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Extreme sea levels at selected stations on the Baltic Sea coast*

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Abstract

The purpose of this article is to analyse and describe the extreme characteristics of the water levels and illustrate them as the topography of the sea surface along the whole Baltic Sea coast. The general pattern is to show the maxima and minima of Baltic Sea water levels and the extent of their variations in the period from 1960 to 2010. A probability analysis is carried out on the annual sea level maxima and minima for 31 water level gauges in order to define the probability of occurrence of theoretical sea levels once in a specific number of years. The spatial distribution of sea levels for hundred-year maximum and minimum water levels is illustrated. Then, the number of storm surges for the accepted criteria are presented: these numbers increased in the 50-year period analysed. The final part of the work analyses some extreme storm events and calculates the static value and dynamic deformation of the sea surface by mesoscale, deep low-pressure systems.

1. Introduction

Extreme water levels on the Baltic Sea are related to sudden storm events caused by deep low-pressure phenomena, which impact as surges and drops in sea level. In the literature, a storm surge is variously defined, depending on the criteria adopted. The *Encyclopaedia of Coastal Science* (2005) defines a storm surge as an increase in ocean water level near the coast generated by a passing storm, above that resulting from astronomical tides. A different definition is provided by the *International Glossary of Hydrology* (1992): here, a storm surge is an elevation of the sea level caused by the passage of a low pressure centre. Gönnert et al. (2001) define a storm surge slightly differently, viewing it as oscillations of the water level within a coastal area and coastal water regions, lasting for several minutes to several days, resulting from the impact of pressure systems on the sea surface. The generation of a storm surge occurs either as a result of the impact of an extremely strong wind and decrease of atmospheric pressure at the sea surface (Weisse & von Storch 2010), or generally, only as a result of a strong wind (Jensen & Müller-Navara 2008). For the German coasts of the Baltic Sea, a storm surge is usually considered to be an increase in sea level of at least 100 cm above the mean level, that is, 600 cm Normal Null. The Polish coastal protection services describe a storm surge as a dynamic rise in sea level above the warning level (570 cm N.N., that is, 70 cm above mean level) and the alarm level (600 cm N.N.), induced by the action of wind and atmospheric pressure on the sea surface (Majewski et al. 1983). Wiśniewski (1997) considered a storm surge to be the dynamic increase of water level under the influence of wind and atmospheric pressure on the sea surface above the level of 570 cm on any section of the Polish coast (maximum storm surges greater than or equal to 70 cm NAP), associated with a temporary pressure system and wind causing the difference in the sea surface elevation. This criterion was also referred to in the later works of Wiśniewski & Wolski (2009a), Wolski & Wiśniewski (2012); it is the one used in this study.

On the south-western coasts of the Baltic Sea, the strongest surge recorded since regular recording began occurred on 13 November 1872 (Majewski 1998, Richter et al. 2012). This surge was recorded in many ports on the western coast of the Baltic, even exceeding 3 m above mean level (3.31 m in Lübeck, 2.22 m in Kołobrzeg). The conditions of catastrophic surges on the German coasts of the Baltic have been studied by many scientists (Stigge 1994, Hupfer et al. 2003, Gurwell 2008, Jensen & Müller-Navarra 2008, Rosenhagen & Bork 2009, Richter et al. 2012). In the Gulf of Finland, the highest surges occur in its eastern part, in the St. Petersburg region. On 19 November 1824, the sea level there reached 4.21 m above the mean sea level (Averkiev & Klevanny 2007, 2010). High surges have also been recorded on the coasts of the Gulf of Riga (Suursaar et al. 2003, 2006, Suursaar & Sooäär 2007). In other parts of the Baltic Sea, storm surges are lower (Averkiev & Klevanny 2010, Kowalewska-Kalkowska 2012). In the Gulf of Bothnia sea levels can be as high as 2 m (Kemi 201 cm, September 1982). On Swedish coasts in the central Baltic increases in water levels usually do not exceed 1 m.

Very high storm surges have also been recorded on Polish coasts. The coasts particularly exposed to these phenomena are along the shallow Bay of Pomerania, where increasing water levels have destroyed dune and cliff systems. Majewski et al. (1983) conducted a detailed analysis of storm surges on southern Baltic coasts from 1951 to 1975. On the other hand, Sztobryn et al. (2005) analysed surges along the Bay of Pomerania between 1976 and 2000. Wiśniewski & Wolski (2009a) compiled the *Catalogues of sea level storm surges and falls* for the whole Polish coast for the period 1947–2007. Other papers on storm surge conditions and regimes on southern Baltic coasts include Wróblewski (1991), Majewski (1986, 1989, 1998), Dziadziuszko & Jednorał (1996), Wiśniewski (1997), Stanisławczyk (2002) and Kowalewska-Kalkowska (2012).

All of the above publications focused on a small number of tide gauges along a limited section of coast, usually in a single country. No research has been carried out on extreme sea levels covering the entire Baltic Sea.

The main purpose of this article is to analyse extreme water levels during storm surges, as shown in the full time spectrum and for the whole Baltic Sea area, i.e. the following questions are addressed:

– what were the absolute water level maxima and minima for the period 1960–2010?

– what is the probability of maximum and minimum sea levels based on a probability analysis of observation data from the sea level gauges in the Baltic Sea?

– what are the numbers of storm surges in the various basins of the Baltic Sea?

– what is the course of the short-term variations in sea level maxima and minima during storm surges and their physical interpretation?

All the characteristics of these extreme sea levels will be presented as spatial characteristics of the Baltic Sea's surface topography.

A considerable contribution to the observational data on sea levels for the purposes of this article was made by the co-authors from abroad. The work compiles hourly sea level data at individual sea level gauges and their recalculation from local zero levels to one single reference level. This level is the Normal Amsterdam Peil (NAP) (Wiśniewski et al. 2014). It is the basis of the European Vertical Reference System (EVRS) currently implemented by all the Baltic countries. Research material worked up in this way enables the spatial display the water surface topography of the Baltic Sea.

2. Material and methods

The first section of the work (3.1) gathers the data on the extreme, highest and lowest sea levels from 1960–2010 for the various sections of the Baltic Sea shores (Table 1, see p. 267). These values were imaged on the map in ArcGis 10.1 software using the observational data obtained from 31 Baltic water level gauges (Table 1). As a result, maps of the sea surface topography were drawn (imaging of the Baltic Sea's surface by means of the isolines of maximum and minimum sea levels) (Figure 2, see p. 266).

The hourly sea level data were obtained from the national meteorological and hydrological institutes of the countries around the Baltic Sea, i.e. SMHI (Sweden), FMI (Finland), DMI (Denmark), BSH (Germany), EMHI (Estonia), LHMT (Lithuania) and IMGW (Poland). The sea levels from Germany, Denmark, Poland, Lithuania and Estonia are adjusted to the zero reference tide gauge of the water-level indicator of NAP (Normaal Amsterdams Peil) using the transformations of the national reference systems (Coordinate Reference Systems), so as to comply with the standards of the European Vertical Reference System (EVRS 2000) (http://www.crs-geo.eu/crseu/). Sea level data are converted to an accuracy of 1 cm. Swedish and Finnish sea level data do not have a general water level 'zero' owing to the rapid uplifting of their lands with different velocities. The values here are given relative to the mean water levels for each station.

The probability of occurrence of theoretical sea levels for several tide gauge stations from different coasts of the Baltic Sea is also determined in this work (section 3.2). These analyses use the maximum and minimum annual sea levels from the period 1960–2010. The Gumbel distribution and the maximum likelihood method were used to determine the maximum theoretical level of a hundred-year water level (the hundred-year return period). The probability density function of the Gumbel distribution is based on statistical distributions of extreme values that occur in regular subperiods of the series. For instance, it can describe the distribution of the annual sea level maxima considered in this paper. The probability density function of the Gumbel distribution is doubly exponential and described by the formula (Gumbel 1958)

$$f(x) = \frac{1}{\hat{a}}\, e \left[-\frac{x-\hat{b}}{\hat{a}} - e \left(-\frac{x-\hat{b}}{a} \right) \right] , \tag{1}$$

where $\hat{a}$ – scale parameter (determining the dispersion of the distribution along the x-axis), $\hat{b}$ – location parameter (determining the location of the distribution along the x-axis), e – the base of the natural logarithm.

The idea of relating the statistical distribution to observational data is to determine the distribution parameters $\hat{a}$ and $\hat{b}$ by means of the maximum likelihood method.

The Pearson type III distribution, the usual one in hydrology (Kaczmarek 1970), was used to determine the theoretical, minimum sea levels

$$f(x) = \frac{\alpha^{\lambda}}{\Gamma(\lambda)}\, e^{-\alpha(x-\epsilon)}\, (x-\epsilon)^{\lambda-1} , \tag{2}$$

where α, ϵ, λ – the distribution parameters which should meet the following requirements: $x \geq \epsilon$ (lower limit of the distribution), $\alpha > 0$, $\lambda > 0$; $\Gamma(\lambda)$ – gamma function of the variable λ.

