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Geographical diversity in the occurrence of extreme sea levels on the coasts of the Baltic Sea

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ABSTRACT

Fluctuating sea levels are an important element of hydrodynamic processes that occur in coastal regions. Extreme sea levels – i.e. the highest and lowest levels recorded over many years in a given year or in a given storm event – can stimulate currents, sea abrasion, and the accumulation of sedimentary material in various coastal sections. The objective of this study was to examine the geographical diversity of extreme sea levels along the entire Baltic Sea coast based on hourly sea levels from 37 tide gauges between 1960 and 2010. In this study, 8 Baltic Sea sub-basins (water regions) with similar sea level fluctuation patterns were identified using cluster analysis. Based on a quantitative analysis of the number of hours with high and low sea levels and analysing the number of storm surges and regularities in the distribution of extreme sea levels, certain geographical patterns were identified. The final stage of the study was to determine the degree of diversity of the individual sub-basins of the Baltic Sea as a function of the intensity of extreme sea levels during a year. Additionally, this classification considered the specific features of each basin, namely the exposure of coasts to the paths of dangerous cyclones, bathymetric relations, as well as the location of tide gauges relative to the open waters of the Baltic Sea. The results of the analyses indicate that the highest extreme sea levels were most intense and lasted longer in sections of great bays located farthest inland, off the northeastern and eastern coasts of the Baltic Sea – the Gulf of Finland, the Gulf of Riga, and the Bothnia Bay. Sub-basins of the Western Baltic, in particular Mecklenburg and Kiel Bays, were among the areas with the deepest negative storm surges and the most frequent low and very low sea levels. The sub-basins of the Swedish coasts of the Central and Northern Baltic were the least exposed to extreme sea levels (both high and low) and had the lowest number of storm surges per year.

1. Introduction

Currently, the Baltic Sea has many rationally-located tide gauges (about 170 mareographs along the entire Baltic coast). Due to this, the phenomena and processes involved in raising and lowering sea levels can be thoroughly characterized. Especially important are extreme sea levels which have reached their highest and lowest levels in many years, in a given year, or during a given storm event. These extremes stimulate current processes, marine abrasion, and accumulation of sedimentary material along different sections of the coastal zone. High sea levels which are usually generated under stormy conditions, often lead to catastrophic situations, such as beach erosion, as well as destruction of shore infrastructure. Storm surges may lead to flooding of low-lying areas, which are typically densely populated and may result in heavy economic losses. On the other hand, low sea levels cause significant disruptions to shipping by decreasing fairway depths at ports and at the ports' seafront. The occurrence of low sea levels can also drain coastal lagoons and lakes. The study of the characteristics of extreme sea levels generated by storm surges and negative storm surges has practical aspects and makes it possible for the maritime administration to determine warning levels, develop flood prevention services, protect coastal areas, as well as ensure the safety of shipping and operation of ports.

Contemporary literature on storm surges and extreme levels of the Baltic Sea generated by such surges is extensive and has mostly studied the coasts of individual Baltic States: Poland (Wiśniewski and Wolski, 2011), Germany (Jensen and Müller-Navara, 2008), Denmark (Hallegatte et al., 2011), Sweden (Hammarklint, 2009), Lithuania (Dailidienė et al., 2006), Estonia (Suursaar et al., 2009), and Finland (Johansson et al., 2004). Moreover, some studies covered only a part of the Baltic seashores – e.g., the western and central part of the South Baltic Sea (Sztobryn et al., 2005; Sztobryn et al., 2009), eastern Baltic

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Sea coast (Averkiev and Klevanny, 2010; Soomere and Pindsoo, 2016).

Not only the spatial scope but also the topics of research work on the extreme sea levels of the Baltic Sea are very diverse. A significant part of the articles includes statistical analyses of observation series of sea levels and storm surges of the Baltic Sea. Clustering methods for the classification of Baltic sea level time series have already been used by Scotto et al. (2009) and Barbosa et al. (2016). Probability analyses and modeling of extreme sea levels have been discussed by Kulikov and Medvedev (2017), Soomere et al. (2018) and MacPherson et al. (2019). The origins of the extreme sea levels of the Baltic Sea have been described in the articles by Wiśniewski and Wolski (2011), Weisse and Weidemann (2017) and Hieronymus et al. (2018).There are also works showing changes of the Baltic Sea level in different spatial and temporal scales (Hünicke et al., 2015; Soomere and Pindsoo, 2016; Weisse and Hünicke, 2019).

The aim of this study is to show the geographical variation in the occurrence of extreme sea levels along the entire Baltic Sea coast based on a series of long-term observations.

The occurrence of extreme sea levels, which are the result of storm surges on Baltic coasts, depends on three components (Wiśniewski and Wolski, 2011):

- the filling-up of the Baltic Sea (the initial sea level prior to the occurrence of an extreme event),
- the action of tangential wind stresses within the given area (wind directions: whether they are shore- or seaward, wind velocities, and the duration of wind action),
- the deformation of the sea surface by the mesoscale, deep low-pressure systems rapidly crossing the Baltic Sea, which generate baric waves (ground effects below the pressure system) and seichelike variations of the Baltic Sea level. The most important features of a low-pressure system that determine whether a deformation will appear are value of pressure in the center, track, and velocity.

Due to the interactions between these three factors, extremely high sea levels can occur during the positive storm surge phase (sea level rise), while extremely low levels can occur during the negative phase (sea level fall).During a storm surge, the advantage of positive sea level oscillations over low ones can be observed (Kulikov and Medvedev, 2017). Such an asymmetry is associated with the effect of decreasing atmospheric pressure during a cyclone, which always causes a rise in sea level independently of wind direction (inverse barometer effect).

Exceptionally low sea levels in the Baltic Sea also occur due to completely different mechanisms, such as eastern atmospheric circulation, during continuous and prolonged eastern and northern winds at the expanded anticyclone over Scandinavia or northwest Russia. Then, if water flows out of the Baltic Sea through the Danish Straits to the North Sea, relatively low sea levels may last up to several weeks (Suursaar et al., 2003; Sztobryn et al., 2009).

The surge in the Gulf of Finland on 19 November 1824 generated the highest recorded levels in the Baltic Sea. In the St. Petersburg area, the sea level reached 4.21 m above the tide gauge zero (Averkiev and Klevanny, 2010). The Gulf of Riga, along with the Pärnu Bay and areas at the west coast of Estonia, frequently have high sea levels (over 2 m above the zero of a tide gauge) and dangerous storm surges. This research topic is addressed in many works by Suursaar and colleagues (Suursaar, 2010; Suursaar et al., 2003, 2006a, 2006b, 2009). The largest surge off the south-western coast of the Baltic since sea levels have been recorded occurred on 13 November 1872 (Rosenhagen and Bork, 2009). In many ports on the west coast of the Baltic Sea, this surge exceeded 3 m above the tide gauge zero (Schleswig 3.49 m, Travemünde 3.30 m, Schleimünde 3.21 m) and resulted in extensive floods, large losses of shoreline, and many fatalities. Significant storm surges and extreme sea levels (1.40 m above the tide gauge zero) also occur off the Polish coast, and the shores of the shallow Pomeranian Bay, are particularly affected since surges can damage dunes and cliffs (Sztobryn et al., 2005; Wolski et al., 2014). High surges have also occurred in the northern Gulf of Bothnia (the tide gauge in Kemi indicated a maximum of 2.01 m above the gauge zero). In the rest of the Baltic Sea, storm surges are lower (Averkiev and Klevanny, 2010; Wolski et al., 2014).

Studies on the geographical distribution of extreme sea levels along the entire Baltic Sea coastline are the collective work of the co-authors of this publication (Wolski et al., 2014; Wolski et al., 2016). The following regularities have been established:

- Bay stations far from the open waters of the Baltic Sea, located in areas with relatively shallow depths (10–20 m), have significantly more extreme sea levels than stations located directly in the open waters of the Baltic Sea
- The Western Baltic (The Mecklenburg and Kiel Bays) is that part of the Baltic Sea where the greatest falls in sea level due to storm surges have been recorded (levels lower than −140 cm), which is associated with the relatively small depths
- The Swedish coasts of the Central Baltic Sea and the Northern Baltic Sea (the Baltic Proper) are the coasts least affected by extreme sea levels (eastern coast exposure). This is determined mainly by the easterly exposure of the coast, i.e. the direction opposite to that in which low pressure systems propagate.

This article is an extension of the above mentioned work Wolski et al. (2014) and, to a lesser extent, work Wolski et al. (2016). In the present publication, the study was based mainly on quantitative analyses of hourly detailed sea level data. To present the geographical differentiation of the occurrence of extreme sea levels, new research methods as cluster analysis and morphometric and bathymetric analysis of individual basins have been introduced.

