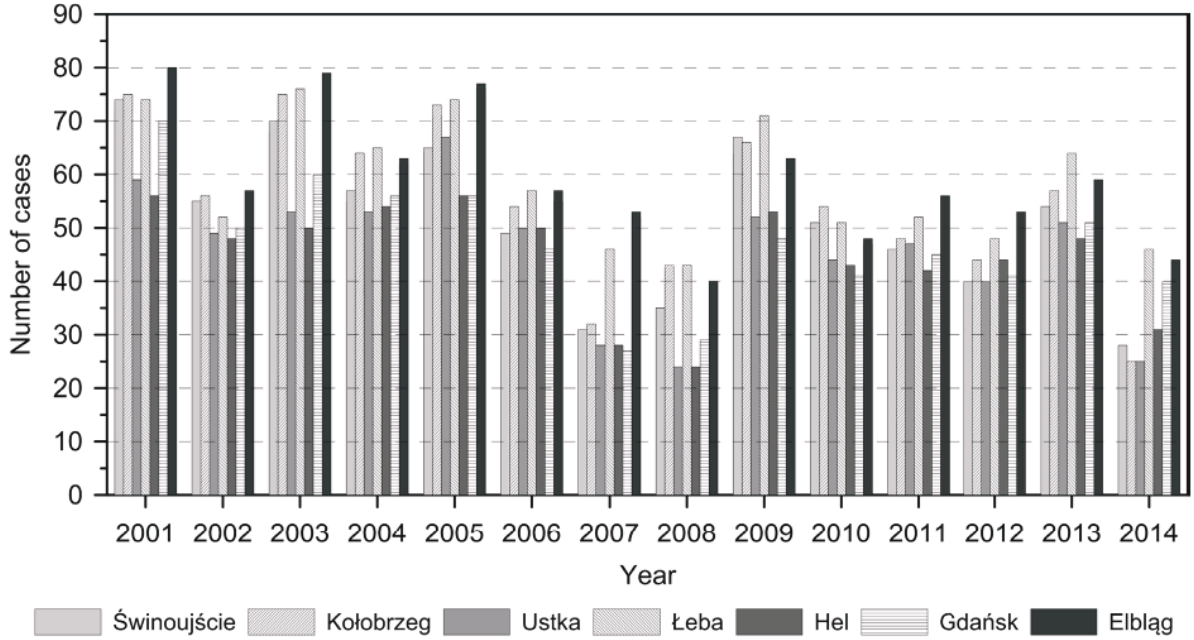

Figure 9

The annual number of instances when the threshold value of 0°C (frost days) was exceeded on the Polish coast of the Baltic Sea, 2001-2014

Filipiak (2004a) and corresponds well with the negative trend identified by Owczarek & Filipiak (2015) in Hel and Ustka in 1951-2015. During the analyzed 60 years, this drop was more than 20 days per year at these 2 stations. The crossing events were less numerous in the late 1950s, the mid-1970s and at the turn of the 1990s. Their number was relatively large in the early 1950s and increased again in the mid-1960s, in the early 1980s and in the late 1990s. The first decade of the 21st century is characterized by a considerable

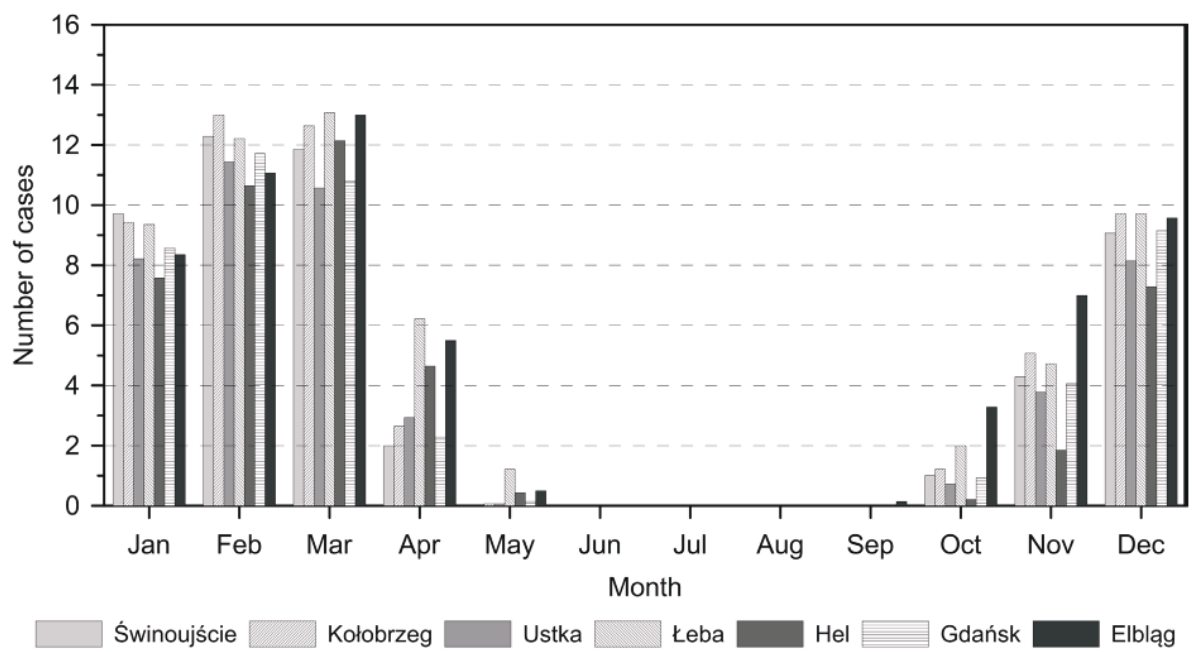

Figure 10

The annual course of the mean monthly number of frost days on the Polish coast of the Baltic Sea, 2001-2014 decrease in the number of crossing events in comparison with the previous decades.