The parameters of the Pearson type III distribution were also assessed by means of the maximum likelihood method. This work studies the consistency of the accepted theoretical distribution with the empirical distribution (with the series of sea level observations) by means of the Kolmogorov test of normality. All the calculations were done with Matlab.

To determine the number of storm surges between 1960 and 2010, the maximum sea levels ≥ 70 cm above the zero of the water level gauge (NAP) were adopted according to the definition of storm surges by Wiśniewski & Wolski (2009a) (section 3.3).

Two storm events representing different extreme spatial and temporal changes in sea level for the whole Baltic Sea area were selected for the analysis of short-term sea level changes (section 3.4). These events occurred on 15–16 November 2001 and 8–9 January 2005. The values of the static and dynamic deformation of the sea surface created as a result of the passage of a low pressure system were determined. For this purpose, the following formulae were applied (Lisowski 1961, Wiśniewski 1996, 1997, 2003, Wiśniewski & Wolski 2009a, 2011).

$$\Delta H_s = \frac{\Delta p}{\rho \times g}, \tag{3}$$

where: ΔH_s [cm] – static water level rise at the centre of the low pressure area (static sea surface deformation), Δp [hPa] – rise or fall of atmospheric pressure in relation to its average value, i.e. 1013.2 hPa, ρ – mean water density 1.010 g cm^{-3}, g – acceleration due to gravity 981 cm s^{-2} and

$$\Delta H_d = \frac{\Delta H_s}{1 - (V_L/\sqrt{g \times H_m}}, \tag{4}$$

where: ΔH_d [cm] – dynamic deformation of sea level, V_L [m s^{-1}] – travelling velocity of the air pressure system, H_m [m] – average sea depth.

Figure 1 illustrates the static and dynamic deformation of the sea surface.

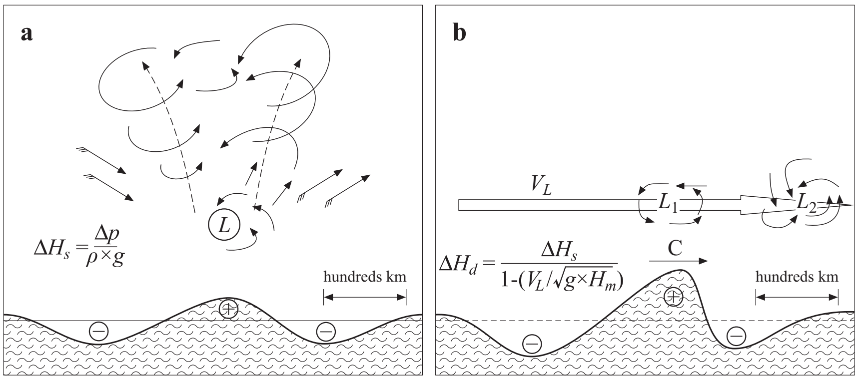

Figure 1. Sea surface deformation caused by a low pressure system a) static sea surface deformation, b) dynamic sea surface deformation (Wiśniewski & Wolski 2009a, 2011)

The calculations were performed for 8 sea level gauges located on different coasts of the Baltic Sea: Skanör (Sweden), Gedser (Denmark), Kiel (Germany), Świnoujście (Poland), Klaipeda (Lithuania), Ristna (Estonia), Hamina and Kemi (Finland) (Figures 9 and 12, see p. 278 and 281). In addition, the following characteristics were determined for each storm surge:

– (p_i) – the pressure at the centre of the low-pressure system [hPa],

– the initial sea level [cm] (the sea level prior to the occurrence of an extreme event),

– extreme sea levels during the surge and their amplitude [cm],

– rates of maximum sea level rise and fall [cm h^{-1}].

Temporal changes in sea level as well as synoptic maps of the temporary low-pressure systems are presented for all storm situations. Additionally, the pressure situation and its impact on the course of a surge along the coasts of the Baltic Sea is discussed. The maps of sea level changes during storms (the topography of the water surface) of the Baltic Sea were drawn in ArcGis 10.1 based on data from the water level gauges located along the coast of the Baltic Sea. The synoptic maps were obtained from the Meteorological Office, Bracknell, UK (http://www.wetterzentrale.de), and the data on wind speed and direction from the National Climatic Data Centre, NOAA (http://www.ncdc.noaa.gov).

3. Results

3.1. The geographical distribution of extreme water levels on the Baltic Sea from the period 1960–2010

The first part of the results of this work includes the distribution and values of the extreme Baltic Sea levels for the 50 years from 1960 to 2010 (Figure 2).

The maps on Figures 2a,b illustrate the topography of extreme (maximum and minimum) sea levels drawn on the basis of real and observed water levels at the gauge stations. The last map (Figure 2c) shows the topography of amplitudes, which was counted from the observed extreme sea levels at the gauge stations.

The diversity of extreme sea levels results mainly from:

– the various exposures (directions) of the parts of the Baltic Sea coasts (coastline configuration) to the trajectories of passing low-pressure systems;

– the location of the water level gauge stations in relation to the open areas of the Baltic Sea (Central Baltic: Northern and Southern Baltic Proper, Western and Eastern Gotland Basin);

– the bathymetric and morphological characteristics of the coast in question.

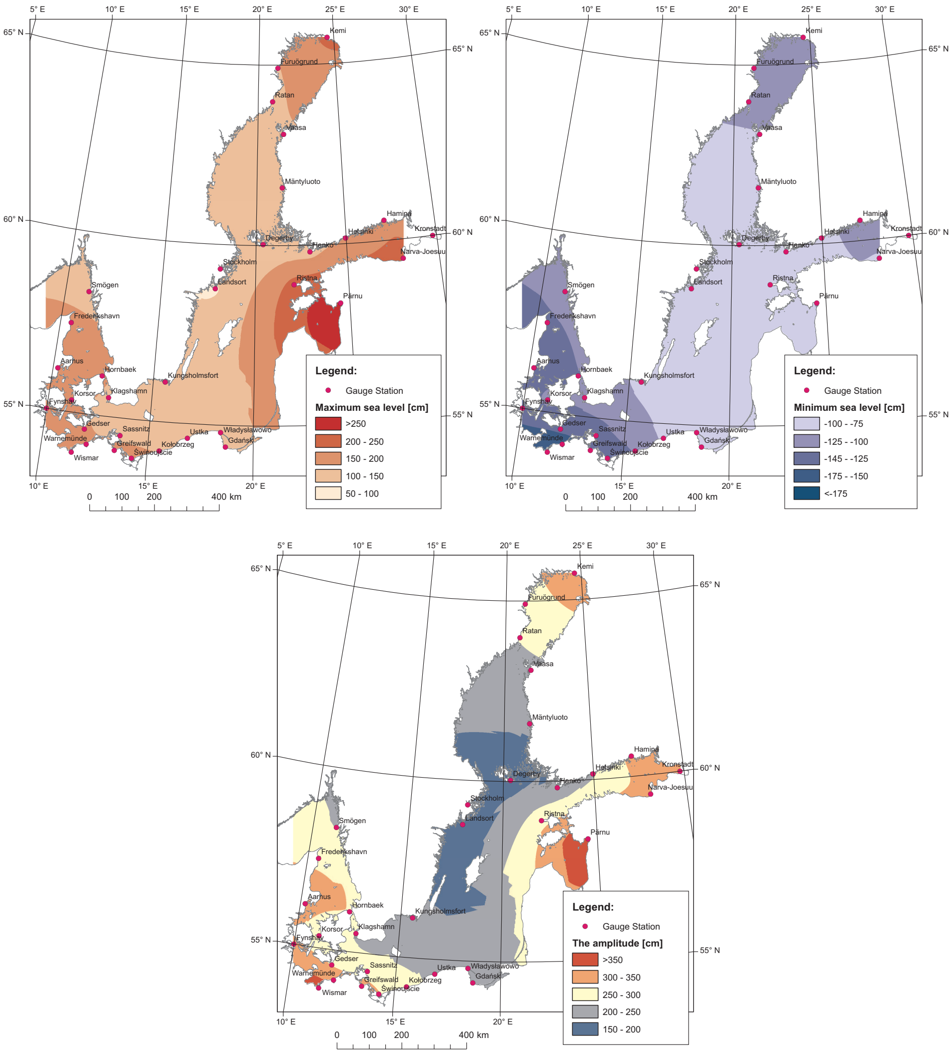

Figure 2. Surface water topography of the Baltic Sea for maximum levels (a), minimum levels (b) and the amplitude of variations (c) from the period 1960–2010

The gulf stations situated far away from the open areas of the Baltic Sea, located in areas of relatively shallow depth, have significantly higher extreme water levels (Gulf of Riga with Pärnu Bay, Pärnu: +288 cm, −112 cm; Gulf of Finland, Hamina: +197 cm, −115 cm; Bothnian Bay, Kemi: +201 cm, −124 cm; Bay of Mecklenburg, Wismar: +198 cm, −190 cm) than the stations located directly by the open areas of the Baltic Sea (Åland Sea, Degerby: +102 cm, −73 cm; Northern Baltic Proper, Landsort: +95 cm, −70 cm; Southern Baltic Proper, Kungsholmsfort: +110 cm, −89 cm)

(Figures 2a,b). It was observed that extreme water levels rise towards the inside of the bay – this is called the bay effect.