2. Material and methods

2.1. Research material

Material research included hourly sea level observations from 37 tide gauges located along the Baltic Sea coasts during 1960–2010 (Fig. 2). A 51-year period was chosen as the longest possible period that could provide sea level data from national meteorological and hydrological institutes of Baltic countries (IMGW-Poland, BSH-Germany, DMI-Denmark SMHI-Sweden, FMI-Finland, EMHI-Estonia). Hourly sea level data was corrected to a single vertical datum, which is NAP (Normaal Amsterdams Peils) in the practical version of the EVRS (European Vertical Reference System) called EVRF 2000 (European Vertical Reference Frame). Although there is now a newer, practical version of the EVRS system (EVRF 2007), most of the Baltic and European states have accomplished their own data transformations using the earlier version, EVRF 2000. Basic calculations were performed using the Coordinate Reference Systems in Europe (CRS EU) using the simultaneous advisory of the relevant institutes of Baltic countries during data acquisition. The sea level data obtained from national hydrological and meteorological institutes have been already corrected for the elevation or subsidence of land. The Swedish (SMHI) and Finnish (FMI) institutes, due to strong isostatic movements in these countries, perform such correction annually in relation to the average sea level in a given year for each gauge. Details and examples of these calculations have been previously presented in another study by the authors - Wiśniewski et al. (2014) . All sea level data obtained in the current work take into account tidal heights in the Baltic Sea.

To determine the morphometric parameters of the Baltic Sea waters and to obtain the hydrological data, we used digital bathymetric data obtained from the Helsinki Commission portal (HELCOM, 2013).

2.2. Quantitative analyses of extreme sea levels and storm surges

Extreme sea levels were determined in this work for statistical analysis. They were defined on the basis of warning and alarm water levels used by hydrological services of the Baltic States during the threat of storm floods. For most of the Baltic coast, the warning level (so-called high water) was higher than 70 cm and the alarm level (very high water) exceeded 100 cm (SMHI, 2019; FMI, 2019; IMGW, 2014). Therefore, at work sea levels ≥70 cm above the NAP zero were considered as high sea levels, and levels ≥100 cm above the NAP zero were considered as very high. In addition, it was similarly determined that low levels are ≤ − 70 cm in relation to NAP, and very low levels are ≤ − 100 cm in relation to NAP. The annual average number of hours with high and low levels and the number of storm surges have been obtained by averaging the total values of these parameters for the whole period 1960–2010.

In the current work, catalogues of storm surges for the Baltic tide gauges were used, which were developed as part of a National Science Centre project (Wolski, 2011–2014).

2.3. Visualization of parameters of extreme sea levels of the Baltic Sea in the ArcGIS program

The ArcGIS program was the basic tool used to visualize the parameters of extreme sea levels in the Baltic Sea sub-basins (water regions). With it, we illustrated the distribution of maximum and minimum sea levels, the number of storm surges, and the duration in hours of extreme sea levels. The advantage of the GIS software is that it links analysed research features with their precise geographical locations. Spatial analysis was primarily based on an ArcGIS module called kriging, which is widely used and recommended for environmental research, including the creation of maps based on data interpolation (Sahebjalal, 2012). Kriging is a geostatistical method to interpolate parameter values. In a broader sense, it is used to estimate continuous surfaces (maps of expected value) by point-wise measurements of quantitative data. The weighted average over a subset of adjacent points is used to obtain a specific interpolation point using the formula (Badura et al., 2012):

$$Z^{*}(x_0) = \sum_{i=1}^{n} w_i Z(x_i) \tag{1}$$

where:

$Z^{*}(x_0)$ – interpolated value at x_0.

$Z(x_i)$ – actual value at the measurement point (sea level in the water gauging station).

w_i – kriging weight.

n – number of points considered in kriging (12 for analyses in the current paper).

The main advantage of using kriging for the spatial analyses in this paper is that isoline maps prepared with this method reveal clear trends in the differentiation of the examined parameters. There is no such effect for maps created with e.g., inverse-distance gridding, on which it is more difficult to see regularities (Badura et al., 2012).

2.4. Separation of sub-basins of the Baltic Sea

To analyse the extreme sea levels in the Baltic Sea, it is important to divide the measuring stations by geographical regions. This division is based on the location of tide gauges in relation to the Baltic open waters or gulf areas, the distance to Danish Straits (the region where the Baltic Sea meets the North Sea), or due to the tide gauges being located on the coasts exposed to the advection of western air masses and paths of very-low-pressure areas (cyclones). Additionally, the bathymetric and morphological characteristics of shallow-water zones are a differentiating element. All these factors shape the graph of the sea level for a given tide gauge, both in the short-term and long-term. Therefore, a cluster analysis (dendrogram, the Ward method) was used to identify sub-basins (water regions) of the Baltic Sea, which are characterized by a similar rhythm of sea level fluctuations. This method makes it possible to identify groups of characteristics with similar variabilities and is widely used in natural science research, especially to study the physical parameters of Baltic Sea waters (Scotto et al., 2009; Barbosa et al., 2016). This analysis consists in grouping objects into ever larger collections (clusters), using a certain measure of similarity or distance. The grouping procedure was based on the Ward method and the similarity function was calculated using the Pearson correlation method. The Ward method aims at minimizing the sum of squares of deviations of any two clusters that can be formed at each stage. The measure of this method is the error of sum of squares -SSE expressed by the formula:

$$SSE = \sum_{i=1}^{k} x_i^2 - \frac{1}{k}\left(\sum_{i=1}^{k} x_i\right)^2 \tag{2}$$

where:

k - number of units in the group.

xi - value of the variable constituting a grouping criterion characterizing the i-th unit in a group.

As a measure of distance the value of 1 - r was taken, where r is the Pearson correlation coefficient. The result of the analysis is a tree called dendrogram, which gives out clusters. The smaller the taxonomic distance between the cluster elements, the stronger the relationship between sea levels read at individual tide gauges.

The analysis used hourly sea levels between 1960 and 2010, which were measured simultaneously at all 31 stations analysed. Due to the specific nature of Danish Straits, Kattegat and Skagerrak (tides), and the temporary nature of the water region, the 6 tide gauges located in this area are considered as a separate water region (sub-basin).

Additional application of ArcGIS software in this study was to calculate the area and volume of individual Baltic basins and sub-basins using bathymetric data obtained from the portal of the Helsinki Commission (HELCOM, 2013). The tool that enabled these calculations was ArcGIS 3D Analyst and Spatial Analyst, an extension of the software.

3. Results

3.1. Sub-basins of the Baltic Sea with similar characteristics of fluctuations in sea level

The cluster analysis made it possible to observe two main characteristic tide gauge clusters (Fig. 1). The first cluster consists of tide gauges located in the western and southern regions of the Baltic Sea (stations from Wismar to Gdańsk). The second distinct cluster is a set of tide gauges that represents the entire central, north and north-eastern part of the Baltic Sea (stations from Oskarshamn to Kemi). The relationships between sea levels are strongest for tide gauges geographically closest to each other. These are most often tide gauges adjacent to a given coast, e.g., gauges located off the Swedish coast (Stockholm, Landsort, Marviken, and Visby) or of the Polish coast (Ustka, Kołobrzeg, Władysławowo, and Gdańsk). Other close relationships are also found for tide gauges located off opposite coasts of the same gulf, e.g., the Gulf of Bothnia (Spikarna, Mäntyluoto, and Vaasa), the Gulf of Finland (Hamina – Narva), Pomeranian Bay (Świnoujście – Sassnitz), or the Mecklenburg Bay (Warnemünde – Gedser) (Fig. 1). The exception is the tide gauge Pärnu. The Pärnu in Fig. 1 is closer to the tide gauges in the Gulf of Finland (Narva, Hamina) than to tide gauges that are located at a shorter geographical distance to it (Ristna, Hanko, Degerby). This is due to the bay characteristics of sea level changes on these tide gauges.

