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SEA LEVEL VARIABILITY IN THE EASTERN PART OF THE POLISH BALTIC SEA COAST 1975-2004

KATARZYNA J. MAROSZ*, EWA JAKUSIK**
*Institute of Oceanography, University of Gdańsk, Poland,
Piłsudskiego 46, 81-378 Gdynia, Poland
E-mail: marosz@ocean.univ.gda.pl

**Institute of Meteorology and Water Management, Poland,
Podleśna 61, 01-673 Warszawa, Poland
E-mail: ewa.jakusik@imgw.pl

ABSTRACT: Sea level, which has been rising over the years, constitutes a higher reference level for storm surges and floods. According to the IPCC, extreme phenomena occurred more frequently and this could be connected with global climate change. The work presents the relative changes of sea level and a determination of its quantitative and qualitative variability in the eastern part of the coast along the Polish Baltic Sea which was investigated for the purpose of this paper. The analysis is based upon the results of four tide-gauges: Władysławowo, Hel, Gdynia and Gdansk–Harbour. The first part of the paper examines long-term and seasonal fluctuations of sea level, then the paper discusses the matter of amplitudes, and the final part analyses the appearance of high water levels and storm surges during the year.

KEY WORDS: sea level change, storm surges, southern Baltic Sea

INTRODUCTION

The Baltic's sea level depends on a combination of factors. A barrage repletion of the basin, hydrometeorological conditions and isostatic lift all need to be taken into account. The last one belongs to a long–term scale variability condition. Short-term, dynamic changes of sea level are connected with anemobaric conditions. Wind speed is determined mainly by the magnitude of horizontal atmospheric pressure gradient (the higher the gradient the greater the wind speed). A long duration together with strong winds towards land moves a mass of water and subsequently accumulates it on the seashore increasing the risk of a storm surge. A barrage repletion of a basin and its direction determine the point of reference from which a waving process is started. When the barrage repletion of the Baltic Sea is low then a storm surge will not be so intense, as in the case with a high barrage repletion.

According to A1B SRES scenario (IPCC 2007), which presupposes the best estimated rate of greenhouse gas emission, in the nineties of the 21st century the average global sea level will be 0.22-0.44 m higher in comparison with the sea level in 1990 and will be rising by about 4 mm/year. The increase of sea level at a global scale has been analyzed and described by many authors (i.e. Nicholls 2003, 2006; P. Woodworth 2002, 2003, 2006; J. Church 2001, 2004, 2006) and its occurrence is beyond doubt. However, the effects of this process vary between the regional and local levels, not to mention the hemispheric or global scales. It is necessary to distinguish relative sea level changes from absolute ones. The first indications regarding changes of sea level was recorded at a tide-gauge and did not take changes of land level as opposed to real changes into consideration (Rotnicki 2008). The consequences of an increase in sea level could be far-reaching, which means that this parameter is important not only for science but also in the economic and social spheres.

An analysis of relative sea level change and a determination of its quantitative and qualitative variability in the eastern part of the Polish Baltic Sea coast is the purpose of this paper. The long-term and seasonal variability of water level fluctuations were studied together with trend analysis. Subsequently, amplitude variability was studied. Finally, analysis of high water levels and storm surges during the year was carried out. The data source comprised of four tide-gauges of the Institute of Meteorology and Water Management (IMGW): Władysławowo, Hel, Gdynia and Gdansk–Harbour (Table1, Fig.1.). All of the stations belong to a first order sea observing station. The time-frame of the analysis is the years 1975-2004.

Observed changes in the climate of the Baltic Sea region are a reflection of those at the global level. In this location, however, a spatial variability of glacio-isostatic movements has an impact upon the average sea level. The northern part of the Baltic Sea basin is being lifted up, and on the other hand the southern part is descending – Fig 2a. The isoline of 0 mm/year, which is the boundary between the land that is being lifted upwards in the North and the subsidence in the South, runs approximately across 56° N. In the northern part of Finland the phenomenon reaches its highest point with 9 mm/year and thereafter decreases towards the South of the country. During the last century the world's oceans rose approximately 1.5 mm/year; the rate that the Baltic Sea area rose, however, increased in half this time (Pustelnikovas 2002). While the rate of sea level increase in the south-eastern part of the Baltic Sea is estimated at about 1.7 mm/year, in the north-western Gulf of Bothnia it has been reversed and is estimated to be at 9.4 mm/year. HELCOM predicted that the isostatic uplift of the Scandinavian land plate will be one of two main factors behind the increase of the average sea level in the southern part of Baltic Sea (sea level changes are the other factor). In fact, the net-balance between isostatic land movements and the global average sea level rise determines the situation in the Baltic Sea area (if sea level is generally rising or lowering in relation to the bedrock). As a re-

Table 1. Coordinates of tide-gauges.