The Bay of Mecklenburg 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 and the above-mentioned bay effect.

The Swedish coasts of the central Baltic (the Northern and Southern Baltic Proper, Western Gotland Basin) are the least exposed to extreme sea levels. This is determined mainly by the easterly exposure of the coast, i.e. the direction opposite to that in which low pressure systems propagate.

The results are consistent with the work of Averkiev & Klevanny (2007, 2010), Suursaar et al. (2003, 2007), Stigge (1994), Jensen & Müller-Navarra (2008), Johansson (2004), Sztobryn et al. (2005, 2009), according to which the south-western and eastern coasts of the Baltic Sea (Bay of Mecklenburg, Gulf of Riga, Gulf of Finland, the northern part of the Bothnian Bay) are exposed to especially dangerous storm surges caused by the deep troughs of low pressure passing through these regions.

Detailed data on the occurrence of maximum and minimum sea levels from 1960 to 2010 for different areas of the Baltic Sea are presented in Table 1.

Table 1. Detailed data on the occurrence of the maximum and minimum sea levels for the period 1960–2010 in different areas of the Baltic Sea

Sea level gauge in the basin	Maximum sea level [cm]	Date of occurrence	Minimum sea level [cm]	Date of occurrence	Amplitude [cm]
Skagerrak					
Smögen	135	16.10.1987	−108	3.01.1976	243
Kattegat					
Frederikshavn	162	1.01.1978	−130	3.01.1976	292
Great Belt					
Aarhus	165	7.11.1985	−154	6.11.1985	319
Korsor	163	1.11.2006	−102	6.11.1985	265
Little Belt					
Fynshav	180	4.11.1995	−139	21.12.2001	319
The Sund					
Hornabeck	166	6.11.1985	−132	5.11.1970	298
Klagshamn	130	29.11.1988	−101	30.01.1987	231

Table 1. (*continued*)

Sea level gauge in the basin	Maximum sea level [cm]	Date of occurrence	Minimum sea level [cm]	Date of occurrence	Amplitude [cm]
Bay of Mecklenburg					
Wismar	198	3.11.1995	−190	4.12.1999	388
Warnemünde	158	3.11.1995	−170	18.10.1967	328
Gedser	158	21.02.2002	−141	18.10.1967	299
Southern Baltic Proper					
Sassnitz	133	17.01.1992	−137	4.12.1999	270
Greifswald	176	3.11.1995	−151	24.11.1981	327
Świnoujście	169	4.11.1995	−134	18.10.1967	303
Kołobrzeg	144	1.11.2006	−130	4.11.1979	274
Władysławowo	144	23.11.2004	−88	4.11.1979	232
Kungsholmsfort	110	16.11.2001	−89	15.02.1996	199
Gulf of Gdańsk					
Gdańsk	144	23.11.2004	−86	4.11.1979	230
Northern Baltic Proper					
Landsort	95	18.01.1983	−70	12.03.1972	165
Stockholm	116	18.01.1983	−69	12.03.1972	186
Ristna	222	9.01.2005	−66	28.03.1980	285
Åland Sea					
Degerby (Foglio)	102	14.01.2007	−73	20.05.1966	175
Bothnian Sea					
Mäntyluoto	132	14.01.1984	−76	31.01.1998	208
Bothnian Bay					
Ratan	142	23.02.2002	−110	26.02.1971	252
Furuögrund	148	14.01.1984	−123	26.02.1971	271
Kemi	201	22.09.1982	−124	31.01.1998	325
The Quark					
Vaasa	144	14.01.1984	−99	31.01.1998	243
Gulf of Finland					
Helsinki	151	9.01.2005	−93	28.01.2010	244
Hanko	132	9.01.2005	−79	28.01.2010	211
Hamina	197	9.01.2005	−115	28.01.2010	312
Narva	207	9.01.2005	−93	30.01.1972	300
Gulf of Riga					
Pärnu	288	9.01.2005	−112	14.10.1976	400

The adoption of the European Vertical Reference System (EVRS 2000) by the Baltic states has enabled all observational data to be converted into one reference level NAP and to show the topography of the surface waters in the whole Baltic Sea area.

3.2. Results of theoretical maximum and minimum sea levels and probabilities of their occurrence (return periods) at selected gauge stations

Owing to the complex nature of the phenomenon, the analysis of extreme changes in water levels during storm surges is complicated. It is hindered by the fact that changes in sea level are largely affected by local conditions – the configuration of the coastline, as well as the morphology and bathymetry of the coastal zone. Therefore, when analysing extreme water levels, it is important to determine the long-term probability forecast based on the longest observation series of maximum and minimum annual sea levels. Probability analysis determines the so-called theoretical sea levels that may occur once in a number of years, e.g. once in 50 or 100 years. Knowledge of the highest sea levels of a given occurrence probability is necessary for determining the characteristics of storm surges. In this work the theoretical value of sea levels for a selected Baltic Sea coast was determined on the basis of the Gumbel distribution (sea level maxima) and the Pearson III type distribution (sea level minima) in the period 1960–2010 (Tables 2 and 3).

Table 2. Theoretical maximum sea levels [cm], the probability of their occurrence (P) and return periods (T) at selected Baltic Sea gauge stations in 1960–2010

T	P	Gauge station						
[years]	[%]	Wismar	Kungsholmsfort	Władysławowo	Stockholm	Pärnu	Helsinki	Kemi
100	1	204.76	135.91	172.42	115.28	249.69	177.57	227.20
50	2	190.83	126.04	158.24	106.60	231.30	163.83	209.80
20	5	172.22	112.86	139.33	95.01	206.77	145.50	186.58
10	10	157.85	102.68	124.72	86.06	187.82	131.33	168.65
5	20	142.87	92.07	109.49	76.73	168.06	116.56	149.95
4	25	137.80	88.48	104.33	73.57	161.37	111.57	143.62
3.33	30	133.51	85.44	99.97	70.90	155.71	107.33	138.26
2	50	120.25	76.05	86.48	62.63	138.22	94.26	121.71
1.33	75	106.30	66.17	72.31	53.95	119.83	80.51	104.30
1.25	80	103.43	64.14	69.39	52.16	116.04	77.68	100.72
1.11	90	96.20	59.02	62.04	47.65	106.51	70.56	91.69
1.01	99	82.44	49.30	47.60	39.08	96.06	57.15	73.42

Table 3. Theoretical minimum sea levels [cm], the probability of their occurrence (P) and return periods (T) at selected Baltic gauge stations in 1960–2010

T	P	Gauge station						
[years]	[%]	Wismar	Kungsholmsfort	Władysławowo	Stockholm	Pärnu	Helsinki	Kemi
1.01	99	−82.92	−35.34	−22.26	−21.90	−44.81	−34.44	−46.82
1.11	90	−91.11	−49.08	−37.20	−30.80	−54.41	−42.66	−65.59
1.25	80	−96.79	−54.62	−43.43	−35.05	−59.85	−47.02	−73.42
1.33	75	−99.35	−56.69	−45.79	−36.75	−62.15	−48.82	−76.39
2	50	−112.10	−64.83	−55.25	−44.05	−72.77	−56.93	−88.27
4	25	−129.12	−72.73	−64.71	−52.15	−85.68	−66.48	−100.13
5	20	−133.79	−74.56	−66.94	−54.17	−89.06	−68.95	−102.93
10	10	−147.90	−79.51	−73.06	−59.97	−99.02	−76.17	−110.60
20	5	−167.20	−85.23	−80.05	−64.50	−113.50	−85.06	−114.35
50	2	−179.21	−88.56	−85.45	−70.24	−119.21	−91.27	−125.40
100	1	−187.55	−90.60	−87.20	−74.70	−125.65	−95.25	−128.28

Tables 2 and 3 show that the height of an extreme sea level with a 100-year return period (a probability of 1%, once per century) depends on the location. At Stockholm, the 100-year annual water level is 115.3 cm for maximum sea levels above zero gauge and −74 cm for minimum sea levels below zero gauge. This results from the fact that this gauge station is located at some distance from the open sea (Ekman 2009, Hammarklint 2009). At the remaining gauge stations the theoretical 100-year extreme (maximum and minimum) sea levels are significantly larger: Kungsholmsfort: 135 cm and −91 cm, Władysławowo (Poland): 172 cm and −87 cm, Wismar (Germany): 205 cm and −188 cm, Kemi (Finland): 227 cm and −128 cm, Pärnu (Estonia): 250 cm and −126 cm. The highest of the maximum values and the lowest of the minimum values of the observed and theoretical sea level series are due to storm surges and their impact on the sea coast.

The probability distributions of theoretical sea levels for two characteristic tide gauge stations in the Baltic Sea (Stockholm – an inland station, central Baltic; Kemi – the station in the northern Bay of Bothnia) are illustrated in Figure 3. This confirms the differentiation in the distribution of the probability of theoretical sea levels depending on the tide gauge's location.