Using the above cluster analysis results and the geographical location of individual tide gauges, the paper has divided the Baltic Sea into

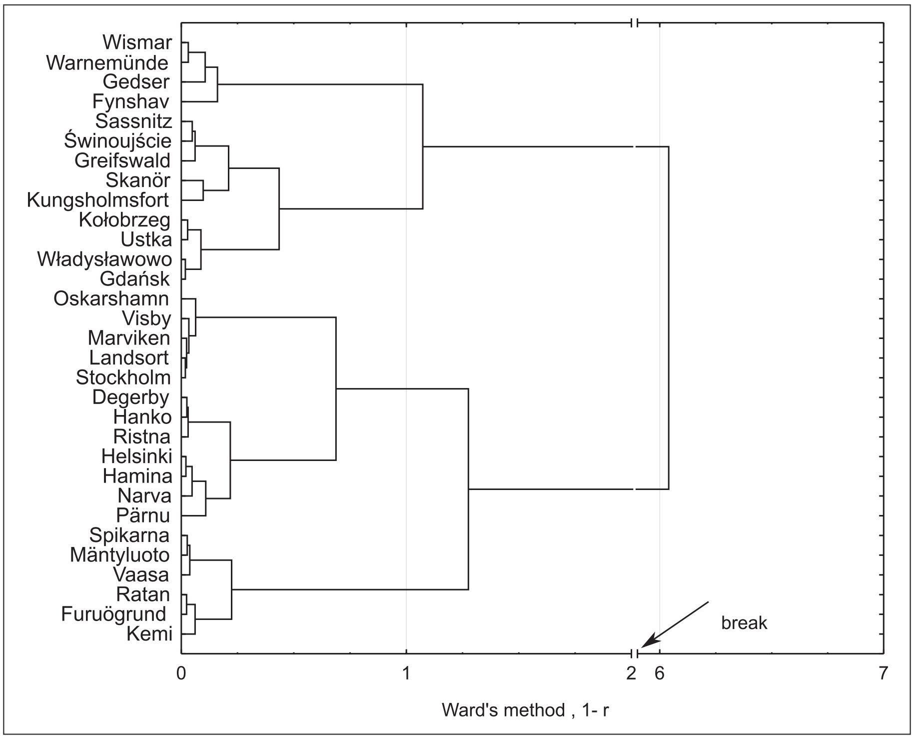

Fig. 1. Dendrogram that groups the sea levels of the Baltic Sea between 1960 and 2010 (hourly data).

eight primary sub-basins: Danish Straits with Skagerrak and Kattegat, Western Baltic, Southern Baltic, Central Baltic, Northern Baltic, Gulf of Riga, Gulf of Finland, and Gulf of Bothnia (Fig. 2). On the other hand, the term "Baltic Proper", used in the later part of this work, will refer to the "open waters" of the Baltic Sea, i.e. the waters consisting of the Southern Baltic, the Central Baltic, and the Northern Baltic.

As previously mentioned, when analysing extreme sea levels, apart from the primary meteorological and hydrological factors (atmospheric circulation, the path of a cyclone, wind activity, and water exchange), hydrographic and bathymetric characteristics of a given water region are also important. The shallow waters of the Baltic Sea (especially bays) with a small water volume during storms will fill up with water or release it faster – depending on the meteorological conditions above the given area – compared to vast and deep waters. Therefore, the basic morphometric parameters of 8 Baltic Sea sub-basins were calculated using the ArcGis software (Table 1) based on the bathymetric data from HELCOM.

3.2. Duration of occurrence and distribution of extreme sea levels of the Baltic Sea

The sub-basins with the longest duration of high sea levels are the inner parts of the following gulfs: The Gulf of Bothnia (Bothnian Bay), the Gulf of Finland, and the Gulf of Riga at Pärnu Bay. The total number of hours of high levels ≥70 cm in these areas between 1960 and 2010 ranges from 5000 to 11,000 h and the number of hours of very high levels ≥100 cm ranges from 1000 to 2000 h. Over this long-term period, only the Pärnu Bay had more hours (i.e. over 2000 h) with very high levels. The areas with the shortest duration of high levels are the Swedish coasts of the Central and Northern Baltic Sea, where the total number of hours with levels ≥70 cm did not exceed 1000 during the long-term period and levels ≥100 cm were practically absent (Fig. 3a, b).

The longest duration of low sea levels (from 2000 to 4000 h over the long-term period) occurs mainly in the Western Baltic (Mecklenburg Bay and Kiel Bay), as well as the Pärnu Bay and Bothnian Bay. The Baltic Sea off the Swedish coast and the southern Gulf of Bothnia (Bothnian Sea) are the least-threatened by low sea levels. In these water areas, the duration of low levels did not exceed 200 h between 1960 and 2010. Even lower sea levels (≤ − 100 cm) occurred mainly in the Kiel Bay and Mecklenburg Bay (ranging from 150 to 600 h over many years and in Bothnian Bay and eastern Gulf of Riga (50 to 100 h in the long-term period). There were practically no extremely low sea levels in the other Baltic Sea water regions (Fig. 3 c,d).

The above analysis indicates that the duration of both high and low sea levels depends on the location of the individual tide gauges and extends from the open waters of the Baltic Sea to the most internal parts of the large Baltic Gulfs: Bothnia, Finland, Riga as well as to the Mecklenburg Bay and Kiel Bay.

Another noticeable regularity is the very clear asymmetry during the occurrence of extreme sea levels. The duration of high levels is many times longer than low levels. This phenomenon is evident in all sub-basins of the Baltic Sea (Fig. 3a, b, c, d, Table. 2). This asymmetry results from the physical nature of the storm surge, which most often occurs with earlier filling of the Baltic Sea (increase above the average levels) and uplift of the water as a result of negative pressure under moving deep low (barometric effect). As a result, the above factors will inhibit rapid and significant drops in sea level during strong seaward winds.

The above regularities have been confirmed by the analysis of historical heights of maximum and minimum sea levels. Similarly to the duration time of occurrence, also the maximum and minimum levels increase from the open waters of the Baltic Sea to the most internal parts of the gulfs (the end of the gulf) (Fig. 4). This can be described as the so-called gulf-effect. The narrowing of the bays is one of the main reasons for this phenomenon. The defined water volume removed or added to a narrowing and shoaling part of the gulf will experience more extreme oscillation sea levels compared with its wider and deeper seaside region.

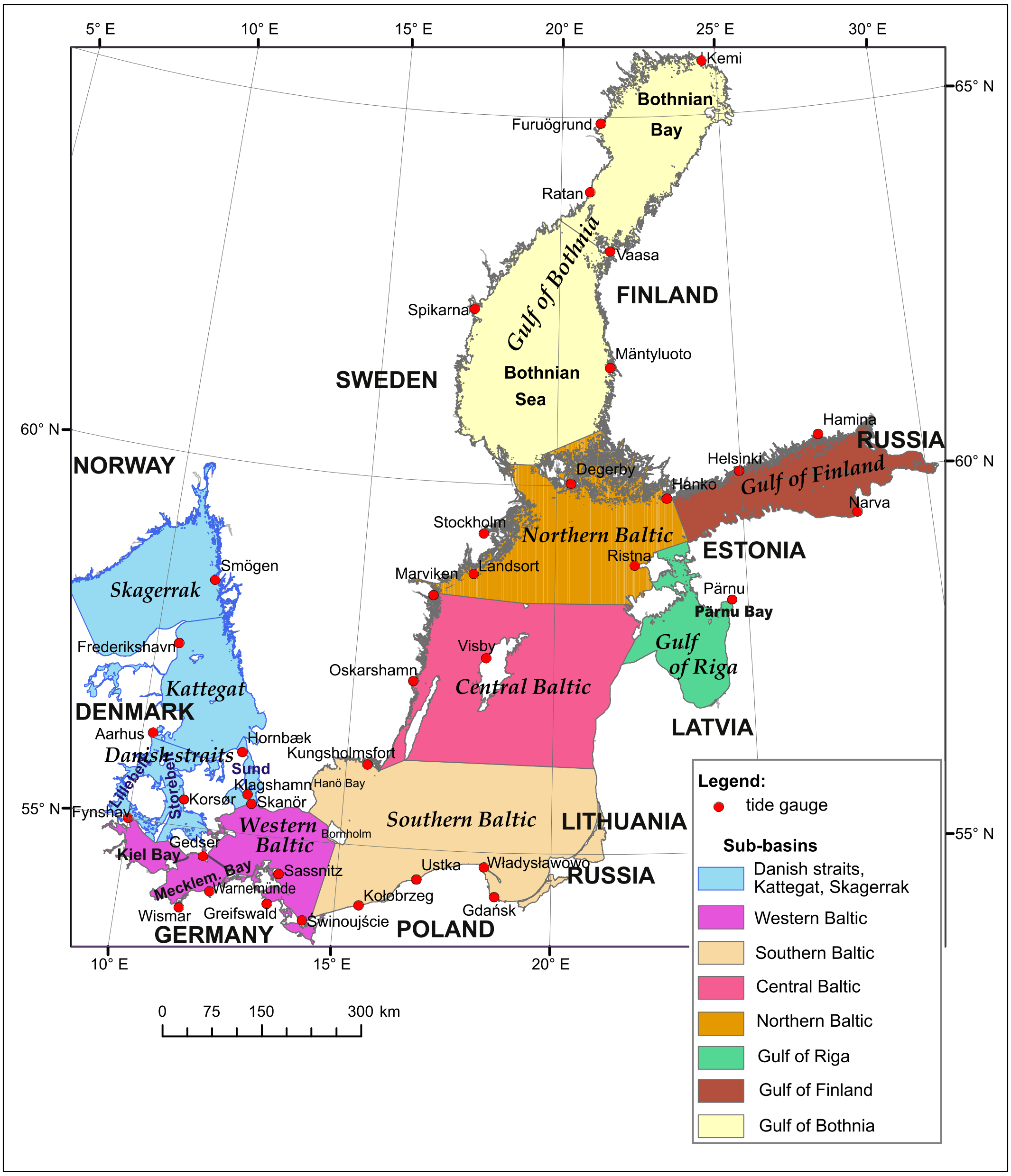

Fig. 2. Division of the Baltic Sea into eight primary sub-basins.