The incidence of sea ice on the Polish coast of the Baltic Sea greatly varies; it is clearly lower in the eastern part than in the western part of the coast (Table 1). The process of ice formation depends mainly on the location of the observational station. The ice cover is intensively formed in the shallow, sheltered estuary sections of the rivers, while the number of days with ice phenomena is considerably lower in the open sea waters – they are usually free of ice. The ice cover in the open sea waters was observed only in cold winters of the 2009-2012 period. According to Girjatowicz (2011), the intensity of ice phenomena in shallow sheltered lagoons and estuaries usually increases eastward following the severity of ice conditions and can be enhanced by river water and ice discharges. The formation of ice in the areas of open sea waters increases westward and is primarily affected by bathymetric factors. The number of days with ice cover in the vicinity of deep waters is very small, as exemplified by the open sea waters observed in Hel. In particular, the Deep of Gdańsk, located east and north-east of Hel was never covered with ice in the analyzed period. The number of days with the drifting ice cover in relation to the total number of days with ice is usually significant, which may have a negative effect on the coastal zone and river estuaries.

The less frequent occurrence of sea ice on the Polish coast of the Baltic Sea is consistent with the multi-annual changes in the development of ice phenomena reported by many scientists. Jevrejeva et al. (2004) studied the evolution of ice seasons in the Baltic Sea during the 20th century and determined a statistically significant declining trend in the probability of ice occurrence in the southern part of the Baltic Sea. The associated reduction in the duration of the ice season and the positive trends toward earlier breakup of ice are associated with the increasing air temperature in winter observed throughout Europe. Sztobryn et al. (2012b) confirmed that the Polish coast of the Baltic Sea experiences a strong decrease in the number of days with ice cover in the second half of the 20th century and the first decade of the 21st century. The highest rate of this decrease has been observed in Świnoujście and Gdańsk and to a lesser extent in Ustka and Kołobrzeg, whereas changes in Hel are least evident. Not only the number of days with ice decreases, but also the occurrence of sea ice changes. In the mid-20th century, the ice cover occurred every year. In the first decade of the current century, the coastal area without sea ice was a common wintertime situation. The predicted impact of climate change on the ice cover development in the southern Baltic Sea (Sztobryn 2012) indicates that a significant reduction in the sea ice cover can be expected by the end of the 21st century. It should be noted, however, that extremely severe winters with an extensive ice cover might still occur.

Extreme events related to wind

The annual value of the N_{p980} index in Hel does not exceed 3 cases per year. In the first 14 years

Table 1

The number of days with ice (including floating ice given in parentheses) on the Polish coast of the Baltic Sea during winter seasons 2000/2001-2013/2014

Winter season	Świnoujście		Ustka		Hel	
	Świna estuary	Open sea	Słupia estuary	Open sea	Open sea	Gulf of Gdańsk
2000/2001	16 (16)	0 (0)	6 (6)	0 (0)	0 (0)	0 (0)
2001/2002	16 (16)	0 (0)	5 (5)	0 (0)	0 (0)	0 (0)
2002/2003	59 (59)	0 (0)	35 (32)	0 (0)	0 (0)	0 (0)
2003/2004	18 (15)	0 (0)	18 (16)	0 (0)	0 (0)	0 (0)
2004/2005	7 (5)	0 (0)	7 (2)	0 (0)	0 (0)	0 (0)
2005/2006	51 (45)	8 (7)	29 (25)	9 (9)	0 (0)	8 (6)
2006/2007	0 (0)	0 (0)	2 (2)	0 (0)	0 (0)	0 (0)
2007/2008	12 (11)	0 (0)	3 (3)	0 (0)	0 (0)	0 (0)
2008/2009	30 (29)	0 (0)	6 (6)	0 (0)	0 (0)	0 (0)
2009/2010	67 (55)	40 (31)	48 (41)	8 (2)	0 (0)	0 (0)
2010/2011	62 (37)	15 (13)	46 (39)	15 (15)	0 (0)	25 (14)
2011/2012	20 (13)	12 (10)	24 (22)	1 (1)	0 (0)	1 (1)
2012/2013	31 (31)	2 (2)	29 (27)	0 (0)	0 (0)	0 (0)
2013/2014	23 (23)	9 (9)	14 (14)	0 (0)	0 (0)	0 (0)
Total	**396 (339)**	**86 (72)**	**266 (234)**	**33 (25)**	**0 (0)**	**34 (21)**
Average	**30.5 (20.3)**	**6.6 (5.5)**	**20.5 (17.5)**	**2.5 (1.9)**	**0.0 (0.0)**	**2.6 (1.6)**

of the present century, 15 deep cyclones below 980 hPa were observed on the Polish coast (Fig. 11a), usually in December and January (Fig. 11b). In 2002, 2003, 2006, 2009 and 2014, no deep cyclones occurred, whereas in 2005 and 2010, 3 such phenomena were observed. The amount of intense cyclones measured with the $\Delta p/\Delta t$ index in the analyzed period reached the maximum number of 7 per year in 2012 (Fig. 11a). The situation was dynamic in 2007 and 2010 when 6 cyclones were observed. No intense cyclone was observed on the Polish coast in 2009, and only 2 cyclones occurred over the southern Baltic Sea in 2010 and 2014. At the remaining situations, from 3 to 6 intense cyclones were noted. In total, 9 intense cyclones struck the analyzed coast in January, 6 cyclones in December and February and 5 in November. In the remaining months, the coast was hardly exposed to this threat (Fig. 11b).