Station	Latitude	Longitude
Władysławowo	54° 47' 48"	18° 25' 07"
Hel	54° 36' 07"	18° 48' 03"
Gdynia	54° 31' 04"	18° 33' 19"
Gdansk–Harbour	54° 23' 59"	18° 41' 53"

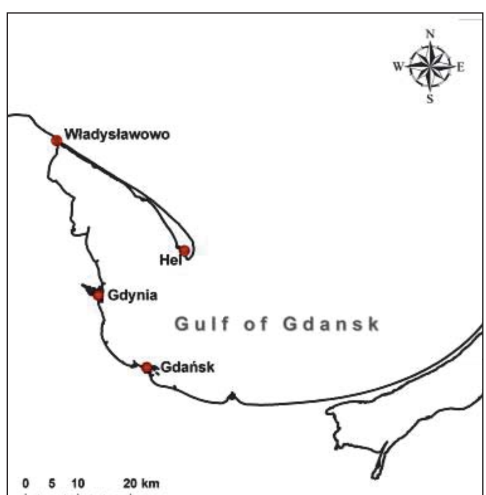

Figure 1. Position of tide-gauges.

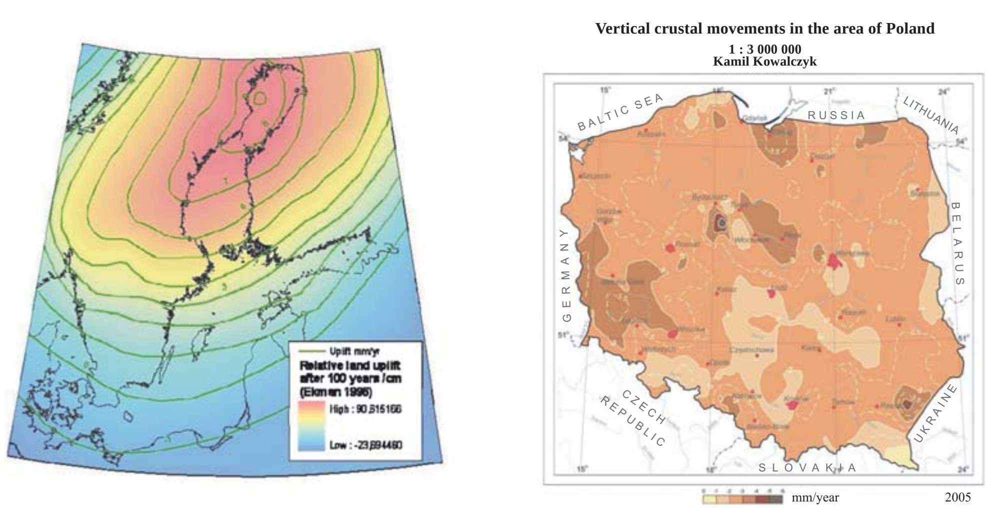

Figure 2. Isostatic lift - Fennoscandia (a); Poland (b).

sult of glacio-isostatic movements, it is predicted that the mean sea level will be higher in the southern Baltic, The Baltic proper, the Gulf of Finland and the Gulf of Bothnia are lower when compared with the annual mean sea level for 1961-1990 (Meier *et al*. 2006). The research results of Kowalczyk (2006) suggests that Władysławowo and Hel are lowering at a rate of about 2 mm/year, whereas Gdynia and the western part of Gdańsk are descending at 3 mm/year (the eastern part that encompasses the Vistula Delta is rising about 4 mm/year) – Fig. 2b. In the last case this is especially important because over 30% of the Gdańsk area is located below 2.5 m a.s.l. and 8% below sea level (Kaulbarsz *et al.* 2006).