Figure 4 illustrates the geographical distribution of the theoretical 100-year maximum and minimum water levels determined from the 50 years between 1960 and 2010, based on the maximum and minimum annual sea levels on the coasts of the Baltic Sea.

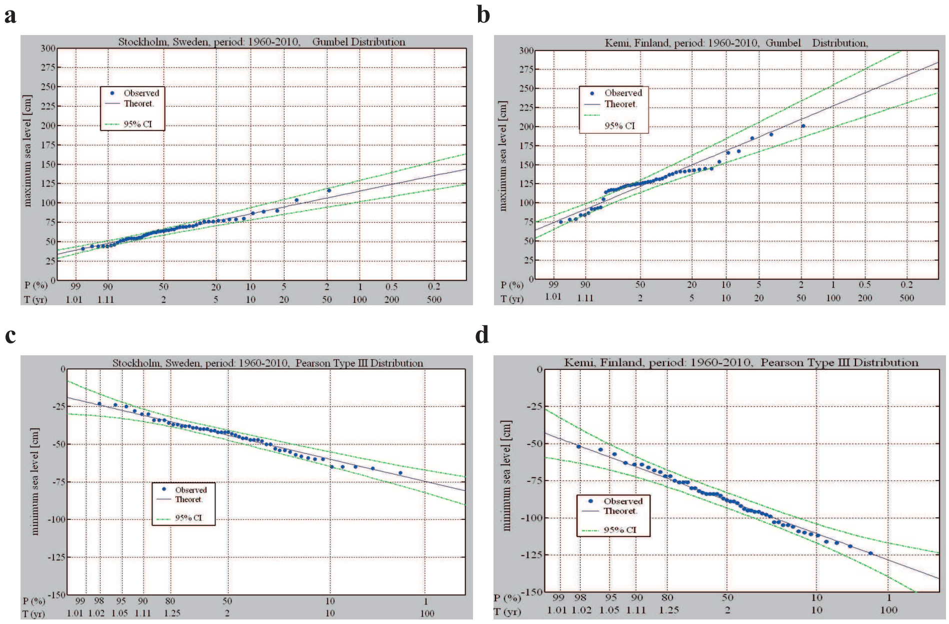

Figure 3. Theoretical and observed maximum (a, b) and minimum (c, d) sea levels at Stockholm (left) and Kemi (right) in 1960–2010

The distribution of the theoretical hundred-year water levels (Figure 4) is similar to that of the real extreme water levels in the Baltic Sea (see Figure 2). This dependence is understandable since the theoretical levels were calculated on the basis of real annual extremes. The most extreme theoretical hundred-year maximum levels (> 200 cm NAP) and theoretical minimum water levels (< −100 cm NAP) would occur in the innermost parts of the Bay of Bothnia, Gulf of Riga, Gulf of Finland and Bay of Mecklenburg. On the other hand, the Swedish coasts of the central Baltic have the lowest theoretical hundred-year water levels (< 140 cm NAP for the maximum theoretical levels and > −100 cm for the minimum theoretical levels). Owing to their transitory location between the North Sea and central Baltic, the Danish Straits (Skagerrak, Kattegat, Sund, the Belts) are regions with intermediate theoretical hundred-year levels, since the Danish Straits hydraulically balance the water levels between the North Sea and the Baltic Sea.

It is particularly important for the methodology of probability calculations to analyse the longest possible series of sea level records (at least tens of years). Only then can the results be considered reliable and practical. The probability of occurrence of high Baltic sea levels can be used in the design

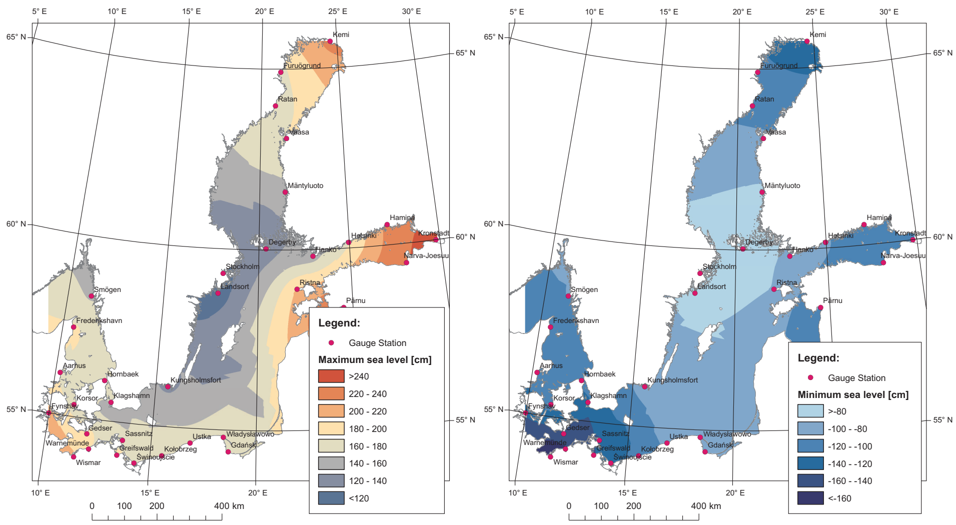

Figure 4. Surface water topography of the Baltic Sea for the theoretical 100-year maximum water level (a) and the theoretical 100-year minimum water level (b); sea levels related to NAP

of coastal hydro-engineering infrastructure, management of the coastal zone and of areas inundated during storm and flood events.

Methods of determining the occurrence probability of extreme sea levels were described by Wróblewski (1975); the prediction of extreme Baltic Sea levels was also considered by Jednorał et al. (2008). However, the methodology of such studies is best described by Wiśniewski & Wolski (2009b), a paper that focused on the Polish coast, and in a later work by the same authors (Wolski & Wiśniewski 2012), which contains calculations comparing the Polish and Swedish coasts of the Baltic Sea.

3.3. Number of storm surges on some coasts of the Baltic Sea

As part of the analysis of extreme sea levels, this work also determines the number of storm surges in the period 1960–2010 for Baltic Sea coasts. The results for selected tide gauge stations are shown in Figure 5 and in Table 4.

Table 4 and Figure 5 show that the number of storm surges on the Baltic coast has been growing steadily in the past 50 years. For example, Gedser, Denmark, from an average of 4.4 to 6.5 storms annually, Wismar, Germany, from an average of 4.2 to 6.2 storms annually, Kemi, Finland, from an average of 5.5 to 7.7 storms per year, and Ristna, Estonia, from an average of 2.1 to 4.1 storms per annum (Table 4). The increasing number of storm surges in the Baltic Sea may be due to climate change, the NAO

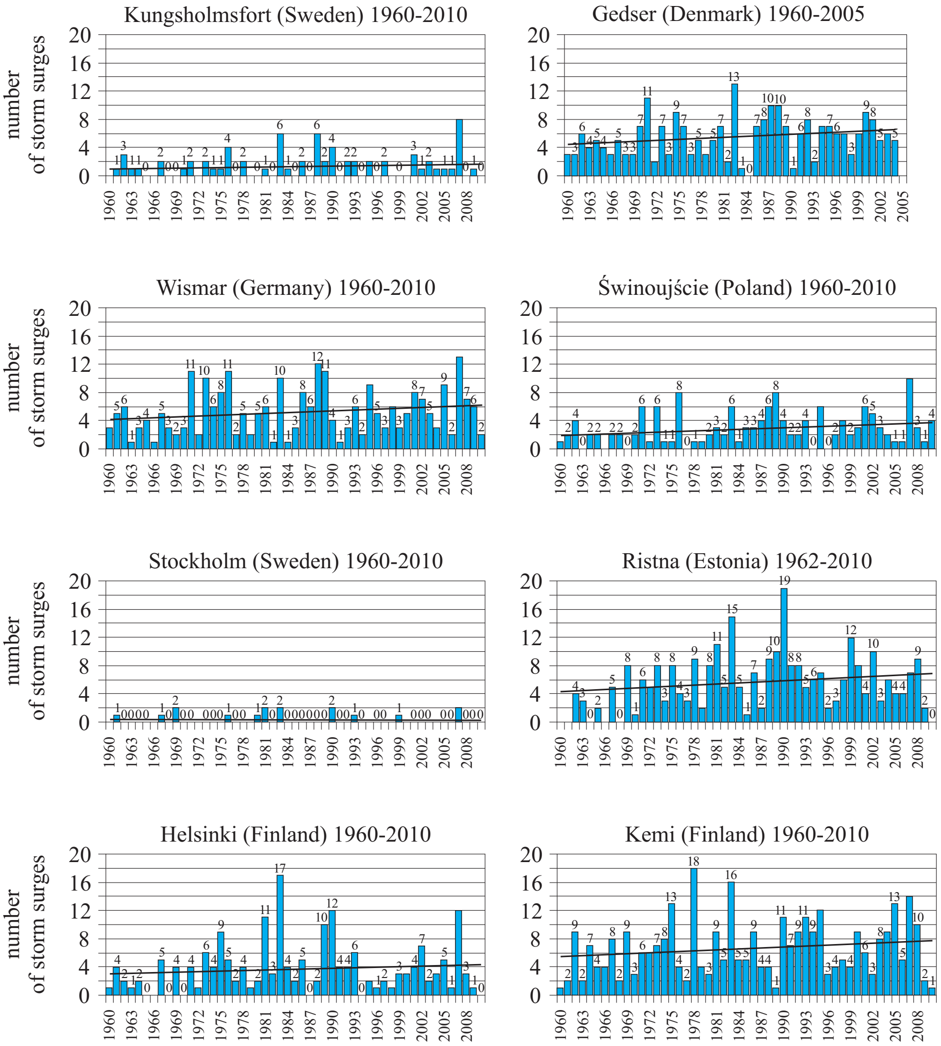

Figure 5. Number of storm surges (maximum of surge ≥ 70 cm above zero NAP) at selected Baltic tide gauge stations

index or local wind conditions (Gönnert 1999, 2004, Johansson et al. 2004, Woth et al. 2006, Suursaar et al. 2007, Suursaar & Sooäär 2007, Woodworth et al. 2007, Ekman 2009, Sterl et al. 2009, Weisse & von Storch 2010).

