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CHANGES OF MAXIMUM SEA LEVELS AT SELECTED GAUGE STATIONS ON THE POLISH AND SWEDISH BALTIC COAST*

Abstract

The focus of this research is the variability of water levels in the Baltic based on the analysis of long-term series of maximum sea levels on the Polish and Swedish coast. The analysed gauge stations were Świnoujście, Kołobrzeg, Gdańsk, Stockholm, Ystad and Furuögrund. In the work linear trends in the long-term sea level changes in the common period of 1889–2006 as well as in the second half of the observational series, 1948–2006, have been identified. The period of 1948–2006 is characterized by a rise of sea levels in all gauge stations. The study also determined the amount of storm surges in the period of 1947–2006. The number of storm surges on the both the Polish and Swedish coast is increasing. Additional analyses included in this study concern the calculations of the levels of storm surges in 1000-year, 100-year and 50-year return periods. The upward trend in the maximum sea levels and the increasing number of storm surges on the Polish and Swedish coast in the last half-century can be partly explained by a climate change, NAO index or by local wind conditions.

Keywords: sea level, Polish and Swedish coast, trend, storm surge.

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Introduction

Fluctuations in sea levels present an important geophysical, oceanographic, and climatological problem. Sea level fluctuations change the water depth and substantially affect the location of important shore components, and thus may contribute to coastal erosion and the landward shift of the shoreline. A considerable part of sedimentological effects on the shore is generated by long-term (on the scale of years or decades) changes in sea level. It is of utmost importance to monitor sea level fluctuations, so that processes and effects in the coastal zone are understood, their adverse consequences are adequately forecast, and, if possible, appropriate preventive measures are taken.

The analysis of long-term series of sea levels can reveal the impact of climate changes on the fluctuations and tendencies of sea levels, both in local sea areas and in the world ocean. The objective of this study is to analyse the variability of water levels in the Baltic on the basis of long-term series of maximum sea levels on the Polish and Swedish coast at selected gauge stations.

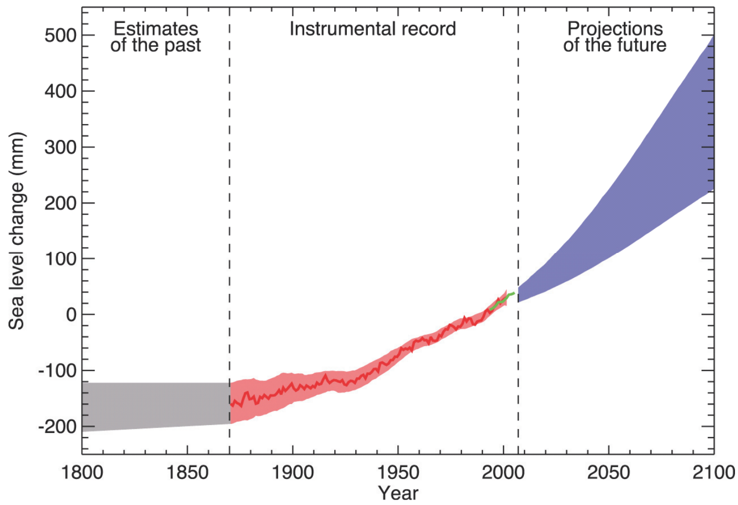
As proposed in the current climatological literature, the global climate is rapidly warming, and studies pinpoint anthropogenic drivers (the increased atmospheric concentration of CO_2 and other greenhouse-house gases produced by fossil fuel combustion) as the underlying causes. Evidence of the changes is sought also in variables other than the global atmospheric temperature increase; a rise in the sea level being used as additional support. The report published by the Nongovernmental International Panel on Climate Change[1] has summarized opinions on the causes of the sea level rise presented by the four IPCC reports of 1990, 1995, 2001, and 2007. All those reports refer to melting of mountain glaciers, small and gigantic icecaps of Greenland and Antarctica, as well as thermal expansion of the water column. The reports contain the subsequent, gradually decreasing, estimates of maximum sea level rise by 2100: 367 (IPCC of 1990), 124 (IPC of 1995), 77 cm (IPCC of 2001), and 59 cm (IPCC of 2007) (Figure 1). The 1990 IPCC report predicted that by 2030, thermal expansion would account for about 55% of the sea level rise, while icecap melting provides explanation for the remaining part of the increase. However, as shown by the data in the 1990 IPCC report, some sources regarded glaciers and ice-

[1] NIPCC. *Nature, Not Human Activity, Rules the Climate*, Summary for Policymakers of the Report of the Nongovernmental International Panel on Climate Change, ed S.F. Singer, The Heartland Institute, Chicago 2008, IL, pp. 40.