Because the intra-annual 1st percentile of the pressure dataset index (P_{1p}) is related to the core pressure of the cyclone, it is clear that P_{1p} indicates a reduction in the storm intensity in parallel with an increase in the N_{p980} value, and the other way around (Fig. 11a). In the annual cycle of P_{1p}, the season of intense storms is limited to the period from November to March (Fig. 11b), which corresponds with the occurrence of deep cyclones indicated by the monthly values of N_{p980}. However, the cases of intense cyclones characterized by some considerable pressure tendencies can be observed in October as often as in March.

Although some noticeable year-to-year variations in the number and magnitude of cyclones occurred in the 21st century on the Polish coast of the Baltic Sea, the intensity of the cyclonic activity analyzed in the present paper does not deviate significantly from the trends observed in the previous decades and centuries. Bärring and Fortuniak (2009) who analyzed the cyclonic activity in the region of southern Scandinavia found no significant overall long-term trend in the cyclone activity in the North Atlantic and the European region since the beginning of the 19th century. The only positive trend was found in the second half of the 20th century, however, both the decline in the cyclonic activity observed in the 1960s and its peak in the 1990s were within the long-term variability. In the 21st century, a decrease in the activity of cyclones can be observed again. Miętus et al. (2005) reported the lack of any statistically significant changes in the value of the P_{1p} index in Hel in the second half of the 20th century, however, the annual number of pressure tendencies exceeding the threshold of 6 hPa in 3 hours reached 10 cases or more in certain seasons.

The annual amount of gale days in Ustka was almost 8 cases and this number varied between 3 in 2013 and 13 in 2007 (Fig. 12a). In 5 cases, the annual number of gale days was at least 10. The mean annual wind speed in Ustka oscillates between 5 and 6 m s^{-1} (Fig. 12a), however, its direct impact on the number of gales is not obvious. In 2002 and 2013, the mean annual wind speed was 5 m s^{-1}, and there were 10 storm days in 2002 and 3 storm days in 2013. Gales are characteristic of the cold season (Fig. 12b) as the total number of gales in the October-March period is considerably greater than during the warm months. Gales occur most often in January – 20 gale days were recorded during this month in the analyzed period,

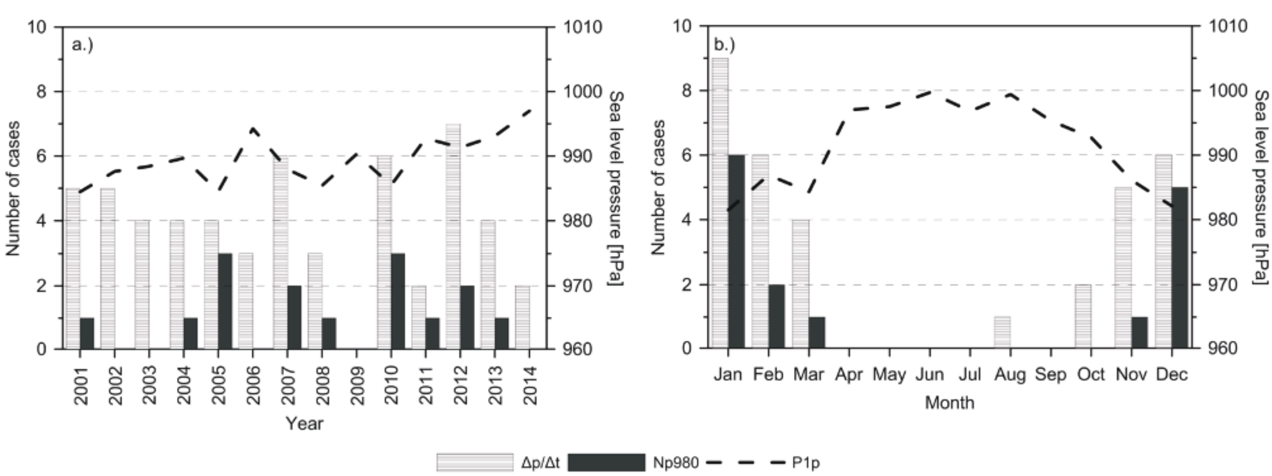

Figure 11

The annual number (a) and annual course (b) of deep cyclones in Hel, 2001-2014, measured with the selected indices. Abbreviations explained in Section 2

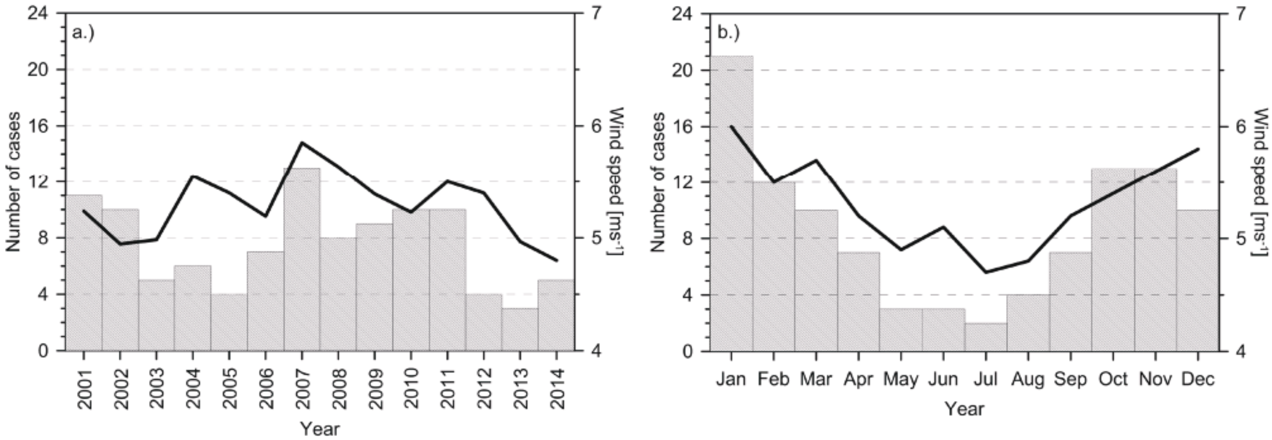

Figure 12

The annual number (a) and the annual course of gale days (b) (bars) and mean annual (a) and monthly (b) wind speed (solid line) in Ustka, 2001-2014

which means that almost 2 gales occur in January every year. In total, eleven gale days were observed in October and November and 10 days in February in the analyzed period.