The numbers of storm surges determined in this work (maximum surge ≥ 70 cm NAP) for all the tide gauge stations for the period 1960–2010 on Baltic coasts are illustrated in Figure 6.

A pattern emerges from Figure 6 that the stations located in the innermost parts of the gulfs, at a long distance from the open waters

Table 4. Number of storm surges (maximum surge ≥ 70 cm NAP and maximum surge ≥ 100 cm NAP) in the period 1960–2010 for selected tide gauge stations of the Baltic Sea

Gauge station	Number of storm surges between 1960 and 2010		The average increase/decrease of the number of storm surges between1960 and 2010
	≥ 70 cm	≥ 100 cm	
Klagshamn	130	29	2.3 → 2.8
Kungsholmsfort	69	7	1.0 → 1.7
Gedser	251	76	4.4 → 6.5
Wismar	265	105	4.2 → 6.2
Świnoujście	145	37	1.9 → 3.8
Gdańsk	113	30	1.4 → 3.1
Stockholm	16	3	0.4 → 0.3
Ristna	154	47	2.1 → 4.1
Pärnu	426	249	8.7 → 11.8
Helsinki	187	48	3.1 → 4.3
Hamina	411	152	5.4 → 10.7
Narwa	317	145	6.8 → 10.8
Kemi	335	127	5.5 → 7.7
Ratan	112	18	1.7 → 2.7

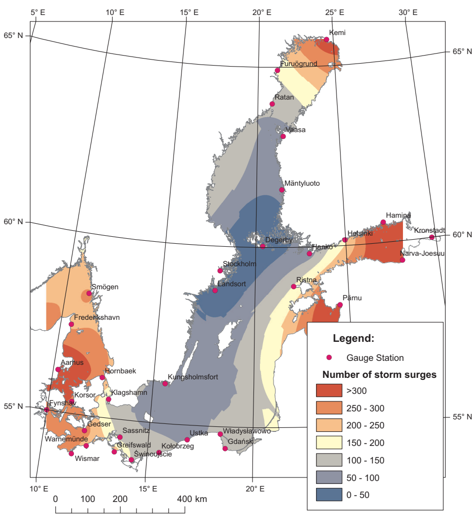

Figure 6. Number of storm surges (maximum surge ≥ 70 cm above zero NAP) on the coasts of the Baltic Sea

of the Baltic Sea (Kemi, Narva, Hamina, Pärnu, Wismar, Gedser) are characterised by the greatest number of storm surges on the Baltic Sea (more than 300 in the whole period 1960–2010). The numbers of storm surges increase from the offshore boundary of a gulf to the point on land farthest from this boundary, which may also be related to the bay effect. The Danish Straits are the regions with the same high number of storm surges as the bays of the Baltic itself (200–300 surges). This is affected by the exchange of waters with the North Sea, the specific morphological and hydraulic system of the straits, and also the tides that raise the level of water, which in this area are from several to several tens of cm (which in total gives a level exceeding 70 cm NAP). On the other hand, the Swedish coasts of the central Baltic (the stations at Kungsholmsfort, Landsort, Stockholm) and also the coasts of the southern part of the Gulf of Bothnia (Hanko, Mäntyluoto) have the lowest number of storm surges on the Baltic Sea (< 100). This is due mainly to the easterly exposure of the Swedish coasts in relation to the trajectories of low pressure systems.

3.4. Storm surge events

The two storm events on 15–16.11.2001 and 8–9.01.2005, showing the various types of short-term changes in the surface topography of the Baltic Sea level, have been chosen in the last part of the paper.

Table 5 contains data describing the features of the low pressure systems, recorded sea levels, as well as the static and dynamic deformations of the sea surface, calculated using formulae (3) and (4). The static surge would be reliable for the Baltic for a low pressure centre if this were stationary. The dynamic sea surface deformation ought to characterise the actual effect of the depression on the sea level near coasts, but it does not involve so-called shallow water factors, such as friction, the energy dissipation rate in the outer port and the roads. The mathematical expression of such factors has yet to be developed for storm events. The world literature contains only shallow-water factors for tides, i.e. regular, periodic sea level changes.

3.4.1. Storm event of 15–16 November 2001

An example of seiche-like fluctuations of the sea level in the whole Baltic Sea

This swaying surface of the Baltic Sea was created by the impact of a deep low-pressure system area that moved quickly from Greenland to the Norwegian Sea on 14 November 2001 (Figures 7a,b). On 15 November 2001, this depression passed at a speed of 63 km h^{-1} through central Scandinavia and the northern Baltic Sea (Figure 7c), causing a rapid decrease in the sea level at the gauge stations in the western and southern Baltic (-150 cm – Skänor, -118 cm – Gedser, -122 cm – Kiel, -74 cm – Świnoujście)

Table 5. Parameters of the storm surges analysed (sea levels related to NAP, explanation of symbols in Material and methods)

Date of storm	Station	Attribute of depression p_i [hPa]	Attribute of depression V_L [m s^{-1}]	Recorded sea level: Initial sea level	Max. [cm]	Min. [cm]	Amplitude [cm]	Maximum sea level rise rate [cm hour^{-1}]	Minimum sea level rise rate [cm hour^{-1}]	Baltic Sea $H_m = 55$ m: ΔH_s [cm]	ΔH_d [cm]
15–16 November 2001	Skanör	978	17.4	40	126	−150	276	47	24	+35.5	+81
	Gedser			43	113	−118	231	34	16		
	Kiel			38	121	−122	243	32	19		
	Świnoujście			49	90	−74	164	25	19		
	Klaipeda			61	115	47	68	11	20		
	Ristna			54	148	45	101	16	13		
	Hamina			57	161	−50	211	23	36		
	Kemi			20	102	−36	138	16	17		
8–9 January 2005	Skanör	961	16.6	24	53	−139	192	30	34	+52.7	+108
	Gedser			7	68	−137	205	16	26		
	Kiel			−7	58	−153	211	24	27		
	Świnoujście			5	33	−84	117	20	24		
	Klaipeda			68	146	66	80	25	12		
	Ristna			65	222	80	142	26	15		
	Hamina			53	194	43	151	40	20		
	Kemi			51	89	34	55	8	6		

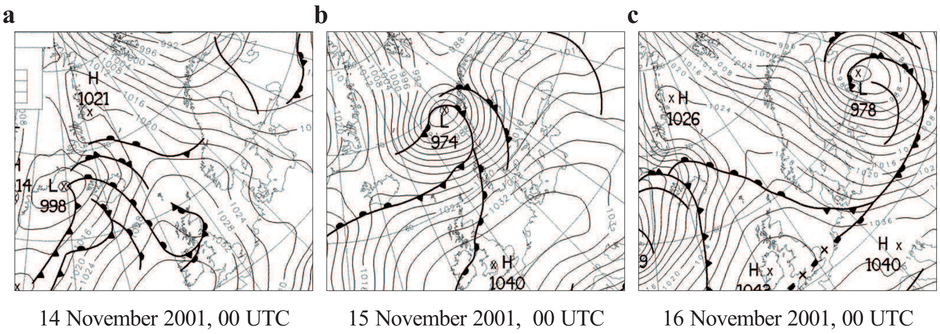

Figure 7. Weather map for northern Europe from the period 14–16 November 2001, (source: Meteorological Office, Bracknell, UK)