3.3. The degree of diversification of the Baltic Sea sub-basins due to the occurrence of extreme sea levels

The annual average number of hours with high and low levels and the annual average number of storm surges have been used to determine the degree of diversification of the Baltic Sea areas due to extreme levels (Table 2, Fig. 5–6). Additionally, maximum and minimum sea levels from 1960 to 2010 have been compared (Fig. 7). The results in Table 2 and Figs. 5-7 confirm the characteristics of the distribution of extreme sea levels from the period 1960–2010. The highest extreme sea levels were most intense and lasted the longest in the parts of bays located farthest inland, off the northeastern and eastern coasts of the Baltic Sea, i.e. the Gulf of Finland, the Gulf of Riga, and the Gulf of Bothnia. Tide gauges in these water areas (Pärnu Kemi, Narva, and Hamina) are located near the rightmost edge of the graph, where the highest values occur (Fig. 5-7). The waters area of the Western Baltic, in particular the Mecklenburg and Kiel Bays, are among the areas with the lowest negative storm surges and the most frequent low and very low sea levels. This can be clearly seen from the data in Fig. 6, where the tide gauges Wismar and Fynshav (the upper edge of the graph) indicate the most frequent negative annual sea level. The Swedish coasts of the Central and Northern Baltic are the least exposed to extreme sea levels (both high and low) and have the lowest number of storm surges per year. Tide gauges (Oskarshamn, Marviken, Visby, Landsort, and Stockholm) have the lowest number of storm surges (Fig. 5), the lowest frequency of sea level fluctuations (Fig. 6), and the lowest extreme sea levels (Fig. 7). The southern region of the Gulf of Bothnia (Bothnian Sea), the north-eastern part of the Northern Baltic, the Southern Baltic and the Danish Straits have moderate risk of extreme sea levels. In addition, Fig. 6 confirms a clear asymmetry when high over low levels occur. The vast majority of the tide gauges are adjacent to the lower edge of the high sea level diagram.

Based on the quantitative parameters found for individual tide gauges (Table 2, Fig. 5-7), this paper determined the degree of diversification of the Baltic Sea sub-basins due to the frequency and height of extreme sea levels. Additionally, this classification accounts

Table 1
Morphometric data of individual Baltic Sea sub-basins (morphometric data obtained using the ArcGis program based on HELCOM, 2013).

Sub-basins of the Baltic Sea	Area [km^2]	Mean depth [m]	Maximum depth [m]	Volume [km^3]
Baltic Sea	**413,946**	**54**	**459**	**20,966**
Danish Straits + Kattegat	**35,967**	**19**	**130**	**677**
Kattegat	23,221	23	130	510
Great Belt	7686	13	60	101
Little Belt	2776	15	81	41
Sund	2284	11	53	25
Western Baltic	**27,092**	**21**	**53**	**573**
Kiel Bay	3418	16	36	56
Mecklenburg Bay	4606	16	30	75
Arkona Basin	19,068	23	53	442
Southern Baltic	**77,924**	**49**	**114**	**3836**
Central Baltic	**69,956**	**77**	**249**	**5412**
Northern Baltic	**54,417**	**65**	**301**	**3554**
Gulf of Bothnia	**100,246**	**56**	**293**	**5600**
Bothnian Sea	63,019	66	293	4147
Bothnian Bay	37,227	41	146	1453
Gulf of Finland	**29,551**	**37**	**123**	**907**
Gulf of Riga	**18,793**	**23**	**51**	**407**

Bold significances are the names of the main sub-basins.

for specific features of each water area, namely the exposure of coasts to dangerous paths of cyclones, bathymetric relations, as well as the location of tide gauges relative to the open waters of the Baltic Sea (Baltic Proper). It was established that the regions particularly exposed to extreme high sea levels include: Gulf of Finland, Gulf of Riga at Pärnu Bay, Bothnian Bay and Western Baltic. At the same time, the Western Baltic with Mecklenurg Bay and Kiel Bay belong to the sub-basins with the deepest storm depressions and the most common low sea levels. The Baltic sub-basins that are least exposed to extreme sea levels are Swedish coasts of the Central and Northern Baltic Sea. In contrast, the intermediate risk level for extreme sea levels is represented by the Bothnian Sea and the north-eastern part of the Northern Baltic, Southern Baltic and Danish Straits.

4. Discussion

4.1. Sub-basins particularly exposed to extreme high sea levels

4.1.1. Gulf of Finland

The Gulf of Finland has an area of 29,551 km^2 and a water volume of 907 km^3 (Table 1), and is an extension of the Baltic Proper in terms of hydrography. The strong influence of active cyclones, the wind regime, and the southwest exposure of The Gulf of Finland coasts are the main factors responsible for creating local variations in sea levels. The most dangerous directions of movement of cyclones causing extreme sea levels in the bay are from SW to NE and ENE (Averkiev and Klevanny, 2010; Suursaar et al., 2009). The passage of the Gudrun cyclone in January 2005 through the Gulf of Finland towards the east-north-east caused record maximum sea levels in Helsinki (151 cm), Hamina (197 cm), and Narva (207 cm) (Fig. 7). In the Gulf of Finland, sea level extremes increase from west to east, which is associated with the gulf-effect (Fig. 4). Tide gauges in the eastern part of the gulf have some of the highest number of hours of high (≥70 cm) and very high (≥100 cm) annual sea levels (189 / 34 h in Narva and 171 / 28 h in Hamina, respectively) on the Baltic Sea (Table 2, Fig. 6). These stations are also characterized (excluding one in Pärnu in the Gulf of Riga) by the highest number of storm surges with a maximum of ≥100 cm in the Baltic Sea (an annual average of three) (Table 2, Fig. 5). The above results correspond well with the work of Soomere et al. (2009) and Suursaar (2010) who found that the enclosed eastern side of the Gulf of Finland has the largest range in sea level fluctuations in the entire Baltic Sea, exceeding 4 m.

4.1.2. Gulf of Riga at Pärnu Bay

The small depths of the Gulf of Riga (average depth 23 m –Table 1) and the semi-enclosed nature of the water exchange with the Baltic Proper (the presence of the islands of Hiiumaa and Saaremaa in the north-west and west of this bay) cause that storm surges associated with the passage of deep lows from the west and south-western direction are particularly dangerous for this area (Suursaar et al., 2006b, 2009).

The Pärnu Bay is a small (411 km^2 in area), narrow, and very shallow water region (average depth 4.7 m, maximum 8 m) located in the northeastern Gulf of Riga (Aun, 1999). This bay is open to the southwest, the direction from which cyclones travel most frequently and the prevailing winds blow (Suursaar et al., 2009; Post and Kõuts, 2014). The Pärnu tide gauge lie at the edge of this bay reached its highest maximum of sea levels during two storm surges in January 2005 (288 cm) and October 1967 (264 cm) (Wolski et al., 2014, 2016). When analysing the entire span between 1960 and 2010, the Pärnu station has the highest in the Baltic Sea average annual number of hours with high and very high sea levels (219 and 47 h per year respectively), the highest number of storm surges per year (eight on average), and the highest maximum sea levels (Table 2, Fig. 5–7). These extremes result from the bathymetric and morphological characteristics of the Pärnu Bay. Extreme sea levels and the dynamics of bay waters are well recognized by hydrodynamic modeling. Suursaar et al. (2003) used a hydrodynamic model to determine that the wind direction of 220° was the most conducive to a sea level rise in the Pärnu Bay. For this direction and at a constant wind speed of 20 m/s, the sea level near Pärnu may reach 1.2 m above the gauge zero. In case of a seiche in the Gulf of Riga with a 5 h period, there is in the Pärnu Bay amplitude of sea level oscillations increases to 1.5 m above and below of gauge zero (Suursaar et al., 2003). Furthermore, other studies have shown that a wind speed increase by 1 m·s^{-1} (in the wind speed range of 27–30 m/s) raises the sea level by 20 cm in the Pärnu Bay (Suursaar et al., 2006b).