RESULTS AND DISCUSSION

In the world ocean an increase of the rate of sea level over time was recorded. Changes in the South Baltic Sea reflected this global phenomenon. In the period 1951-1990 the rate of sea level increase in Gdańsk was 4.02 mm/year whereas in the years 1971-1990 the pace quickened to 7.67 mm/year (Rotnicki and Borzyszkowska 2008). Clearly an increase in the rate of this phenomenon can be observed for the time series 1880-2000 in Gdańsk (Fig. 3).

The variability of sea level is seasonal; this means that it changes during the year. Long-term monthly mean relative maximum, average and minimum values of sea level increased from Władysławowo through Hel, Gdynia to Gdansk–Harbour where the highest value from among all the points occurred (Fig.4). In an annual cycle the highest long-term mean maximum and average values of sea level appeared in January and the minimum in July. The maximum sea level was observed between March and May. In turn long-term average minimum values at all the analyzed tide-gauges appeared in May. Average sea level in the years 1975-2004 at Władysławowo station was 505.0 cm, Hel 505.4 cm, Gdynia 507.8 cm, Gdansk–North Harbour 510.4 cm. If we compare those values with the years 1951-1975 once can notice a rise in Władysławowo by over 6.6 cm ± 1.2 cm; Hel over 4.7 cm ± 1.2 cm and in Gdynia

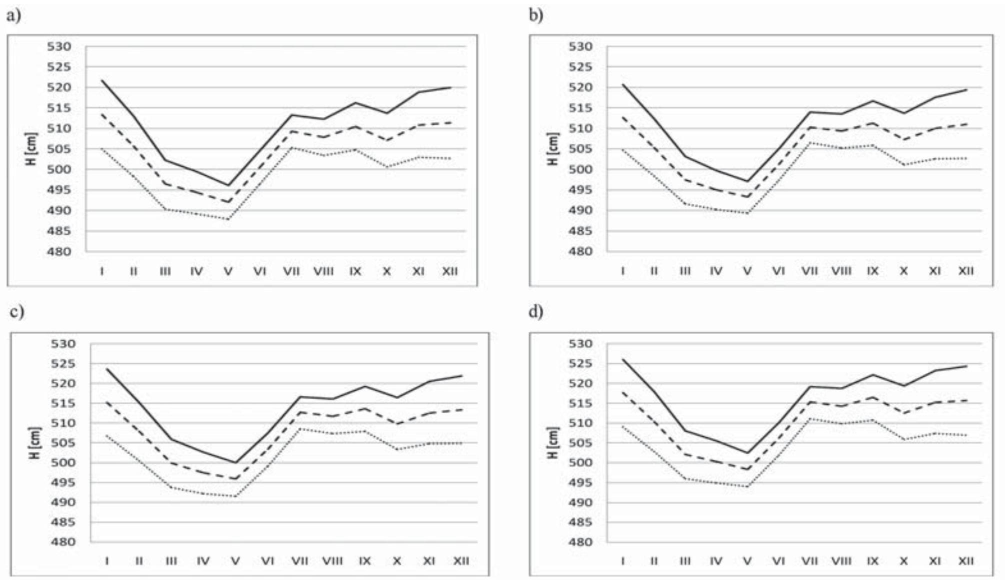

Figure 3. Annual course of mean month values of maximum, average and minima of sea level (1975-2004): a) Władysławowo; b) Hel; c) Gdynia; d) Gdansk–Harbour; dotted line - minimal values; dashed line - average values; solid line - average with maximal values.

over 5.8 cm ±1.1 cm (Dziadziuszko and Wróblewski 1990). For Gdansk–North Harbour there are no comparative values from this period because earlier observations were carried out in Gdansk–New Harbour.

In the analyzed thirty-year period there was a noticeable increase of minimal, average and maximal relative values of sea level and we can assume that this process will continue. Analyses displayed that the maximum sea level values rose from 0.14cm/year (Hel) to 0.88 cm/year (Władysławowo) and only at this tide-gauge computed trend was statistically significant (at level 0.05). There