Wind speed of a particular gale on the Polish coast of the Baltic Sea may reach 20-25 m s^{-1}. The highest wind speed recorded on the Polish coast during the last 60 years occurred in Ustka during the autumn storm 27/28 Sept. 1957 and was 30 m s^{-1}. Wind speed over the Baltic Sea is probably even higher than that recorded at land stations due to smaller roughness over the sea. Analysis of the meteorological data results in the conclusion that the force of a particular gale in the southern Baltic Sea reached 10 on the Beaufort scale (> 24 m s^{-1}). However, there is an uncertainty related to the lack of meteorological observations at sea carried out under such harsh weather conditions (Międus et al. 2004b, modified).

The prevailing wind directions observed at the beginning of the 21st century on the southern coast of the Baltic Sea were W, SW and S (Fig. 13 presents the wind chart for Ustka); total frequency of winds from the above-mentioned 3 directions exceeded 50% at all analyzed synoptic weather stations. However, the greatest threat to the coast accompanying the storm surges occurs with north-westerly, northerly and north-easterly winds. Such wind directions are on average recorded with a frequency of 25-30% in total, but the annual frequency of strong winds (with the speed exceeding 10 m s^{-1}) blowing from these directions does not exceed 10% of the total number of observations. The highest annual frequency of strong winds is observed in Ustka and Łeba. The analysis of wind charts for particular stations on the Polish coast reveals that the greatest threat to the coast occurs at the stations in Ustka and Gdańsk (due to strong, northerly winds).

The largest number of storm surges was observed in 2007; the maximum number of 10 in Świnoujście, while only 2 such cases were observed in the same location in 2009 (Fig. 14a). In Ustka, such events were less frequent – approximately 7 cases were observed in 2007 and 2012, whereas in 2009 and 2010, the warning sea level was exceeded only once. In Hel, 10 cases were recorded in 2012 and no storm surges occurred in 2011. During the periods of 2004-2006 and 2009-2010, the frequency of storm surges was smaller, whereas in 2001-2002, 2007-2008 and 2012, their number was

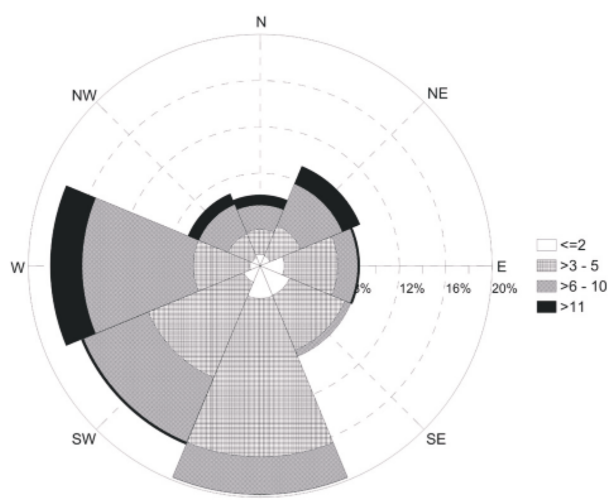

Figure 13

Mean annual frequency [%] of wind directions in the following classes: 0-2, 3-5, 6-10 and > 10 m s^{-1} in Ustka, 2001-2014

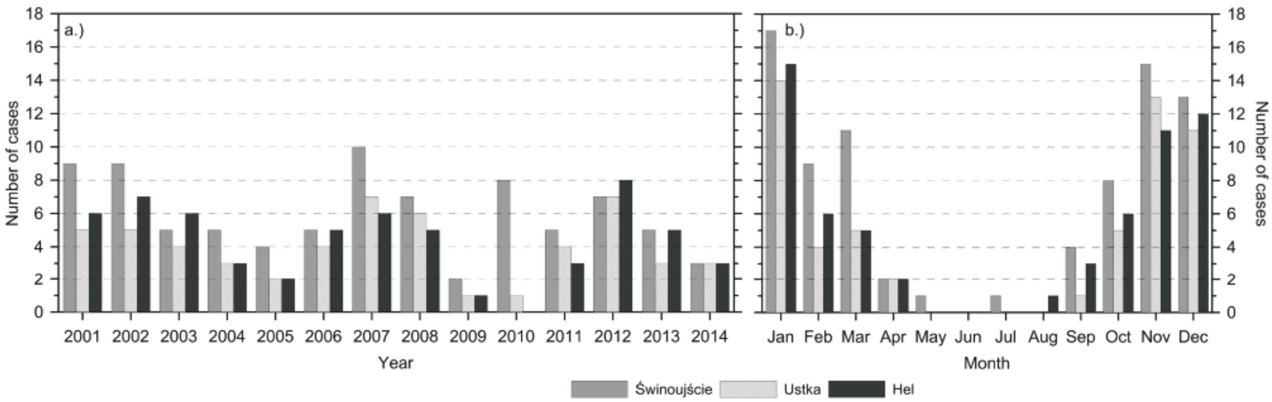

Figure 14

The annual (a) and monthly (b) total number of storm surges on the Polish coast of the Baltic Sea, 2001-2014

much higher. In January, November and December, the Polish coast was greatly exposed to this threat (Fig. 14b). In January, a total of 17 storm surges were recorded in Świnoujście, 15 in Hel and 14 in Ustka. In November and December, the number of storm surges observed at the analyzed stations was only slightly lower.