4.1.3. Bothnian Bay

The Bothnian Bay is located in the northern region of the Gulf of Bothnia is more than 350 km away from the open waters of the Baltic Sea. Despite these significant distances, the quantitative parameters of extreme sea levels for the Kemi tide gauge located in the innermost part of the Gulf of Bothnia, are similar to the Hamina and Narva tide gauges in the eastern Gulf of Finland and to the Pärnu gauge in the Gulf of Riga. Kemi has many hours of high and very high sea levels (204/35 h on average per year, respectively), as well as many hours of low and very low sea levels (43/3 h on average per year, respectively) (Table 2, Fig. 6). These parameters are greater only in the Pärnu station. Such a high frequency of low sea levels in Kemi and Pärnu compared with Hamina or Narva in the Gulf of Finland is due to the shallower seabed (about 10 m deep) in the ends of the Gulfs of Bothnia and Pärnu where the gauging stations are located. The Bothnian Bay is similar to the Gulf of Finland in that the range of sea level extremes increases from the bay entrance (Vaasa), through the central parts of the bay (tide gauges: Ratan and Furuögrund), all the way to Kemi (Fig. 4a).

4.1.4. Western Baltic – Kiel Bay and Mecklenburg Bay

The western part of the Baltic Sea is shaped like a bay and extends from the southwest (Kiel and Mecklenburg Bays) to the northeast to Cape Arkona on the island of Rügen. The probability of extreme fluctuations in the sea level of this area decreases from west to east. Some main reasons for this phenomenon are the size of the open water area compared with the length of the coast and the westward narrowing and shallowing of the bay (Sztobryn et al., 2009). This phenomenon is called the gulf-effect (Fig. 4c).

According to Tiesel (2008), coasts located in the Western Baltic Sea have two particularly distinct wind conditions that are fundamentally important for the creation of storm surges. These are the northwestern

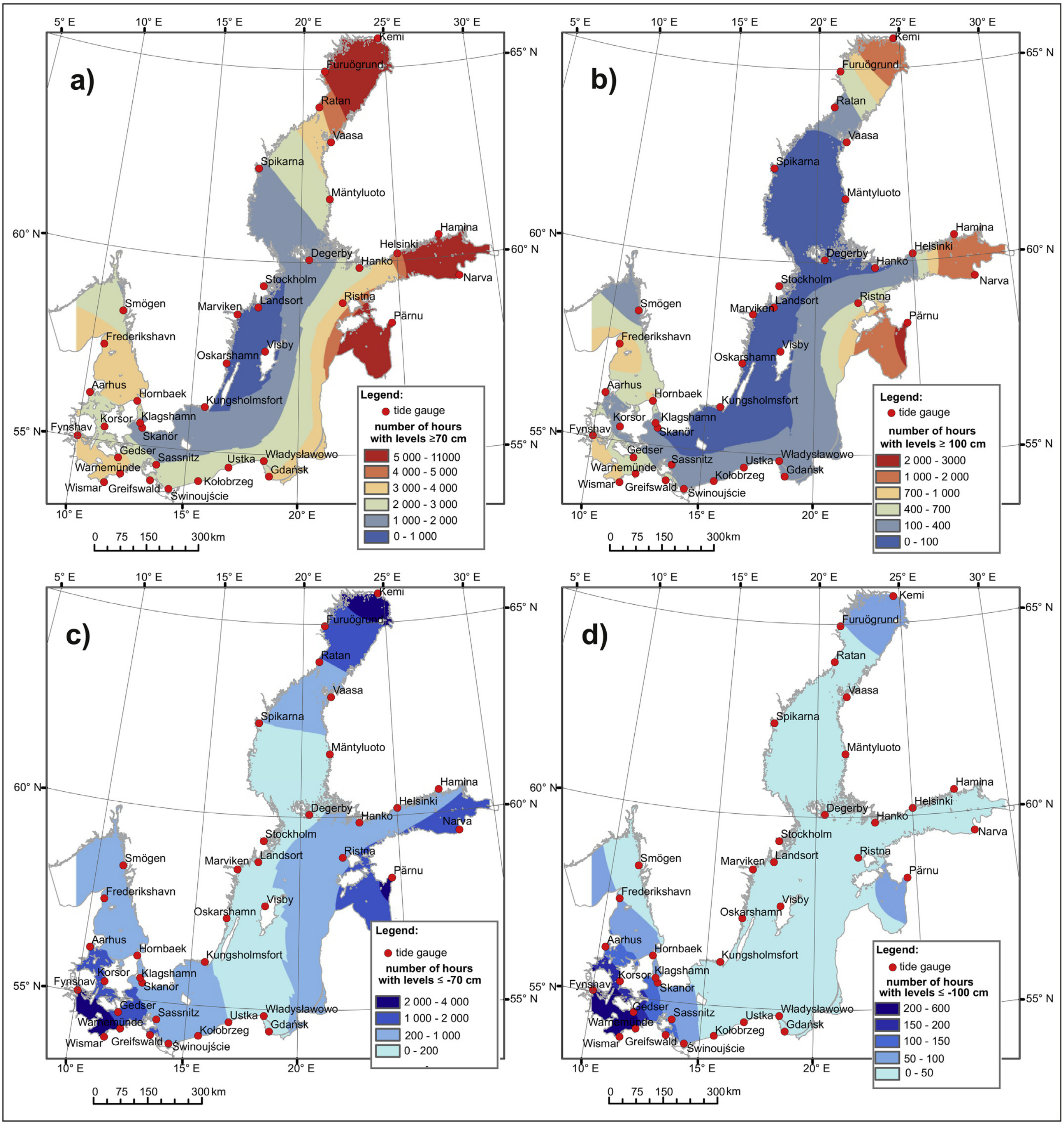

Fig. 3. Total number of hours with extreme levels in the Baltic Sea between 1960 and 2010: a) the number of hours with levels ≥70 cm, b) the number of hours with levels ≥100 cm, c) the number of hours with levels of ≤ − 70 cm, d) the number of hours with levels of ≤ − 100 cm (sea levels relative to the NAP zero).

and northeastern wind systems, which are caused by different types of pressure systems. In the northwestern system, deep cyclonic systems pass from west and northwest (North Sea) to the east, through Scandinavia towards the eastern Baltic coasts, and north of the German coast (Sztobryn et al., 2005). The northwestern wind tailing an active cyclone and reaching a coast is particularly strong since the wind path over the open sea is considerably longer (Flensburg – Kiel Bay – Fehmarn Belt – Mecklenburg Bay). This specific wind is called "Warnemünder wind". The northwestern storm surge usually lasts for a short time, but the storm waves weaken only after a certain time following the passage of a cyclone (Tiesel, 2008). On the other hand, the northeastern wind system is usually more dangerous for the Western Baltic Sea (Tiesel, 2008), in which case, the storm surge lasts longer and typically produces an extended anticyclonic system over Scandinavia. The large pressure gradient on the periphery of this anticyclone and of the cyclone reaches and covering on the Baltic Sea create and develop, over a longer time, a region of northeastern wind, which can cover the entire Baltic Sea from St. Petersburg to Lübeck.

When winds circulate predominantly from north-west and when there are mesoscale cyclones, the authors of these works do not take

Table 2
Parameters of extreme sea levels in individual sub-basins of the Baltic Sea (sea levels relative to the NAP zero).

Tide gauge	The number of hours per year with levels:				Number of storm surges per year with a maximum:	
	High ≥ 70 cm	Very high ≥100 cm	Low ≤ − 70 cm	Very low ≤ −100 cm	≥70 cm	≥100 cm
Danish Straits, Kattegat and Skagerrak						
Smögen	37.5	2.4	3.2	0.0	5.0	0.6
Frederikshavn	84.7	20.4	14.2	0.2	4.6	0.9
Aarhus	54.4	6.4	9.5	0.9	7.3	1.4
Korsør	29.3	3.6	2.1	0.0	3.6	0.6
Hornbaek	86.1	14.6	18.5	1.2	5.5	2.0
Klagshamn	14.9	1.7	7.2	0.0	2.5	0.6
Western Baltic						
Fynshav	75.4	18.1	63.3	11.1	5.6	1.9
Wismar	69.4	16.5	74.5	11.3	5.2	2.1
Warnemünde	54.8	8.9	32.5	3.8	4.4	1.2
Gedser	82.7	13.0	33.7	4.9	5.5	1.7
Sassnitz	35.6	3.8	11.7	1.2	2.7	0.7
Greifswald	72.9	12.3	25.3	2.5	4.6	1.5
Świnoujście	54.8	7.0	14.0	0.6	2.8	0.7
Skanör	24.7	1.7	20.8	2.5	2.8	0.4
Southern Baltic						
Kungsholmsfort	16.9	0.4	2.6	0.0	1.4	0.1
Kołobrzeg	57.5	6.5	4.8	0.2	2.6	0.7
Ustka	50.5	3.8	2.4	0.0	1.8	0.4
Władysławowo	39.7	3.0	1.2	0.0	2.3	0.4
Gdańsk	71.7	6.7	0.8	0.0	2.2	0.6
Central Baltic						
Oskarshamn	7.7	0.0	0.6	0.0	0.6	0.0
Marviken	7.3	0.0	0.2	0.0	0.3	0.0
Visby	2.6	0.0	0.1	0.0	0.1	0.0
Northern Baltic						
Landsort	7.3	0.0	0.1	0.0	0.2	0.0
Stockholm	10.0	0.3	0.0	0.0	0.3	0.1
Degerby	23.9	0.0	0.0	0.0	0.0	0.0
Hanko	48.1	1.0	0.4	0.0	1.5	0.2
Ristna	62.2	8.9	4.4	0.0	3.0	0.9
Gulf of Bothnia						
Spikarna	32.0	0.7	0.6	0.0	1.2	0.1
Mäntyluoto	48.4	1.2	0.2	0.0	1.2	0.2
Vaasa	75.6	2.0	3.2	0.0	1.6	0.3
Ratan	72.4	4.2	11.1	0.4	2.2	0.4
Furuögrund	96.1	8.0	20.7	0.9	3.1	0.6
Kemi	203.6	35.1	43.2	2.9	6.6	2.5
Gulf of Finland						
Helsinki	90.7	6.6	4.4	0.0	3.7	0.9
Hamina	171.1	28.2	15.8	0.2	8.1	3.0
Narva	189.0	33.9	23.4	0.6	6.2	2.8
Gulf of Riga						
Pärnu	219.4	47.2	47.5	2.1	8.4	4.9