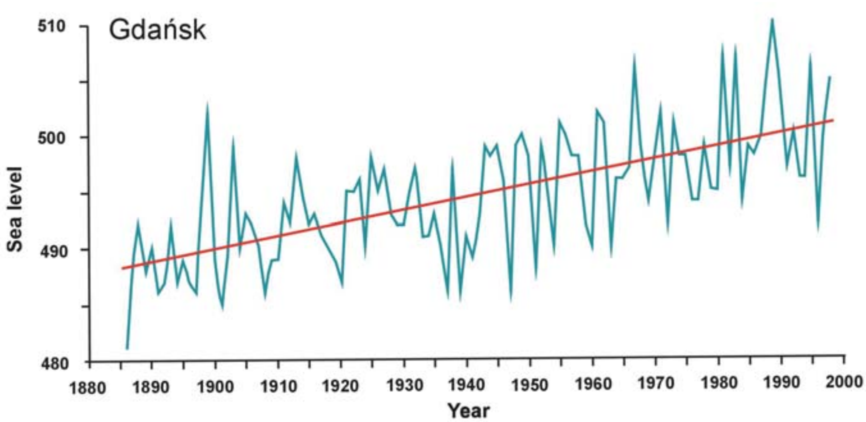

Figure 4. Changes of sea level in Gdańsk for the years 1880-2000
(Source: Miętus, M. 2006).

was a visible increase of maximum sea levels which was the most dynamic from among all analyzed tide-gauges (Fig. 5). The rise of maximum sea levels in Władysławowo was almost twice faster than the increase of the minimal value, which was also the fastest from among the analyzed stations. Gdansk–Harbour is the second station after Władysławowo where minimal and average values of sea levels rose at the greatest pace. For the average sea level values the computed trend for Władysławowo equals 0.26 cm/year which was statistically significant at level 0.028. Also at Gdansk–Harbour the sea level rise was almost significant (at level 0.057) and was 0.23cm/year. Hel is characterized by the least dynamic increase of all characteristics of sea levels (minimum, average, maximum). At Władysławowo and Gdynia maximum sea levels increased at a greater rate, whereas average values increased at the slowest rate. On the other hand, at the tide-gauges at Hel and Gdansk–Harbour, the minimum values of sea level increased at the fastest rate and maximal values increased at the slowest rate. The computed trend coefficient for minimum sea level values came from 0.28cm/year (Hel) to 0.48cm/year (Władysławowo) but were not statistically significant.

A rate of amplitude, which informs about oscillation's spectra between extreme values, is an important parameter in the matter of relative sea level fluctuations. During the analyzed period, extreme high sea levels at particular stations fluctuated