Marosz (2010) identified a statistically significant positive trend regarding the occurrence of storm surges in Gdańsk in 1987-2006. Kowalska et al. (2012) demonstrated only small positive trends concerning the number of cases when the sea level exceeded the warning threshold in Świnoujście and Hel in 1955-2008. The number of storm surges increased particularly rapidly in both locations in 1971-1990, which was confirmed by the results presented by Bärring and Fortuniak (2009). Weisse and Weidemann (2015) who reconstructed the western Baltic Sea levels from 1948 to 2012 found that storm surge climate showed considerable year-to-year and decadal fluctuations but could not determine any substantial long-term trends over the analyzed period. However, the phenomenon of a systematic sea level rise poses a potential threat to the coast. This means that a storm surge may result from a systematically rising mean sea level (Miętus 1999).

Not only the sea level increases during storms, but also the wave height as a derivative of wind speed may significantly increase. Storm waves affect the sea material transport and are troublesome for the navigation and harbors. In the shore zone, the waves may undercut the cliffs and destroy the sea defences and hydrotechnical installations. Using the 5-year hindcast data set of the HYPA model in its shallow-water version (Gayer et al. 1995), Miętus et al. (2002, 2003b, 2004c) calculated the 99th percentile of wave height at grid-points (spatial resolution of 15.875 km) in the southern Baltic Sea located, inter alia, in close proximity to the stations analyzed in this work. The 99th percentile of wave height reaches 4.6 m in Ustka and Łeba; in the case of Hel, it is 4.5 m for the open sea and 3.6 m for the Gulf of Gdańsk off the harbor entrance. In the reconstruction of the total significant wave height and corresponding wind waves and swell heights in the Proper Baltic Sea Basin in 1947-1988, Miętus and von Storch (1997) did not detect any statistically significant trends in the variability of the wave height as well as its amplitude. Comparative analysis of both the model and observational results was not possible due to the lack of sufficient long-term systematic observations of waves on the southern Baltic Sea. The visual observations of the wave height were finished by IMGW-PIB in the 1990s.

Over 130 long-lasting strong winds were recorded in the period from 2001 to 2014 on the Polish coast of the Baltic Sea; such winds blew for less than 5% of the total time in the analyzed period. The most frequent events occurred in 2007 and 2002, when 17 and 15 cases of long-lasting winds were observed respectively (Fig. 15). Eighteen events out of the total number of the analyzed cases were the strongest ones, lasting continuously for at least 24 hours, and the middle strip of the coast was the place where such events occurred most frequently. No more than 2 cases occurred per year and in 2012 none of these phenomena was recorded. The longest of the observed extreme events lasted 2 days and occurred in December 2012 in Ustka and Łeba. In annual terms, such events occur most frequently between October and April, with the maximum observed in January and February. The low temperatures may enhance the destructive activity of such winds (Borówka 1980, 2001). The long-lasting strong winds were not recorded in summer months.

In 1961-1990, Jania & Zwoliński (2011) reported

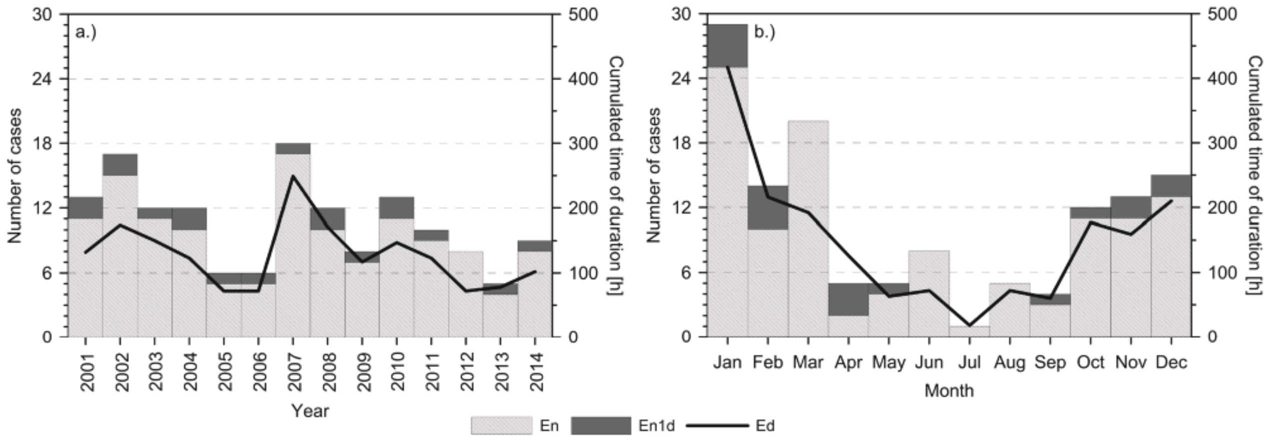

Figure 15

The annual (a) and monthly (b) total number (bars) and cumulative duration (solid line) of long-lasting strong wind events on the Polish coast of the Baltic Sea, 2001-2014. Abbreviations explained in Section 2.

24 very strong long-lasting wind events in Świnoujście and only 6 events in Kołobrzeg. The dates of the strongest events recorded in each location did not overlap. Several strong eolian events were observed on the coast in the 1980s. As there are no data on the intensity of eolian transport in 2001-2014, it is not possible to refer the obtained results to the long-term variations of the analyzed parameter. Assuming that each of the strong long-lasting wind events identified in the 21st century could contribute to the sand material transportation, it seems that the intensity of the phenomenon does not change much. It appears that mostly the western and central parts of the Polish coast are exposed to this threat.