into account the reduced pressure of a travelling cyclone and instead prioritize the role of wind in shaping the sea level extremes. This is only justified during slow-moving cyclones which prolongs the duration of the wind action. It is in this situation that a stable northwestern wind plays the main, though not exclusive, role in the formation of extremes for tide gauges in the Western Baltic Sea.

The Western Baltic, in particular, the Gulf of Kiel and Mecklenburg, is the second largest area in the Baltic Sea in terms of the duration of high sea levels, their maximum values, and the number of storm surges. These parameters are worse only compared with large northeastern gulfs, the Gulfs of Finland and Riga and the Bothnian Bay (Table 2, Fig. 5-7) Both wind situations described above generate a large number of hours per year with high and very high sea levels at tide gauge stations in these waters – Fynshav: 75 and 18 h, Wismar: 69 and 16 h, and Gedser: 83 and 13 h. The number of storm surges occurring at these tide gauges is also high, at about 5 per year.

4.2. Sub-basins having deepest storm negative surges and most-frequent low sea levels Kiel Bay and Mecklenburg Bay

The Mecklenburg and Kiel Bays are the Baltic sub-basins with the deepest negative storm surges and the most-frequent and longest-lasting low and very low sea levels (Table 2, Fig. 6-7). The decisive factors generating these processes are a cyclone's path, appropriate coastal exposure, and bathymetric characteristics of the coastal zone.

The eastern exposure of the Kiel and Mecklenburg Bays is conducive to “discharging” water from these regions by a fast-moving mesoscale cyclone (≥ 16 m/s) from west to east or northeast. The reduced pressure of the moving cyclone (< 980 hPa) creates a water cushion, which together with the wind system remove water from the Western Baltic Sea (the negative phase causes negative storm surges) and dams the water in the northern and eastern Baltic Sea (Wolski et al., 2014; Wolski et al., 2016). This is conditioned by the bathymetric relations in the Kiel and Mecklenburg Bays. With very shallow depths (average of 16 m) and extremely low water volume (56 km^3 and 75 km^3, respectively)

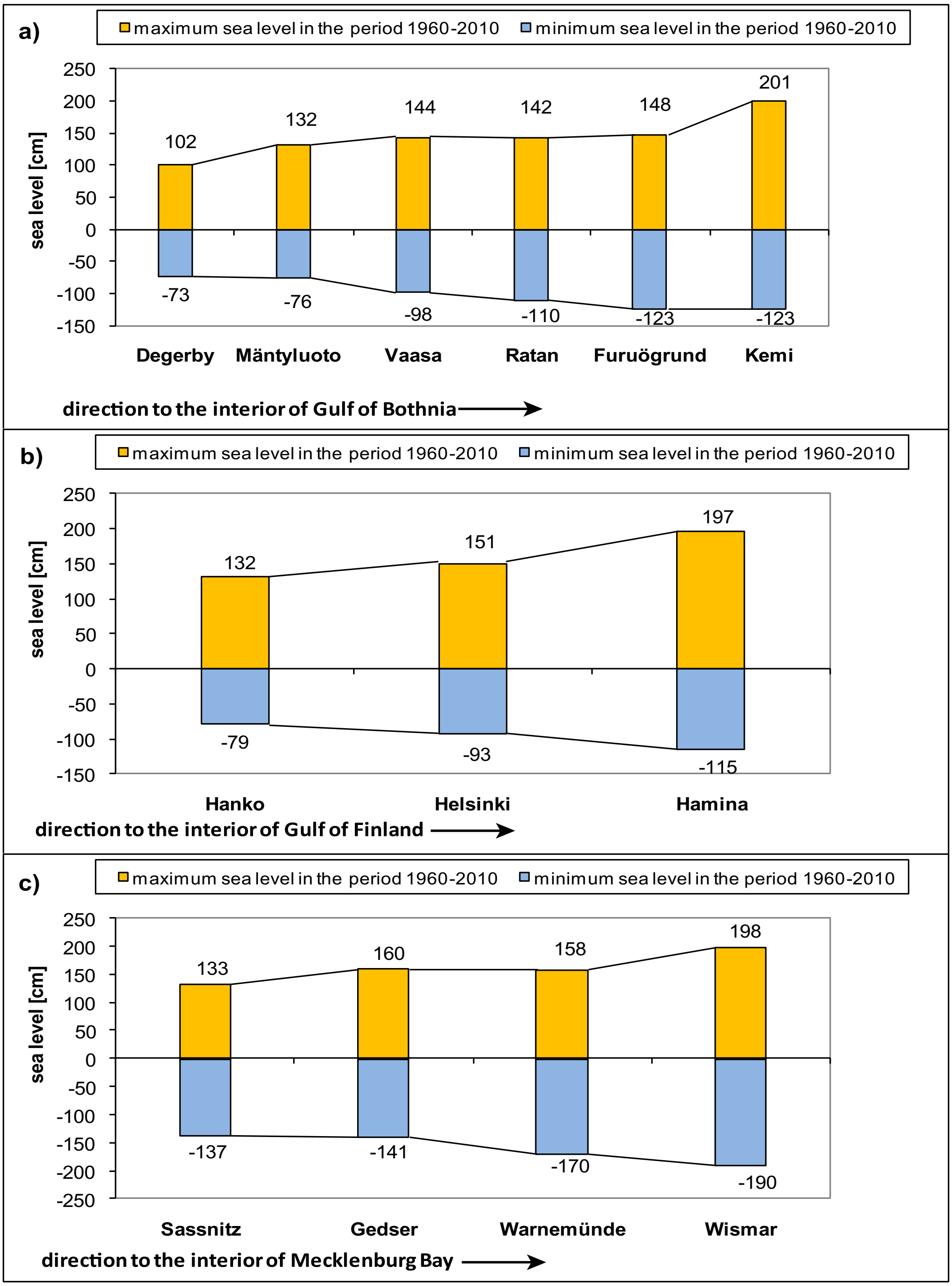

Fig. 4. Extreme sea levels from 1960 to 2010 for tide gauges from the sea border to the innermost parts of gulfs.

(Table 1) compared with other Baltic Sea sub-basins, the exchange of waters (emptying or filling the bays) is very dynamic during a storm. Thus, if a cyclone moves east, the Western Baltic will have the deepest and most frequent negative water surges in the entire Baltic Sea. The lowest sea levels recorded between 1960 and 2010 occurred at Wismar station (−190 cm) and Warnemünde station (−170 cm) (Fig. 7). The highest annual number of hours with low and very low levels was recorded at Wismar station (74.5 and 11 h, respectively) and Fynshav (63 and 11 h, respectively) (Table 2, Fig. 6).