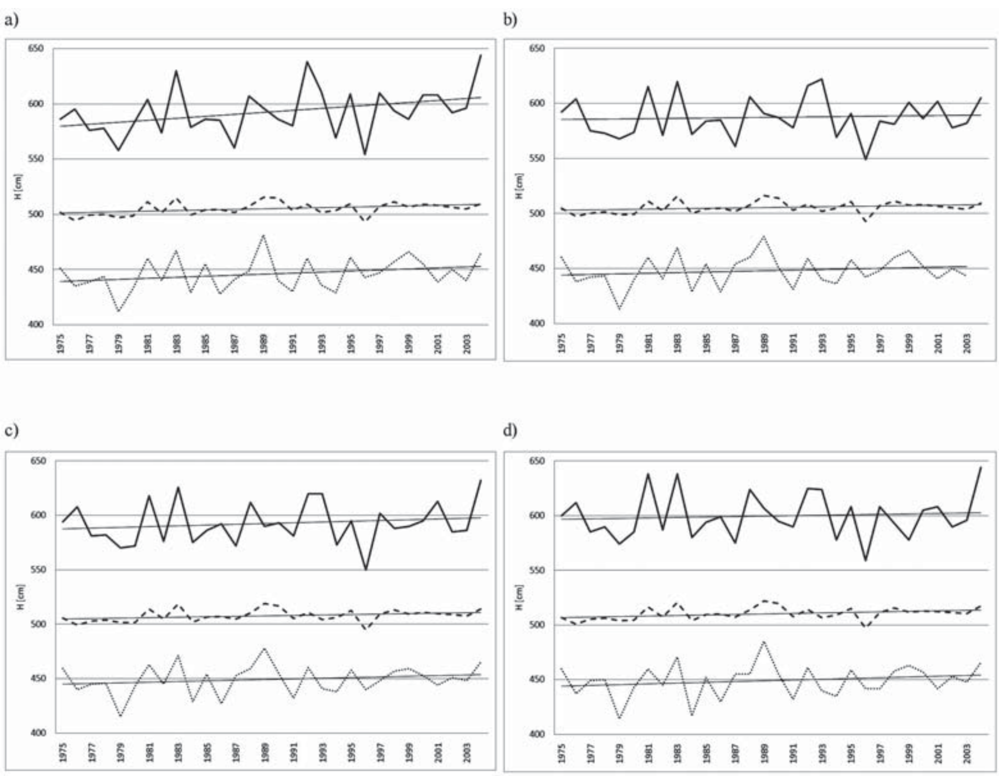

Figure 5. Course of average and extreme values of sea level at each of the tide-gauges (1975-2004): a) Władysławowo; b) Hel; c) Gdynia; d) Gdansk–Harbour; dotted line - minimum values; dashed line - average; solid line - maximum values.

between 622 and 644 cm. In three cases this situation occurred on 23th November 2004 (Table 2). In turn, minimal values are characterized by lesser variability (412-415 cm) and were noticed on 11th April 1979 at all stations. An amplitude of sea level fluctuations oscillated between 209 cm in Hel to 232 cm in Władysławowo, and in each case exceed 200 cm (Table 2). For comparison in a different twenty-year period, 1951-1970, at the Władysławowo station the amplitude reached 195 cm, Hel 180 cm and Gdansk–Harbour 200 cm (Łomniewski 1975). Annual amplitudes were accounted for too. In the analyzed thirty-year period the lowest amplitudes oscillated between 107-115 cm whereas the highest between 179-184 cm range (Table 3). From among all stations the lowest amplitude reached 107 cm and occurred at Hel in 1987 and in 1996 while the highest one occurred at Gdansk–Harbour. At this tide-gauge amplitudes were the highest from among all the stations (Table 3).

In Poland, a standard to assign a storm surge is reached or exceeded at an arbitrarily defined sea level (Sztobryn and Stigge 2005) and a proper value of sea level is established individually for each area. For the analyzed tide-gauges this level was defined at 570 cm. However, according to a European Union directive on the assessment and management of flood risks, if the result of any scale flood is flooding of an area that in normal circumstances is not under water, this incident will be termed a flood (Directive 2007/60/EC). During the examined period of time, in an annual scale the first sea level of ≥ 560 cm occurs in August and ceases to occur in April; however, the cases of events of the highest intensity were recorded from November to January. In Gdansk–Harbour, for example, (Dziadziuszko and Wróblewski 1990) one can observe that a high sea level occurred with greater frequency. At this station in the years 1946-1976 there were 110 registered sea level occurrences of ≥ 550 cm whereas in the years 1975-2004 a sea level higher by 10 cm (of ≥ 560 cm) occurred at least three times more often than at the other tide-gauges: Władysławowo, Gdynia, Gdansk–Harbour (Table 4). In Gdansk–Harbour a sea level of ≥ 560 cm was registered 470 times in 30 years, which means 4.2 times more often than the ≥ 550 cm sea level in Gdansk–Harbour in the years 1946-4976.

Table 2. Extreme sea level

Station	Maximum value		Minimum value		Amplitude [cm]
	H [cm]	Appearance date	H [cm]	Appearance date	
Władysławowo	644	23.11.2004	412	11.04.1979	232
Hel	622	14.01.1993	413	11.04.1979	209
Gdynia	632	23.11.2004	415	11.04.1979	217
Gdansk–Harbour	644	23.11.2004	414	11.04.1979	230

Table 3. Maximal and minimal annual amplitudes (1975-2004).

Tide-gauge	Minimal amplitude [cm]	Year	Maximal amplitude [cm]	Year
Władysławowo	111	1996	179	2004
Hel	107	1987, 1996	182	1993
Gdynia	110	1996	179	1993
Gdansk–Harbour	115	1999	184	1993