Discussion and conclusions

The variability in many elements analyzed in this paper is consistent with long-term trends in these parameters observed in the second half of the 20th century. The variability of frost days coincides with a determined statistically significant negative trend (Owczarek & Filipiak 2016), coherent with the warming trend in winter and spring air temperature in Poland (Biernacik et al. 2010). We found that the rare occurrence of the sea ice phenomena in the 2001-2014 period is a continuation of a significant reduction in the sea ice cover observed at the coasts of the southern Baltic Sea in the 20th century (Jevrejeva et al. 2004). However, some clear interannual variations in the number and magnitude of cyclones occurred in the 2001-2014 period, e.g. intensification of cyclonic activity observed in particular years, as well as its reduction. The obtained results correspond well with the overall long-term insignificant changes in the cyclone activity in the North Atlantic and the European region since the beginning of the 19th century (Bärring & Fortuniak 2009). The number of storm surges and their considerable year-to-year variability in the analyzed area are consistent with the results obtained by Kowalska et al. (2012). Our results confirm a slow increase in the number of threshold warning value crossings by the sea level in Świnoujście and Hel observed since 1955.

The frequency of extreme precipitation events such as intense and widespread precipitation totals is consistent with the number of phenomena observed in the study area since the mid-20th century (Koźmiński & Michalska 2004, Lorenc & Olecka 2006, Malinowska & Filipiak 2009). However, the coastal stations were characterized by the positive trends in extreme precipitation events in the short periods of the 20th century; after 1990, these tendencies were considerably reduced. As the amount of water vapor in the atmosphere is increasing, any decrease in the heavy precipitation events should not be expected. Besselaar van der et al. (2013) reported that summer fluctuations in precipitation may occur, particularly those related to the torrential rains affecting economies and landforms and causing floods, but they are substantially weaker than in the other seasons, especially in winter and spring. The same authors have found that positive trends in the widespread precipitation amounts may be expected in Northern Europe.

The storms caused and manifested by an extreme wind speed, wave action and a high sea level, understood as characteristic features of deep and intense cyclones, are potentially the greatest threat to the coast. The most frequent storms occur in the cold months of the year and they are related to the amplification of a positive phase of the North Atlantic Oscillation (NAO). NAO is the most recognized mode of variability in the atmospheric circulation over the North Atlantic and the European region. In the positive mode, the subtropical high over the Azores is stronger than usual, because there is an area of low pressure near Iceland, which supports the strong westerly flow of moist, mild air and polar maritime air from the Atlantic Ocean over Europe. All wind-driven processes and effects are associated with the increased cyclonic activity over Northern and Central Europe. The particularly intense westerly circulation was caused by a long-term positive phase of NAO identified in the 1990s. In the first decade of the 20th century, however, a number of extremely strong negative incidents of the NAO phase occurred.

Because NAO significantly affects the air temperature and ice conditions over the Polish coast, the decreasing number of cold days, in particular the shortage of ice phenomena may also be associated with this mode of variability in the regional circulation. During the periods of warming and strong winds associated with the intensification of cyclonic activity, the shores exposed to such winds are susceptible to destructive effects of ice fields (Girjatowicz 2014). Due to the fact that frost days associated with exceeding the threshold of 0°C by the daily minima are more frequent in March and February than in December and January, it seems that the change in the probability distribution of air temperature directly related to the general regional warming in winter and spring air temperature predominates over the simple effects of the NAO positive phase (Miętus & Filipiak 2004a).

Precipitation events seem to have the secondary importance to the coastal environmental processes. The intensive rainfalls occurring in late spring and summer may exceed the infiltration capacity of soil and form a rapid runoff, which in turn may wear out the entire soil layer. However, their effect on the stability of steep slopes seems to be limited in the coastal region. On the other hand, precipitation in the widespread form associated with the deep cyclones may constitute a much more serious factor negatively affecting the ground stability.

Based on the above discussion, it is evident that extreme weather events occurring in winter seasons pose the greatest threat to the coast. Of all the studied elements, the phenomena related to the passage of deep and intense cyclones – extreme winds, storm surges and waves play the most important role in the coastal processes. The comparison of the indices studied in the paper with the long-term values of the parameters allows the identification of the process of a systematic increase in the occurrence of this most dangerous phenomenon in the first years of the 20th century. The long-term variations of other elements, less significant for the coast, do not reveal any increasing threat.

Acknowledgements

Janusz Filipiak was supported by the Polish National Science Centre, grant no. 2012/07/B/ST10/04214.

References

BACC II Author Team. (2015). Second Assessment of Climate Change for the Baltic Sea Basin. Springer Open.

Bärring, L. & Fortuniak, K. (2009). Multi-indices analysis of southern Scandinavian storminess 1780–2005 and links to interdecadal variations in the NW Europe–North Sea region. *Int. J. Climatol.* 29(3): 373-384. DOI: 10.1002/joc.1842.

Besselaar van der, E.J.M., Klein Tank, A.M.G. & Buishand, T.A. (2013). Trends in European precipitation extremes over 1951–2010. *Int. J. Climatol.* 33(12): 2682-2689. DOI: 10.1002/joc.3619.

Biernacik, D., Filipiak, J., Miętus, M. & Wójcik, R. (2010). Zmienność warunków termicznych w Polsce po roku 1951. Rezultaty projektu KLIMAT In: E. Bednorz & L. Kolendowicz (Eds.), *Klimat Polski na tle klimatu Europy. Zmiany i ich konsekwencje* (pp. 9-21). Poznań: Bogucki Wydawnictwo Naukowe, Studia i Prace z Geografii i Geologii, 16 (In Polish).