4.3. Sub-basins of the Baltic Sea least exposed to extreme sea levels – Swedish coasts of the Central Baltic and Northern Baltic

The quantitative parameters of extreme sea levels (Table 2) show that the Swedish coasts of the Central and Northern Baltic are the areas least susceptible to extreme sea levels. In these water regions, tide gauges record the lowest average number of hours per year with both high and low sea levels in the Baltic Sea. High levels ≥70 cm persist over a time ranging from 10 h in Stockholm to less than 3 h per year on average in Visby. Low sea levels ≤ − 70 cm are rare, occurring only once every few years. In contrast, very high ≥100 cm and very low ≤ −100 cm sea levels do not occur at all in this area (Table 2,

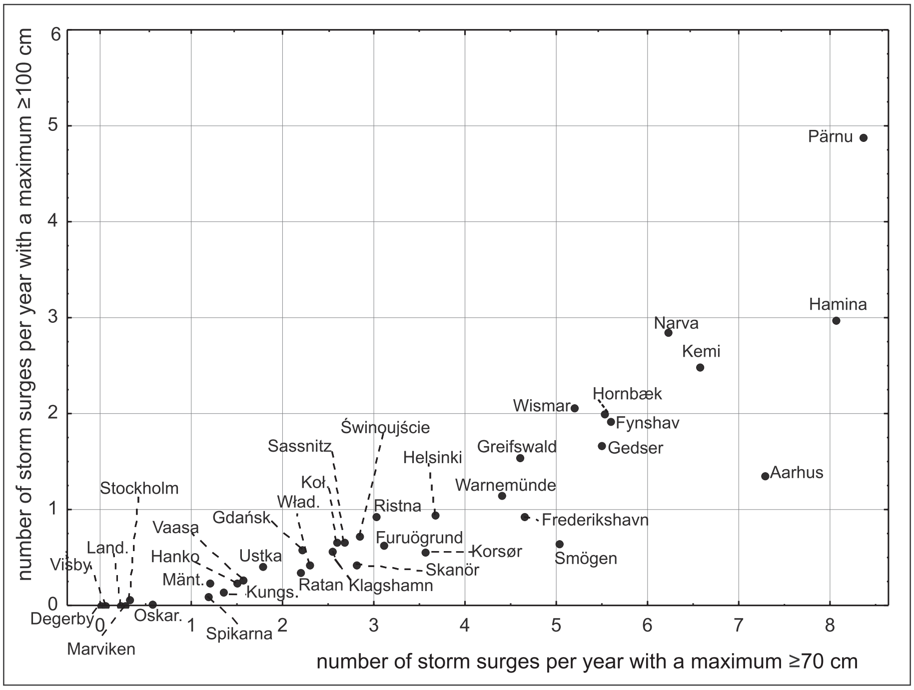

Fig. 5. Number of storm surges per year for tide gauges in the Baltic Sea (annual averages from 1960 to 2010).

Fig. 6-7), and storm surges reaching a maximum of 70 cm across the western part of the Central and Northern Baltic appear sporadically every few years. Among the tide gauges in this region and of the entire Baltic Sea, the Visby station has the least extreme sea levels. The maximum level was 85 cm in the period between 1960 and 2010 and the minimum level during the multi-year period reached −72 cm (Fig. 7). Such small sea level extremes are influenced by two main factors. First is the central location of water regions in relation to the entire Baltic Sea basin, which makes the Central Baltic tide gauges nodal points for seiche fluctuations in sea levels (Leppäranta and Myrberg, 2009). According to Wolski et al. (2014, 2016), during the passage of the deep low-pressure area through the Baltic Sea, seiche fluctuations of sea level between the north-east and south-west coast are formed. In such situations, the tide gauges of the western parts of the Central and Northern Baltic (Visby, Marviken, Landsort, Stockholm) showed the lowest sea level oscillations. Therefore, data from these gauges provide a good proxy for changes in the Baltic Sea Volume (Weisse and Hünicke, 2019).

The considerable average depth and volume of the Central Baltic waters (77 m and 5412 km^3, respectively) (Table 1) compared with other sub-basins of the Baltic Sea reduces the dynamics of oscillation and is also responsible for this lowest range of sea level fluctuations.

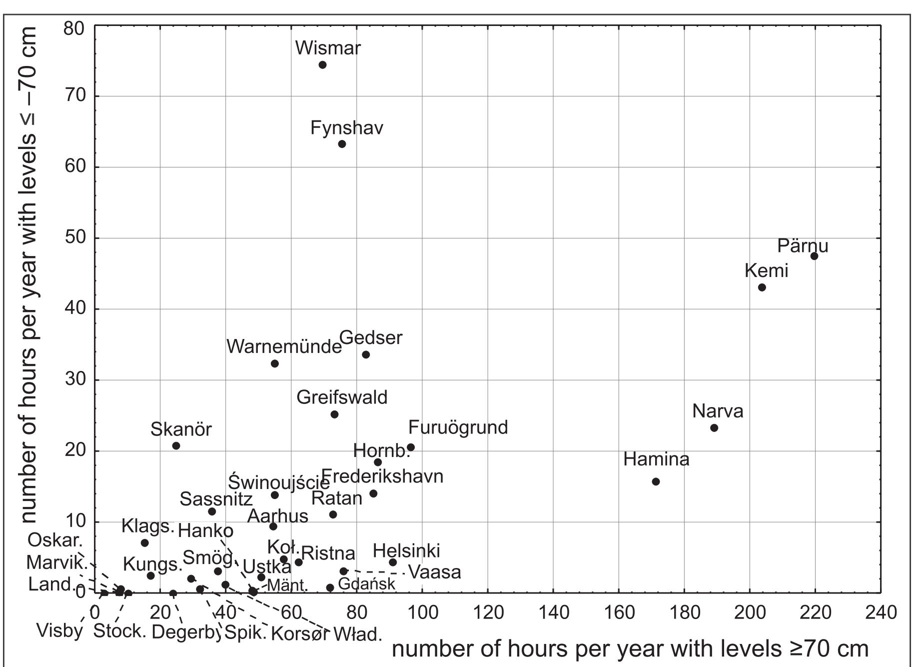

Fig. 6. Number of hours per year with extreme sea levels for tide gauges in the Baltic Sea (annual averages from 1960 to 2010).

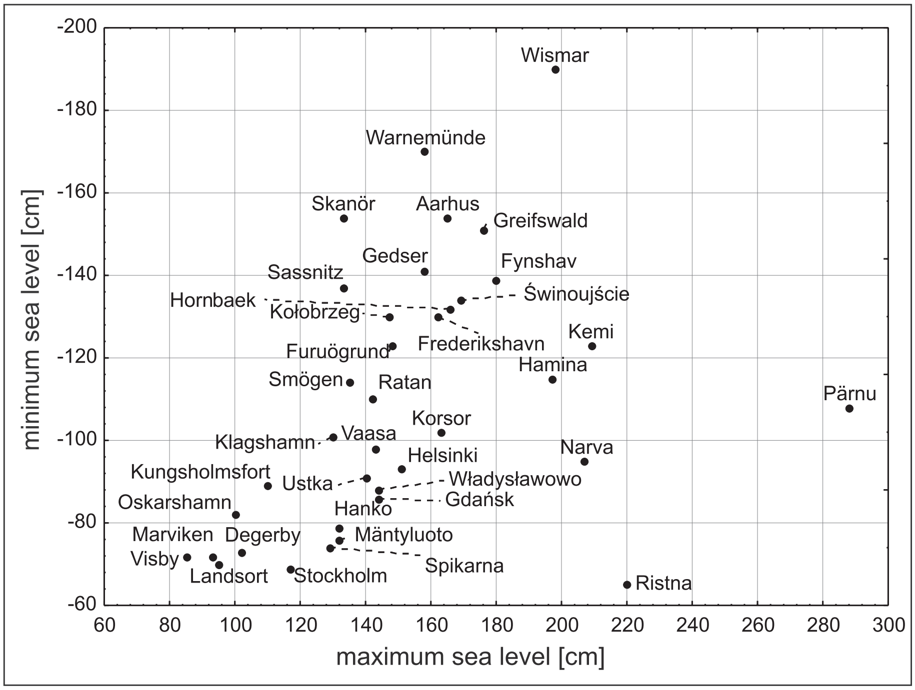

Fig. 7. Extreme sea levels for tide gauges in the Baltic Sea from 1960 to 2010.

The second factor influencing the lower sea level extremes for the Swedish coasts of the Central and Northern Baltic is the eastern exposure of the coastline, i.e. the direction opposite to the prevailing direction of cyclone propagation. The characteristics of extreme sea levels between the west and east coasts of the Baltic Sea are quite different, as exemplified by comparing the sea level parameters of the Landsort and Ristna tide gauges. These gauges lie on the opposite coasts of the Baltic Sea, at similar latitudes, within the open waters of the Northern Baltic. Situated on the Estonian island of Hiiumaa and exposed to the southwest, i.e. towards prevailing cyclones and wind systems, the Ristna tide gauge repeatedly records extreme sea level values that are higher than the Landsort gauge off the east coast. The contrast is visible when comparing the annual average number of hours with high sea levels (62 h in Ristna and 7 h in Landsort), the annual average number of storm surges (3 in Ristna, 0.2 in Landsort), (Table 2).

4.4. Baltic Sea sub-basins with intermediate degree of risk of occurrence of extreme sea levels

The Bothnian Sea, the eastern and northern parts of the Northern Baltic, Southern Baltic and the Danish Straits with Kattegat and Skagerrak have moderate risk for extreme hydrological events. This is mainly due to geographical location of these sub-basins and the transient characteristics of parameters of extreme sea levels (Table 2). The number of hours with high and low levels per year and the number of annual storm surges in these waters range between the largest extremes (Gulf of Finland, Gulf of Riga, and Bothnian Bay) and the parameters of the waters with the lowest sea level oscillations (Swedish coasts of the Central and Northern Baltic).