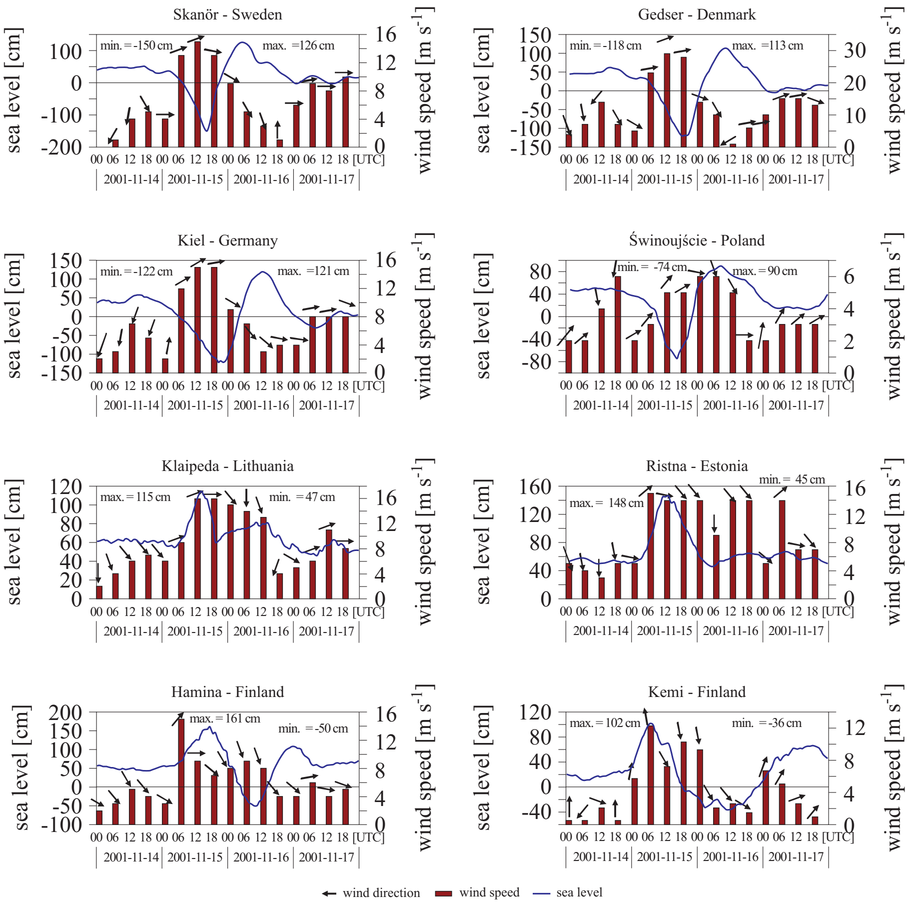

Figure 8. Changes in water levels at selected tide gauge stations of the Baltic Sea against the background of wind speed and directions from 14 to 17 November 2001

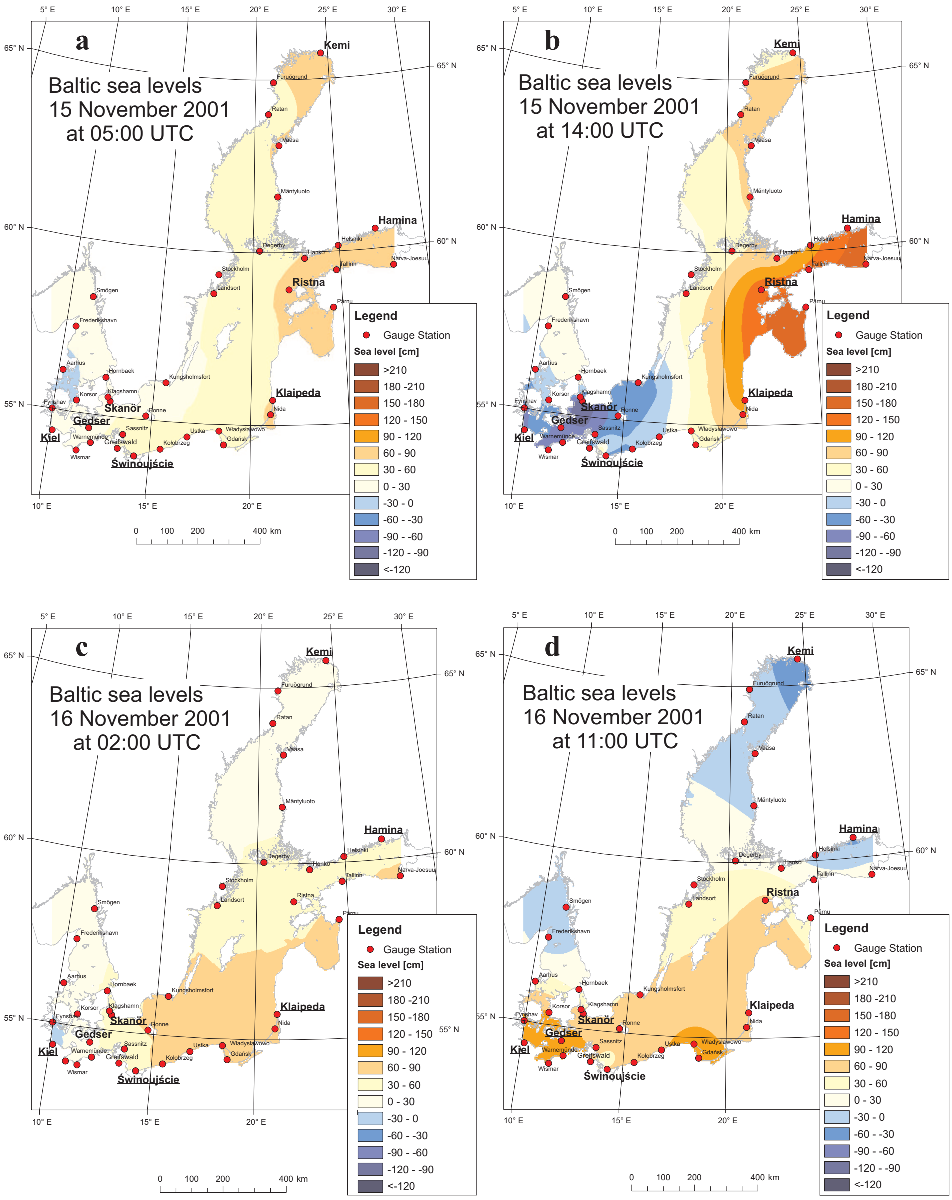

Figure 9. Short-term changes in the surface topography of Baltic Sea water on 15–16 November 2001 (sea levels related to NAP)

(Figure 8). At the same time, sea levels rose rapidly at gauge stations in the Gulf of Riga (+171 cm – Pärnu), Gulf of Finland (+161 cm – Hamina) and Gulf of Bothnia (+102 cm – Kemi) (Figures 8, 9a,b). On 16 November 2001, a change in the deformation phase of the Baltic Sea surface occurred.

The high water levels of 15 November occurring so far on the eastern coast of the Baltic Sea turned into negative water levels (−50 cm – Hamina, −36 cm – Kemi). Simultaneously, in the western Baltic and the Danish Straits, sea levels increased above 1 m (+126 cm – Skänor, +113 cm – Gedser and +121 cm – Kiel) (Figures 8, 9c,d). These dynamic changes in the Baltic Sea surface and the extreme amplitudes of the water level fluctuations in one day cannot be explained only by wind field characteristics (wind speed and direction in Figure 8). Negative pressure within the depression (974 hPa), which quickly moved across the Baltic Sea, also contributed to the creation of this hydrological situation (sea surface deformation).

3.4.2. Storm event of 8–9 January 2005

An example of the impact of a family of atmospheric low-pressure systems with the dominant mid-latitude depression Gudrun (Erwin) on water levels in the Baltic Sea.

On 7 January 2005, a group of deep atmospheric low pressure systems of 959–979 hPa connected with frontal systems were generating a predominantly SW and W wind field over the Baltic Sea with a speed of ca 10 m s^{-1} (Figure 10). This resulted in a small decrease in the water level in the western Baltic (Gedser −36 cm, Kiel −56 cm) and the filling up of the Baltic Sea in the eastern and northern part (Klaipeda +84 cm, Ristna +113 cm, Hamina +121 cm) (Figure 11). The next day, 8 January, the mid-latitude depression Gudrun left Scotland and moved at a speed of 60 km h^{-1} across the North Sea into the southern part of the Gulf of Bothnia, where the pressure fell to 961 hPa (9 January, 00 UTC) (Figures 10a,b). On 8 January 2005, the wind speed increased to 20 m s^{-1} throughout the Baltic

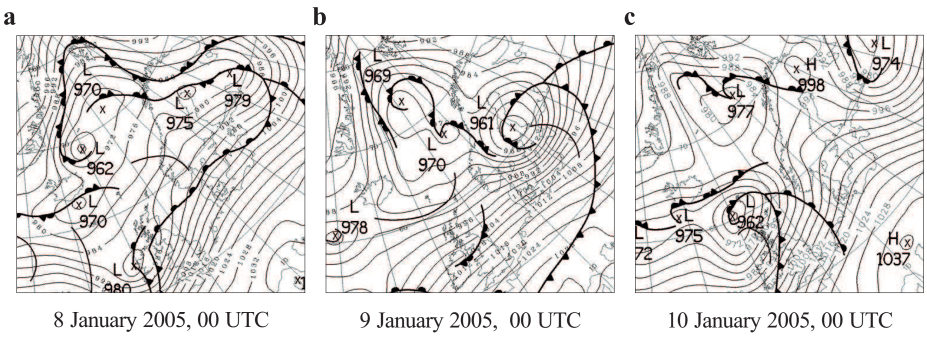

Figure 10. Weather map of northern Europe for 8–10 January 2005, (source: Meteorological Office, Bracknell, UK)