caps as being responsible for 77% of the sea level rise. Additionally, the 2007 IPCC report put forth a prediction of a sea level rise caused by melting of the Greenland icecap.[2]

The Commission on Sea Level Changes and Coastal Evolution of the International Union for Quaternary Research (INQUA) has presented different forecasts of changes in the sea level. As shown by measurements taken in Europe, the sea level was rising by 1.1 mm/yr between 1850 and 1940, but the increase stopped after 1940, and by 2100 the sea level may increase by 5–10 cm.[3]

Figure 1. Changes in the world's ocean level as estimated for the 19th century, recorded at present, and predicted to occur by 2100



Source: ICCP AR4 2007.

Consequently, a question arises as to which scenario is the closest one to the hitherto known sea level records from the Polish and Swedish coast. To address this question, the authors made an attempt to identify trends in multi-annual and century-

[2] ICCP AR4. *The Intergovernmental Panel of Climate Change, Fourth Assessment Report*, Working Group I – The Physical Science Basis of Climate Change, Chapter 5 – Observations: Oceanic Climate Change and Sea Level, Chapter 10 – Global Climate Projections, 2007.

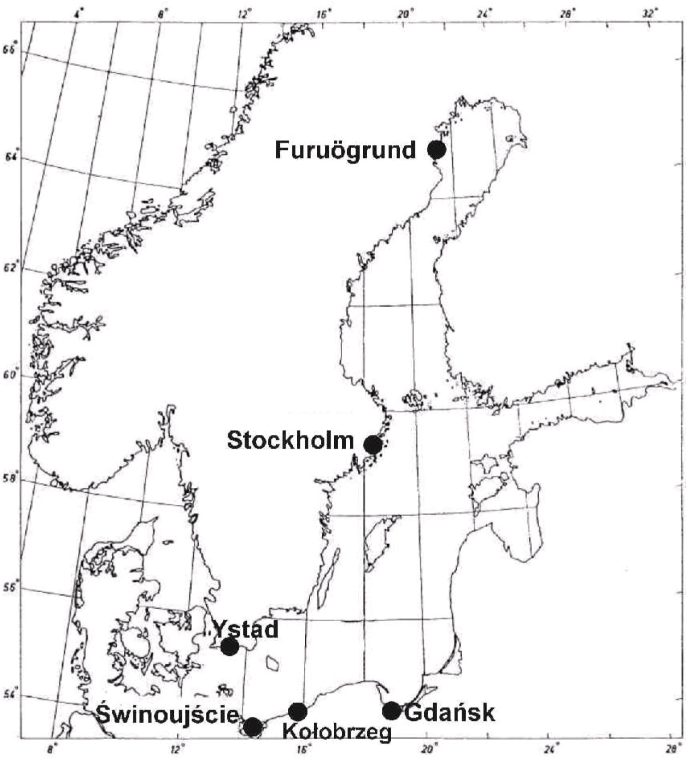
[3] N.A. Mörner, *Estimating future sea level changes from past records*, "Global and Planetary Change" 2004, No. 40 (1–2), pp. 49–54.

old changes in the mean sea level; the results were used to verify the scenarios for the Polish and Swedish coast.

1. Materials and methods

The analysed gauge stations were in Świnoujście, Kołobrzeg, Gdańsk (the Polish coast), Stockholm, Ystad and Furuögrund (the Swedish coast) (Figure 2). These stations are characterized by very long, about centennial series of observational sea level and can reflect well ancient tendencies of their changes. For the analysis of the maximum sea levels the adopted common period was 1889–2006 and the second half of the observational series, that is the period 1948–2006 (due to the

Figure 2. The locations of the analyzed gauge stations in the Baltic Sea



Source: Authors' own work

lack of data and the later start of the observation, the length of the analyzed series for the two stations was slightly shorter – Świnoujście: 1901–2006, Furuögrund: 1916–2006).

The maximum annual sea levels, including the Polish gauge stations were compiled by the authors based on the data published in: *Catalogues of sea level storm surges and falls…*,[4] *Baltic Hydrological Sea Annals*,[5] *Marine Hydrological-Meteorological Bulletins*[6] *and Environmental Conditions in the Polish Zone of the Southern Baltic.*[7]

Data from the Swedish gauge stations were obtained by the Swedish Meteorological and Hydrological Institute (SMHI) by means of the measuring system in force in Sweden, i.e. RH 2000. This system takes into account the vertical, postglacial land uplift.[8] In this paper, to focus solely on the eustatic sea level, the measured -series in the system of the height RH 2000 were reduced by the component caused by vertical, postglacial land uplift (Figure 3).