Borówka, R.K. (1980). Współczesne procesy transportu i sedymentacji piasków eolicznych oraz ich uwarunkowania i skutki na obszarze wydm nadmorskich. Poznań: Poznańskie Towarzystwo Przyjaciół Nauk, Prace Komisji Geogr-Geol. Pozn. Tow. Przyj. Nauk, 20 1-126 (In Polish).

Borówka, R.K. (2001). Natężenie transportu eolicznego i jego uwarunkowania na obszarze wydma nadmorskich Mierzei Łebskiej In: K. Rotnicki (Ed.), *Przemiany środowiska geograficznego nizin nadmorskich południowego Bałtyku w vistulianie i holocenie* (pp. 95-99). Poznań: Bogucki Wydawnictwo Naukowe (In Polish).

Gayer, G., Gunther, H. & Winkel, N. (1995). Wave climatology and extreme value analysis for the Baltic Sea area off the Warneműnde harbour entrance, *Deutsche Hydrographische Zeitschrift* 47(2): 109-130. DOI: 10.1007/BF02732014.

Girjatowicz, J.P. (2011). Ice Conditions on the Southern Baltic Sea Coast. *J. Cold Regions Eng.* 25 (1): 1-15. DOI: 10.1061/(ASCE)CR.1943-5495.0000020.

Girjatowicz, J.P. (2014). Ice Thrusting and Hummocking on the Shores of the Southern Baltic Sea's Coastal Lagoons.

Journal of Coastal Research 30 (3): 456-464. DOI: 10.2112/JCOASTRES-D-12-00032.

IPCC. (2012). Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change [Field, C.B., Barros, V., Stocker, T.F., Qin, D., Dokken, D.J., Ebi, K.L., Mastrandrea, M.D., Mach, K.J., Plattner, G.-K., Allen, S.K., Tignor, M. & Midgley, P.M. (Eds.)]. Cambridge: Cambridge University Press.

Jania, J.A. & Zwoliński, Z. (2011). Ekstremalne zdarzenia meteorologiczne, hydrologiczne i geomorfologiczne w Polsce. *Landform Analysis* 15: 51-64 (In Polish).

Jevrejeva, S., Drabkin, V.V., Kostjukov, J., Lebedev, A.A., Leppäranta, M., Mironov, Ye.U., Schmelzer, N. & Sztobryn, M. (2004). Baltic Sea ice seasons in the twentieth century. *Clim. Res.* 25: 217-227. DOI: 10.3354/cr025217.

Jones, P.D., 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. DOI: 10.1002/(SICI)1097-0088(19971115)17:13<1433::AID-JOC203>3.0.CO;2-P.

Klein Tank, A.M.G., Zwiers, F.W. & Zhang, X. (2009). Guidelines on analysis of extremes in a changing climate in support of informed decisions for adaptation. Geneva: WMO. (WMO-TD No. 1500).

Kowalska, B., Sztobryn, M., Stanisławczyk, I., Letkiewicz, B., Kańska, A. & Krzysztofik, K. (2012). Ocena długoterminowych zmian występowania charakterystycznych poziomów morza wzdłuż polskiego wybrzeża. In: J. Wibig & E. Jakusik (Eds.), *Warunki klimatyczne i oceanograficzne w Polsce i na Bałtyku Południowym* (pp. 170-188). Warszawa: IMGW-PIB (In Polish).

Koźmiński, C. & Michalska, B. (2004). *Atlas zasobów i zagrożeń klimatycznych Pomorza*. Szczecin: Akademia Rolnicza w Szczecinie (In Polish).

Lorenc, H. & Olecka, A. (2006). Tendencje występowania opadów o dużym natężeniu w Polsce. In *Współczesne problemy klimatu Polski – fakty i niepewności* (pp. 23-36). Warszawa: IMGW (In Polish).

Lorenc, H., Cebulak, E., Głowicki, B. & Kowalewski, M. (2012). Struktura występowania intensywnych opadów deszczu powodujących zagrożenie dla społeczeństwa, środowiska i gospodarki Polski. In H. Lorenc (Ed.), *Klęski żywiołowe a bezpieczeństwo wewnętrzne kraju* (pp. 7-32). Warszawa: IMGW-PIB (In Polish).

Łupikasza, E., Hänsel, S. & Matschullat, J. (2010). Regional and seasonal variability of extreme precipitation trends in southern Poland and central-eastern Germany 1951–2006. *Int. J. Climatol.* 31(15): 2249-2271. DOI: 10.1002/joc.2229.

Majewski, A., Dziadziuszko, Z. & Wiśniewska, A. (1983). *Monografia powodzi sztormowych 1951-1975. Ogólna charakterystyka powodzi sztormowych u polskiego wybrzeża Bałtyku.* Warszawa: WKiŁ (In Polish).

Malinowska, M. & Filipiak, J. (2009). Opady ekstremalne w zlewniach Trójmiasta. In R. Bogdanowicz & J. Fac-Beneda (Eds.), *Zasoby i ochrona wód. Obieg wody i materii w zlewniach rzecznych*. (pp. 342-352). Gdańsk: FRUG (In Polish).

Marosz, K. (2010). Wezbrania sztormowe w rejonie Gdańska w latach 1987-2006. In T. Ciupa & R. Suligowski (Eds.). *Woda w badaniach geograficznych*. (pp. 75-80) Kielce: UJK (In Polish).

Miętus, M. (1999). *Rola regionalnej cyrkulacji atmosferycznej w kształtowaniu warunków klimatycznych i oceanograficznych w polskiej strefie brzegowej Morza Bałtyckiego*. Materiały Badawcze IMGW Seria Meteorologia (29), Warszawa: IMGW (In Polish).