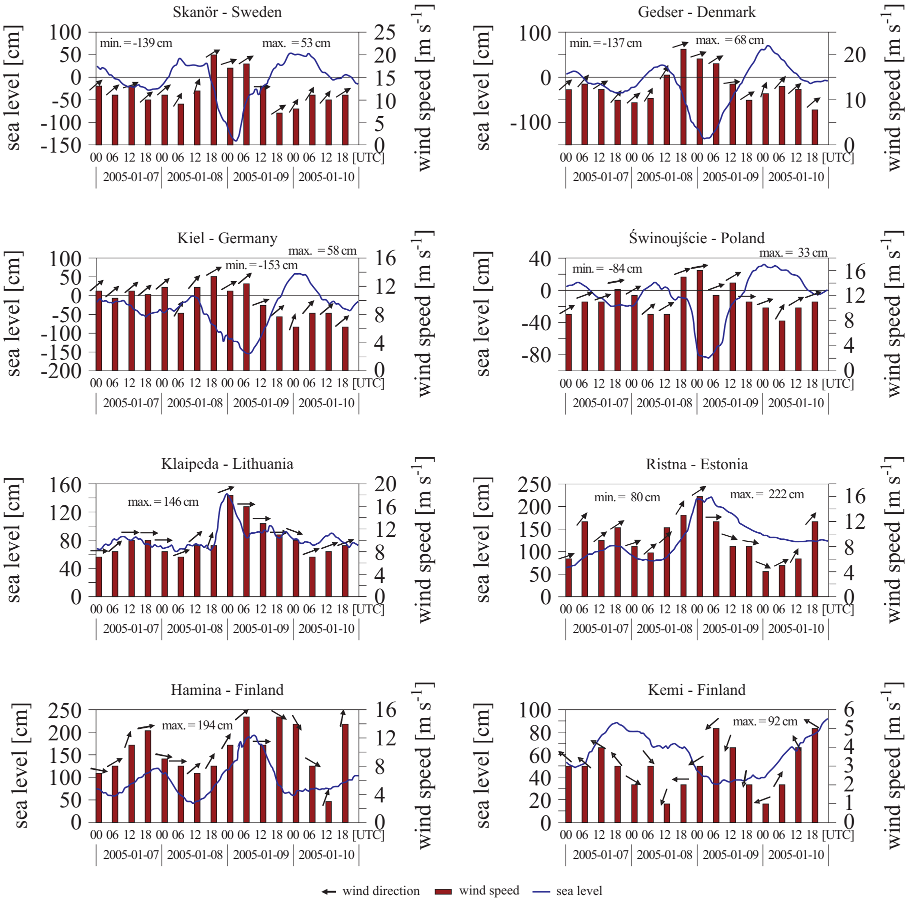

Figure 11. Changes in water levels at selected tide gauge stations in the Baltic Sea against the background of wind speed and directions from 7 to 10 January 2005

Sea region. Such a quick passage of the depression caused deformations of the Baltic Sea surface. A slight rise in sea level and a subsequent rapid decrease were observed in the western part of the Baltic towards the end of 8 January (Frederikshavn, from +99 to −40 m, Gedser, from +26 m to −136 m, Kiel, from 0 to −153 cm) (Figures 11, 12a). At the same time, in the north-eastern Baltic, sea levels rose sharply to extreme values (Klaipeda +146 m, Ristna +222 m, Hamina +194 m) (Figures 11, 12b,c). On 9 and 10 January 2005, depression Gudrun moved north-eastwards through southern Finland to western Russia (Figures 10b, c). A change in the deformation phase of the Baltic Sea surface occurred. Sea levels rose sharply in the western Baltic (Gedser +68, Kiel +58 m) but dropped in the eastern part of the sea (Figures 11, 12d).

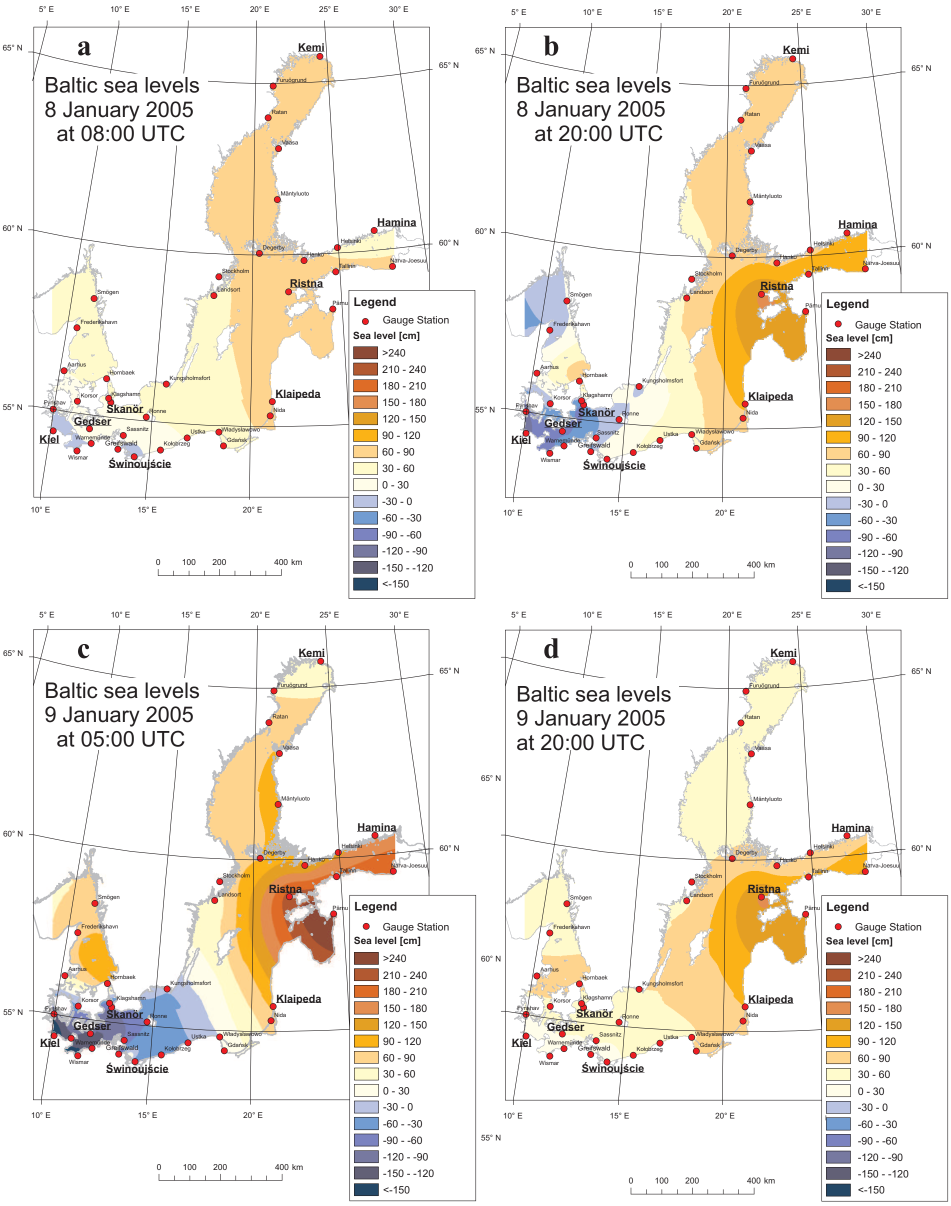

Figure 12. Short-term changes in the surface topography of the Baltic Sea water level on 8–9 January 2005 (sea levels related to NAP)

4. Discussion

The occurrence of extreme sea levels, which are the result of storm surges on the Baltic coasts, depends on three components:

– the volume of water in the respective basins 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 duration of wind action),

– deformation of the sea surface by the mesoscale, deep low-pressure systems passing rapidly across the Baltic, which then generate seiche-like variations of the sea level in the Baltic.

The volume of water filling a water basin prior to an extreme sea level has been stated in a few publications in the context of the Polish coast (storms in the southern Baltic) (Wiśniewski 1996, Stanisławczyk & Sztobryn 2000, Sztobryn et al. 2005, Wiśniewski & Wolski 2009a). For example, the volume of water filling a basin was determined by calculating, on the basis of observations, the mean sea level along the Kołobrzeg-Kungsholmsfort transect or by reference to records from other ports like Degerby, or other transects in the Baltic (Stanisławczyk & Sztobryn 2000). In general, the water exchange between the North Sea and the Baltic and changes in the Baltic water volume produced by long-lasting stationary pressure systems were described by Wielbińska (1964). In the context of the two storm situations analysed in this work, basin filling is represented by the starting (reference) sea level prior to the changes caused by the storm (Table 5).