In case of the Polish coast the elevation of the zero gauge as a reference is 500 cm N.N. (the Amsterdam zero). In order to compare the Polish sea level data with the data analyzed in the Swedish the reference is one gauge zero elevation. Linear regression and the least squares method were applied to determine the long-term sea level trends. Fourier spectral analysis was applied to detect cycles of water level fluctuations. To determine the level of 100-year and 1000-year return time surges the Gumbel distribution was fitted to the observations and the parameters of the distribution were estimated by the maximum likelihood method. To determine the number

[4] B. Wiśniewski, T. Wolski, *Katalogi wezbrań i obniżeń sztormowych poziomów morza oraz ekstremalne poziomy wód na polskim wybrzeżu*, Akademia Morska w Szczecinie, Szczecin 2009, p. 158.

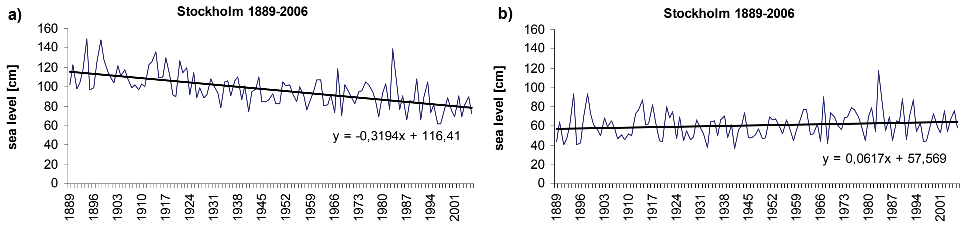
[5] *Rocznik Hydrograficzny Morza Bałtyckiego* (1947–1970), Państwowy Instytut Hydrologiczno-Meteorologiczny, Wydawnictwa Komunikacji i Łączności.

[6] *Morski Komunikat Hydrologiczno-Meteorologiczny*, (1961–1990), Instytut Meteorologii i Gospodarki Wodnej, IMGW, oddział Morski, Gdynia.

[7] *Warunki środowiskowe polskiej strefy południowego Bałtyku* (1986–2001), Materiały oddziału Morskiego IMGW, Gdynia.

[8] R. Svensson, J. Ĺgren, P.-A. Olsson, P.-O. Eriksson, M. Lilje, *The New Swedish Height System RH2000 and Geoid Model SWEN 05LR*. Shaping the ChangeXXIII FIG Congress, Munich, Germany, October 813, 2006; K. Liu, *A study of the possibility to connect local leveling networks to the Swedish height system RH., 2000 using GNSS*. Reports in Geodesy and Geographical Information Systems, LMV – rapport 2011:3, LANTMÄTERIET, Gävle, 54 pp.

Figure 3 Sea levels at Stockholm in the RH 2000 system (a) and reduced by the component caused by the postglacial land uplift (b) for the annual maximum sea levels



Source: Authors' own calculations

of storm surges in the period of 1947–2006, a threshold of the sea level ≥ 70 cm above the gauge zero elevation was adopted as a definition of a storm surge.

1.1. Fourier spectral analysis and periodogram

Spectral analysis is used to explore the harmonic structure of a time series. It decomposes a time series, containing cyclic components, into a number of basic sine and cosine functions with defined wavelengths (frequencies) to identify those particularly strong or important – the periodogram. The sine and cosine functions are independent of each other (orthogonal); therefore, to obtain a periodogram, squared coefficients for each frequency (period) can be added. Values of the periodogram used were calculated as:[9]

$$S(f) = \frac{\Delta}{n}\left(\left(\sum_{t=-n}^{n-1} x_t \cos(2\pi f t\Delta)\right)^2 + \left(\sum_{t=-n}^{n-1} x_t \sin(2\pi f t\Delta)\right)^2\right) \quad (1)$$

where:

f – the frequency,

n – number of observations in the time series x_t,

Δ – $(n + 1)/2$ for odd n and $(n + 2)/2$ for even n.

[9] P. Bloomfield, *Fourier Analysis of Time Series: An Introduction*, 2nd Edition, Wiley and Sons, 2000.

1.2. The Gumbel distribution

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 annual maxima considered in this paper. The density function of the Gumbel distribution is double exponential and described by the formula:[10]

$$f(x) = \frac{1}{\hat{a}} exp\left[-\frac{x-\hat{b}}{\hat{a}} - exp\left(-\frac{x-\hat{b}}{a} \right) \right] \quad (2)$$

where:

$\hat{a}$ – scale parameter (it determines dispersion of the distribution along x-axis),
$\hat{b}$ – location parameter (it determines location of the distribution on x-axis).