The increase in the frequency of occurrence and duration of storm surges is one of principal determinants of climate change along a coast line. The comparative research period 1951-1990 and two other decades, 1971-1990, prove that in Gdańsk the frequency of the occurrence of storm surges increased by 75% (Rotnicki 2008). According to Dziadziuszko and Wróblewski (1990) for the analyzed period (1946-1976) storm surges of ≥ 600 cm were observed 13 times in Gdansk–Harbour, which signifies that on average they occurred every two years and four months. In the next thirty years in Gdansk–North Harbour their number increased to 24 (Table 5) which means that on average they were observed every one year and three months. Storm surges over ≥ 600 cm in Władysławowo, Hel and Gdynia were noticed the least often, about 34-38 % in relation to the tide-gauge in Gdańsk, an increase in the number of observed storm surges is especially noticeable at the Władysławowo station. In the first decade (1975-1984) storm surges ≥ 600 cm were observed in two years out of ten, on average every two years. In the third decade (1995-2004) such great storm surges were noticed in five years out of ten, an average of one every 15 months (Table 5). This

Table 4. Number of occurred daily maximal sea level of ≥560 cm in the years 1975-2004.

Station	H [cm]	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Σ
Władysławowo	≥560	93	42	34	6	0	0	0	4	12	18	68	55	330
Hel	≥560	89	35	35	6	0	0	0	5	13	17	57	51	308
Gdynia	≥560	107	45	42	6	0	0	0	6	15	23	71	49	364
Gdansk-Harbour	≥560	116	63	46	7	0	1	0	9	21	43	92	68	466

Table 5 Number with daily maximal sea level ≥600 cm in years 1975-2004.

	Decade I (1975-1984)		Decade II (1985-1994)		Decade III (1995-2004)	
Station	Year	Number of appearances	Year	Number of appearances	Year	Number of appearances
Władysławowo	1981	1	1988	1	1995	2
	1983	4	1992	1	1997	2
			1993	1	2000	1
					2001	1
					2004	2
Hel	1976	1	1988	2	1999	2
	1981	1	1992	1	2001	1
	1983	5	1993	1	2004	1
Gdynia	1976	1	1988	2	1997	1
	1981	1	1992	1	2001	1
	1983	4	1993	3	2004	1
Gdansk-Harbour	1975	1	1988	3	1995	1
	1976	1	1989	1	1997	2
	1981	2	1992	2	2000	1
	1983	5	1993	2	2001	1
					2004	2

means that there was an increase of over 63 % in comparison with the first decade, in spite of the untypical 1983 year (January and February were extraordinary stormy, which has been noted in many papers). In Gdynia and Hel in each decade there were three years in which storm surges of ≥600 cm were observed. In Gdansk–Harbour in the last decade (1995-2004) such a high sea level was noticed on average every two years (Table 5).

In the years 1975-2004 sea levels of ≥ 600 cm were observed at all the tide-gauges in November, January and February. One can notice that storm surges with an order of magnitude of 600 cm not only appeared more often but what followed was a lengthening of the storm surge season. In the years 1946-1976 sea levels of ≥ 600 cm were observed first of all in November and in January, rarely in February (Dziadziuszko and Wróblewski 1990), and were therefore characteristic for 1/3 of the year.

CONCLUSIONS

An increase of sea level is an alarming phenomenon as it poses a threat for individuals and economies. First of all it contributes to a higher reference level for storm surges which in turn causes more intensive abrasion of the coast line and destruction of harbours' infrastructure. Moreover, a rise in sea level results in an increase in the groundwater level and sea-water intrusion. Coastal areas lose the capability of dewatering which is significant for rainfall floods when even smaller intense rainfall events will be able to cause flash floods. Analysis carried out with reference to the eastern part of the Polish coast of the Baltic Sea is coherent with the research of the IPCC which describes the increase of the mean sea level. These findings state that there has been an increase in the fluctuations of minimal, average and maximum of sea level in the eastern part of the Polish Baltic Sea, which is probably connected with global climate change. For the time period of 1975-2004 the computed trend for the average sea level value rose from 0.18 cm/year (Hel) to 0.26cm/year (Władysławowo) but only for the least tide-gauge it is statistically significant. The analysis confirms the increase in the frequency of the appearance of high sea level during the year and as a result storm surges appear earlier and disappear later during the year. There is a marked extension of the duration of sea levels of ≥ 600 cm in the analyzed third decade (1975-2004) for April (Władysławowo – 4 cases, Gdynia – 3, Gdansk–Harbour -1) and for September (Gdynia – 1 case) which means that the time span of a possible occurrence of such a high sea level covers 2/3 of the year. From among analyzed tide-gauges Gdansk–Harbour is the most endangered by high sea levels and storm surges.

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