4.4.1. Bothnian Sea and the north-eastern part of the Northern Baltic

The Bothnian Sea is a sub-basin that, in terms of hydrography, is fairly isolated from the Baltic Proper (Northern Baltic), separated by underwater steps and archipelagos. According to research by Suursaar et al. (2009) and Averkiev and Klevanny (2010), the cyclones causing storm surges most dangerous for the coasts of this region are those heading from the southwest. Considering that the volume of waters of the Bothnian Sea (4147 km^3) is much larger than the Bothnian Bay (1453 km^3) (Table 1), the water dynamics of this region that are influenced by the passing a low-pressure system will be much smaller. This is reflected in the lower values of the extreme sea levels in the Bothnian Sea. For example, the number of hours with high sea levels in Bothnian Sea ranged from 32 to 48 h per year, while in the Bothnian Sea from 72 to 204 h (Table 2, Fig. 6).

The north-eastern part of the Northern Baltic is a region of open waters which can be described as a hydrographic foreland of the Gulf of Finland since there is no underwater step between these water regions. Due to this property, the Ristna and Hanko tide gauges usually record moderate extreme sea level parameters due to the transitional location between the Central Baltic and the Gulf of Finland. This is reflected primarily by the moderately long duration of high sea levels per year (48 h in Hanko and 62 h in Ristna). The Ristna sea-level indicator, due to its far offshore location (the Kõpu peninsula on the island of Hiiumaa), is characterized by higher sea level extremes than Hanko (Table 2, Fig. 6).

4.4.2. Southern Baltic

The Southern Baltic, situated within the Baltic Proper, is the largest water region of the Baltic Sea (after the Gulf of Bothnia) with an area of 77,924 km^2 and an average water depth of 49 m (Table 1). According to Majewski et al. (1983), the high sea levels on the southern coasts of the Baltic Sea cause cyclones travelling mostly from the North Sea and the Norwegian Sea east to and southeast. Additionally the transitional location of the open waters of the Southern Baltic affects the magnitude of extreme sea level oscillations. The nature of these oscillations is caused by the lowest ranges of sea level fluctuations in the western part of the Central Baltic (Swedish coasts) and distinct extremes in the Mecklenburg and Kiel Bays (Western Baltic). This can be seen primarily on the Polish coast, which, from Władysławowo westward to Kołobrzeg station, has prolonged durations of high and very high sea levels, as well as low sea levels (Table 2, Fig. 6.). This conclusion closely corresponds with the results of the work of Wiśniewski and Wolski (2009), who agreed that the Polish coast has increased extreme sea level amplitudes from the eastern section of the coast (Gdynia – Hel) to the western coast (Świnoujście – Kołobrzeg). Lower characteristics of the extreme sea levels of Kungsholmsfort are associated with the location of this tide gauge in southern Sweden. This gauge is shielded from the north by the Swedish coast and from the east and west by the islands of the Blekinge archipelago.

4.4.3. Danish Straits, Kattegat and Skagerrak Straits

The Danish Straits, along with the Kattegat and Skagerrak Straits, constitute a morphometrically specific water exchange region between the North Sea and the Baltic Sea. The water flowing through Danish Straits depends on local air circulation over this area (Schinke and Matthäus, 1998) and regional circulation over the Baltic Sea (Kauker and Meier, 2003) more strongly than large-scale circulation – NAO (Jevrejeva et al., 2005; Omstedt et al., 2014). The sea level in these straits depends directly on the water level in the Kattegat Strait and the degree of filling in the southern regions of the Baltic Sea. Sea level fluctuations caused by tides reach ± 20 cm in the straits (Leppäranta and Myrberg, 2009). Due to the relatively small cross-sections of the Belts and the Sund and their significant lengths, the flow of water through the straits is limited and longer, which makes the straits act as low-pass filters for sea level fluctuations. The high frequencies of sea level fluctuations in the Kattegat are effectively suppressed, and the low frequencies pass unchanged (Carlsson, 1997). The suppressing effects of straits are reflected, primarily in the different durations (number of hours) of high and very high levels measured by tide gauges located on both sides of the straits. For example, the number of hours with high levels per year decreases from Frederikshavn (northern Kattegat – 85 h) through Aarhus (southern Kattegat – 54 h) to Korsør (central part of the Great Belt – 29 h). A similar decrease is observed in Sund, where a similar regularity occurs at low sea levels (Table 2, Fig. 6.).

The highest sea levels within the southern end of the Danish Straits are recorded during prolonged northeastern storms, as the wind blowing over a large area of the Baltic Sea dams the water in its southwestern region and also causes a negative surge in Kattegat (up to −1.4 m below the average) and in Skagerrak (Gustafsson, 1997). This situation is conducive to the outflow of waters into the North Sea. The situation is opposite from strong western and northwestern storms, when waters from the North Sea and Skagerrak flow into Kattegat, causing the sea level in its southern part to rise to 2 m above its average level and to 1.5 m in the northern part of the Sund. During this time, the southern outlets of the Danish Straits record low and very low sea levels, up to < −1.5 m below zero in southern Sund. Such a situation occurred because of the deep "Gudrun" cyclone on January 9, 2005, when in the morning (5.00 UTC), a very significant relative sea level difference (denivelation of nearly 2 m) between Skagerrak–Kattegat and the southern outlet of the Danish Straits caused waters to flow into the Baltic Sea (Wolski et al., 2014).

5. Conclusions

The analysis of the distribution and quantitative characteristics of extreme sea levels and the storm surges in the Baltic Sea show clear regularities. They are as follows:

1. The eastern and northeastern coasts of the Baltic Sea are especially at risk of extreme hydrological events, since they are exposed to the inflow of western air masses related to a western atmospheric circulation, including the dominant tracks of low-pressure systems. In particular, it refers to the Gulf of Finland, the Gulf of Riga along with Pärnu Bay, and the Gulf of Bothnia (Bothnian Bay). These sub-basins experience the largest number of storm surges, the longest duration of high sea levels (≥70 cm), and the highest sea levels in general. In contrast, the Swedish coast of the Central and Northern Baltic are the least threatened by extreme sea levels within the Baltic Sea area.This is explained mostly by their eastern exposure, which constitutes an opposite direction to the inflow of western air masses and to the propagation direction of low-pressure systems. In the conditions of western circulation, the filling up of the Baltic Sea increases, and the inclination of the water surface towards eastern coasts of the Baltic Sea also increases.
2. The southwestern coasts of the Baltic Sea: The Bay of Mecklenburg and Bay of Kiel are sub-basins with the most frequent and the deepest falls as well as of the lowest sea levels (≤ − 70 cm). The eastern exposure of these bays favours the water outflow from their basins by fast-moving mesoscale low-pressure systems crossing the Baltic Sea from west to east. At the same time, the Bay of Mecklenburg and Bay of Kiel give way only to big northeastern gulfs in terms of frequency of occurrence of high sea levels, maximum heights of sea level, and number of storm events. This is a peculiar phenomenon among the sub-basins (water regions) of the Baltic Sea.
3. The Bothnian Sea, northeastern part of the Northern Baltic, Southern Baltic, and Danish Straits are sub-basins with moderate risk of extreme hydrological events occurrence. It follows mainly from the transitional location of these areas between sub-basins with the highest extremes (Gulf of Finland, Gulf of Riga, and Bothnian Bay, Western Baltic) and the sub-basins with small sea level oscillations (Swedish coast of the Central and Northern Baltic
4. Extreme phenomena, related to water dynamics, increase from the open sea waters of the Baltic Sea (Baltic Proper) to the innermost parts of its bays (Gulf of Bothnia, Gulf of Finland, Gulf of Riga, Bay of Mecklenburg, and Bay of Kiel). The gulf-effect, i.e. the impact of the geomorphological and bathymetrical configuration of the coastal zone on water dynamics, is responsible for this situation.
5. An important role in the formation of extreme sea levels in the Baltic Sea is played by the seiche water fluctuations caused by the passage of deep low-pressure area. This mesoscale low pressure system lowers sea levels on the south-western shores of the Baltic Sea and at the same time raises the tilt of the water table on the northeastern shores to turn in a few hours or more. On the other hand, the local seiche in the eastern bays of the Baltic coast amplifies any increases or decreases in sea level (the strongest in the Pärnu Bay)
6. In all sub-basins of the Baltic Sea, the duration of high sea levels was clearly longer than low sea levels. This asymmetry is due to the physical nature of the storm surge, which occurs most often when the Baltic Sea is filled earlier and the water is raised due to the negative pressure under moving deep low pressure area (barometric effect). As a result, these factors will inhibit rapid and significant drops in sea level with negative storm surges and strong seaward winds.

Declaration of Competing Interest

The authors whose names are listed immediately below certify that they have NO affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or nonfinancial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

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