Miętus, M. & Storch von, H. (1997). *Reconstruction of wave climate in the Proper Baltic Basin*. Geesthacht: GKSS. (External Report 97/E/28)

Miętus, M., Filipiak, J., Owczarek, M., Sztobryn, M. & Krzymiński, W. (2002). Statistical characteristics of hydrological and meteorological conditions of Polish harbours, Gdynia, Gdańsk i Świnoujście, 1971-2000. Gdynia: IMGW (CD-Rom).

Miętus, M., Filipiak, J. & Owczarek, M. (2003a). Czasowo-przestrzenna struktura opadów w rejonie Zatoki Gdańskiej i jej możliwe zmiany w skali XXI wieku. In J. Cyberski (Ed.), *Powódź w Gdańsku*. (pp. 35-55). Gdańsk: GTN (In Polish).

Miętus, M., Filipiak, J., Owczarek, M., Sztobryn, M. & Krzymiński, W. (2003b). Statistical characteristics of hydrological and meteorological conditions of Polish harbours, Ustka i *Łeba*, 1971-2000. Gdynia: IMGW (CD-Rom).

Miętus, M. & Filipiak, J. (2004a). The temporal and spatial patterns of thermal conditions in the area of the southwestern coast of the Gulf of Gdansk. *Int. J. Climatol.* 24(4): 499-509

Miętus, M., Filipiak, J. & Owczarek, M. (2004b). Klimat wybrzeża Południowego Bałtyku. Stan obecny i perspektywy zmian. In J. Cyberski (Ed.), Środowisko Południowego Bałtyku w perspektywie przystąpienia Polski do Unii. (pp. 11-44.). Gdańsk: GTN (In Polish).

Miętus, M., Filipiak, J., Owczarek, M., Jakusik, E. & Sztobryn, M. (2004c). Statistical characteristics of hydrological and meteorological conditions of Polish harbours, Hel, 1971-2000. Gdynia: IMGW (CD-Rom).

Olechnowicz-Bobrowska, B. (1970). *Częstość dni z opadem w Polsce*. Warszawa: PWN (In Polish).

Owczarek, M. (2002). Wpływ warunków meteorologicznych na energetykę na przykładzie Zakładu Energetycznego Słupsk S.A. *Wiadomości IMGW* 2: 55-68 (In Polish).

Owczarek, M. & Filipiak, J. (2016). Contemporary changes of thermal conditions in Poland, 1951-2015. *Bull. of Geogr. Phys. Geogr. Ser.*, 10: 31-50. http://dx.doi.org/10.1515/bgeo-2016-0003

Ren, F., Cui, D., Gong, Z., Wang, Y., Zou, X., Li, Y., Wang, S. & Wang, X. (2012). An Objective Identification Technique for Regional Extreme Events. *J. Climate* 25(20): 7015-7027. DOI: 10.1175/JCLI-D-11-00489.1.

Sztobryn, M. & Stigge, H. (2005). *Wezbrania sztormowe wzdłuż południowego Bałtyku (zachodnia i środkowa część)*. Gdynia: IMGW (In Polish).

Sztobryn, M. (2012). Severity of sea ice in the Southern Baltic Sea, Gulf of Finland and Gulf of Bothnia up to 21st century. *Oceanology* 52(6): 741-747. DOI: 10.1134/S0001437012060069.

Sztobryn, M., Kowalska, B., Stanisławczyk, I. & Krzysztofik, K. (2012a). Wezbrania sztormowe – geneza, tendencje i skutki działania w strefie brzegowej Bałtyku. In H. Lorenc (Ed.), *Klęski żywiołowe a bezpieczeństwo wewnętrzne kraju* (pp. 195-217). Warszawa: IMGW-PIB (In Polish).

Sztobryn, M., Wójcik, R. & Miętus, M. (2012b). Występowanie zlodzenia na Bałtyku – stan obecny i spodziewane zmiany w przyszłości. In: J. Wibig & E. Jakusik (Eds.), *Warunki klimatyczne i oceanograficzne w Polsce i na Bałtyku Południowym* (pp. 189-215). Warszawa: IMGW-PIB (In Polish).

Ustrnul, Z. & Czekierda, D. (2009). *Atlas of extreme meteorological phenomena and synoptic situations in Poland*. Warszawa: IMGW.

Wang, X.L., Horsburgh, K., Swail, V.R. & Woodruff, S.W. (2014). On the Development of Marine Climate Extreme Indices. Presentation on the Fourth JCOMM Workshop on Advances of Marine Climatology (CLIMAR-4) and of the First ICOADS Value-Added Database (IVAD-1) Workshop, 9-12 June 2014, Asheville, NC, USA. Abstract presented in JCOMM Technical Report No. 79. (pp. 14-15). Geneva: WMO.

Weisse, R. & Weidemann, H. (2015). Storm surge climate in the Western Baltic Sea 1948-2012. Presentation on the 10th Baltic Sea Science Congress (Riga, Latvia). Abstract presented in Book of Abstracts, p.18.

WMO. (1988). Hydrological Aspects of Combined Effects of Storm Surges and Heavy Rainfall on River Flow. Geneva: WMO. (WMO-TD No. 704).

WMO. (2010). Guide to Meteorological Instruments and Methods of Observation. Geneva: WMO. (WMO-No.8, 9th edition updated).

WMO & UNESCO. (2012). *International Glossary of Hydrology*. Geneva: WMO. (WMO No. 385).

WMO. (2013). The Global Climate 2001-2010. A Decade of Climate Extremes. Geneva: WMO. (WMO No. 1103).