The role of tangential wind stresses in the generation of drift currents and their resultant contribution to the rise or fall of sea level in the ports of an area is understandable; the magnitude of a rise or fall depends not only on the wind speed, but also on the wind duration, direction, wind fetch over the sea surface, and compensatory flows in the inshore zone. The wind effects are directly related to the pressure distribution over an area. However, as shown by tide gauge records, true sea level surges and falls can be several times higher than the values resulting from the action of tangential wind stress upon a fluid surface (Wiśniewski & Holec 1983). Suursaar et al. (2003) pointed out that the highest surge events on the west Estonian coast are associated with deep depressions producing strong SW and W winds in suitably oriented bays such as Pärnu Bay. An example is the mid-latitude depression Gudrun, which occurred in January 2005 and caused the heaviest storm surge along the coasts of the Gulf of Riga (Suursaar et al. 2006). The sea level at Pärnu was 2.75 m higher than the mean level there. In the Gulf of Finland, record increases in sea level were measured as well, e.g. at Helsinki (1.51 m). Skriptunov & Gorelits (2001) showed that significant wind-induced variations in the water level near the River Neva as well as their magnitude and duration result from the wind regime and the morphology of the near-mouth offshore zone. Averkiev

& Klevanny (2007, 2010) analysed the effects of atmospheric pressure as well as wind direction and speed on the sea level in the Gulf of Finland. They showed the low pressure system trajectory to be potentially important in generating storm surges particularly damaging for St. Petersburg (Russia).

The problem of sea surface deformation by concentric, mesoscale, fast-moving deep low-pressure systems was addressed by Lisowski (1960, 1961, 1963), Wiśniewski (1996, 1997, 2003), Wiśniewski & Holec (1983), Wiśniewski & Kowalewska-Kalkowska (2007) and Wiśniewski & Wolski (2009a, 2011). It seems, however, that this factor has been generally underestimated, even downright ignored, in the literature, a situation that has been detrimental to attempts at explaining mechanisms of such extreme phenomena as coastal floods or low sea levels that adversely affect navigation safety, stability of hydraulic engineering structures, etc. It is true that a lowered atmospheric pressure system (a tropical cyclone or a concentric low pressure system) overlies a water cushion, moving together with the pressure system at the sea surface. Wave height depends on the pressure decrease in the centre of the system. A pressure drop of $\Delta p = 1$ hPa results in a static sea level rise of $\Delta H_s = 1$ cm under a stationary low (Figure 1a, formula (3)). When the depression moves over the sea surface, the latter becomes dynamically deformed (ΔH_d). The sea level deformation shows positive wave elevations in the centre and negative elevations on the flanks of the deformation (Figure 1b, formula (4)). During the passage of a deep low pressure system, the sea level rise may be 2–4 times higher than that produced by static conditions.

Thus, storm-generated surges and falls of sea level are the net effect of wind action and sea surface deformation resulting from the baric field's characteristics. Wind and sea surface deformation can produce the same effect, i.e. both factors cause the sea level on the coast to rise or fall; but they can also produce opposite effects, when one factor raises the sea level and the other lowers it. The effects of surface deformation may be several times greater than those of wind action. When the storm abates, the sea level – knocked out of balance – will undergo free, damped oscillations until equilibrium is restored (seiche-like variations).

The contribution to sea surface deformation by mesoscale, fast-moving deep low-pressure systems in the overall picture of rises and falls in sea level is confirmed by the examples of the storm events selected for this work, i.e. 15–16 November 2001 and 8–9 January 2005.

In addition to the hydrological and meteorological factors discussed above, extreme water levels are also affected by local conditions, that is, mainly the geographical location of the water level gauge station as well as the geomorphological and bathygraphic characteristics of the coastal zone.

These local conditions generate the so-called bay effect. This causes an increase in extreme sea levels (maxima and minima) at the bay stations of the Baltic Sea from the sea boundary of the bay to the furthest internal point intersecting with the land (the end of the bay). One of the main reasons for this phenomenon is the size of the area of open water relative to the length of the coast and the widening of the bay. The specific volume of water removed or added to that part of the bay where it becomes narrower and shallower increases the extreme water level when compared to the wider mouth of the bay. This interpretation is consistent with the results of Sztobryn et al. (2005, 2009), which describe storm depressions and surges from the Bay of Mecklenburg and the western part of the Polish coast. According to those authors, the probability of extreme sea level events occurring in this area decreases from west to east (from Wismar to Kołobrzeg) as a result of the configuration of the shoreline and bathymetry of the Bay of Mecklenburg (this Bay becomes narrower and shallower to the west).

5. Conclusions

Extreme water levels in the Baltic Sea are understood in this study as the maximum and minimum sea levels considered at various time intervals. A good way of characterising extreme water levels is to present the spatial topography of the absolute maximum and minimum sea levels of the Baltic Sea from 1960 to 2010 (Figure 2). The analysis shows that the areas of the Baltic Sea particularly exposed to extreme sea levels are the south-western coasts (the Bay of Mecklenburg) and the eastern coasts (the Gulf of Riga with Pärnu Bay, the Gulf of Finland, the northern part of the Gulf of Bothnia). The water level gauge stations located in the innermost parts of these gulfs (Pärnu, Narwa, Hamina, Wismar, Kiel) record the highest extreme water levels on the Baltic Sea (above 200 cm relative to the NAP zero). This is mainly due to the so-called bay effect, which is the increase in extreme water levels towards the interior of the gulf as it becomes narrower and shallower.

The Bay of Mecklenburg is the Baltic basin where the greatest falls in sea level due to storm surges have been recorded (levels lower than −140 cm relative to NAP), which is also related to its relatively small depths.

The Swedish coasts of the central Baltic (Northern and Southern Baltic Proper, Western Gotland Basin) are the coasts least exposed to extreme sea levels (extreme levels within +150 cm to −100 cm). This is determined mainly by the easterly exposure of the coast, which is the opposite direction to that in which low pressure systems propagate.

The probability analyses carried out in this work show that the distribution of the theoretical hundred-year water levels (Figure 4) is similar to that of real extreme water levels in the Baltic Sea, shown in Figure 2. This dependence is understandable, since the theoretical levels were calculated on the basis of real annual extremes. The most extreme theoretical hundred-year maximum water levels occur within the large bays of the Baltic Sea (Bay of Mecklenburg, Gulf of Riga, Gulf of Finland, Gulf of Bothnia). On the other hand, the Swedish coasts of the central Baltic (Northern and Southern Baltic Proper, Western Gotland Basin) have the lowest theoretical hundred-year water levels. The Danish Straits, due to their intermediate position between the North Sea and central Baltic, are water regions with intermediate theoretical hundred-year water levels. It is particularly important for the methodology of probability calculations to analyse the longest possible series of sea level observations (at least tens of years). Only then can the results be considered reliable and practical.

As a part of the characteristics of extreme sea levels, the number of storm surges in the period 1960–2010 at selected water level gauges in the Baltic Sea (Table 4, Figure 5) was determined. In the last 50 years, the number of storm surges along various Baltic coasts has been increasing steadily. This phenomenon can be explained by climate change, changes in the NAO index, or change in the local wind conditions.

The next regularity related to the number of storm surges confirms the bay effect. The water level gauge stations located deep in the gulfs (Kemi, Narva, Hamina, Pärnu, Wismar, Gedser), at a long distance from the open Baltic Sea waters, have recorded a greater number of storm surges and are characterised by the greatest number of storm surges on the Baltic Sea (more than 300 in the whole period from 1960 to 2010) (Figure 6). The Danish Straits as well as the bays of the Baltic Sea are areas with a high number of storm surges (200–300 surges). This is affected by the exchange of waters with the North Sea, the specific morphological and hydraulic system of the straits and also by the tides that increase the water level. In contrast, the Swedish coasts of the central Baltic (the stations of Kungsholmsfort, Landsort, Stockholm) and also the coasts of the southern part of the Gulf of Bothnia (Hanko, Mäntyluoto) have the lowest number of storm surges on the Baltic Sea (< 100). This is due mainly to the easterly exposure of the Swedish coasts in relation to the trajectories of the low pressure systems.

The last part of this paper analyses two examples of storm situations in which storm surges and falls occurred at the same time. This analysis provides a physical interpretation of storm surges and storm falls, as a result not only of the impact of the wind field but also the dynamic deformation of the sea surface by mesoscale, deep low-pressure systems. In such cases, seiche-like reactions of the Baltic Sea waters take place. These storm examples are explained overall by the synoptic situation, the variations in water level at the gauge stations and the surface water topography of the Baltic Sea (Figures 8, 9, 11 and 12). Sea surface deformation, which is caused by rapidly moving low-pressure systems, is a factor that will have to be included in future models developed to forecast storm surges and falls.

An important advantage of this study was to obtain the surface waters of the Baltic Sea in the homogeneous, geodetic system EVRS, which is based on the NAP reference level. This enabled observational data obtained from the water level gauge stations in particular Baltic countries to be related to the single reference level NAP. According to the progressive increase in the amount and accuracy of geophysical observations and satellite measurements, the definition of new parameters of the geoid and ellipsoid is to be expected.

Acknowledgements

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