The value of the parameters $\hat{a}$ and $\hat{b}$ can be estimated given a set of measurement data. In this paper, the Kolmogorov test is applied to check whether or not the observations can be described by the Gumbel distribution.[11]

2. Trends in long-term series of the annual maximum sea level at the Polish and Swedish coast'

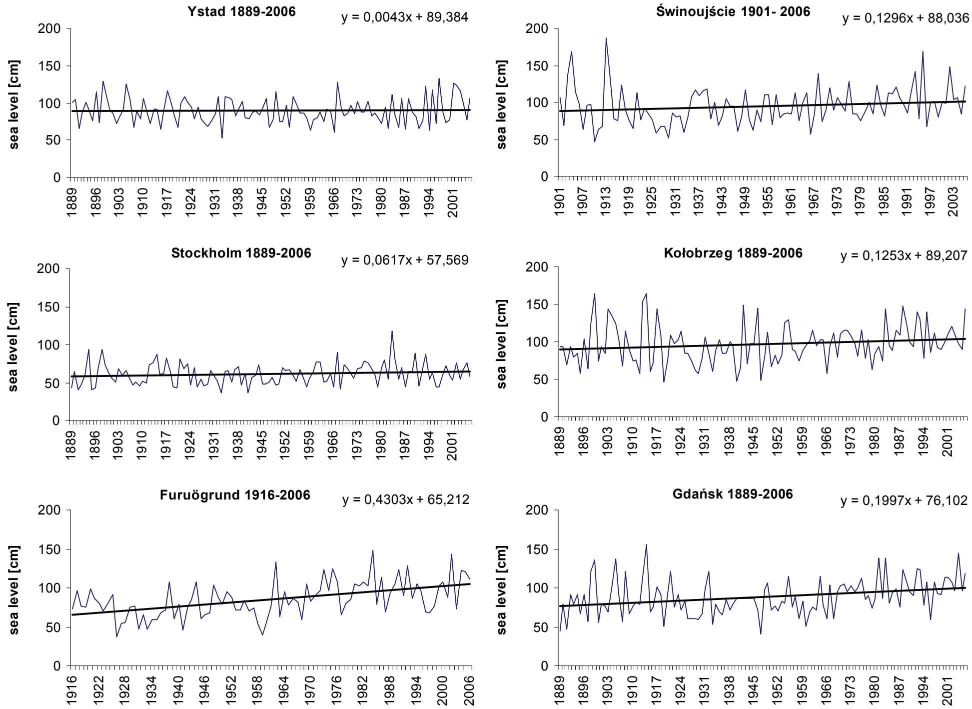
Figure 4 presents the long-term trends of the annual maximum sea levels in Ystad (1889–2006), Stockholm (1889–2006), Furuögrund (1916–2006), Świnoujscie, (1889–2006), Kołobrzeg (1889–2006) and Gdańsk (1889–2006). For all the stations except Furuögrund a slight increasing trend in the sea level is observed, which ranges from 0.06cm ±0.03/year in Stockholm to 0.20 cm ±0.05/year in Gdańsk. In Furuögrund station, where the shortest period of many years of the observation was the shortest, the trend of the sea level attains a value of 0.43 cm ±0.07/year. We have also estimated the trends of the maximum sea levels over the second half of the observation series, that is the period of 1948–2006 (Table 1, Figure 4). The trend of the maximum water levels on both the Polish and Swedish Baltic coast for the last 60 years has been much higher than over the whole period of 1889–2006. The values of

[10] E.J. Gumbel, *Statistics of Extremes*, Columbia University Press, 1958.

[11] A. Byczkowski, *Hydrologia*, t. 1 i 2, SGGW, Warszawa 1996.

the trends are in the range of 0.09 cm ±0.03/year in Stockholm to 0.51 cm ±0.16/year in Furuögrund and 0.54 cm ±0.14/year in Gdansk. The gauge stations closest to the Danish Straits – Ystad and Świnoujscie are characterized by intermediate values of trends of the maximum sea level (0.22 cm ±0.13/year in Ystad, and 0.39 cm ±0.15/year in Świnoujscie and Kołobrzeg).

Figure 4. Trends in sea level in Ystad (1889–2006), Stockholm (1889–2006), Furuögrund (1916–2006), Swinoujscie, (1901–2006), Kolobrzeg (1889–2006) and Gdańsk (1889–2006) for the maximum annual levels the sea



Source: Authors' own calculations

Similarly, one could select a different period where the trend is clearly upward but the statistical significance of this trend will be small. For these reasons, when determining the trends it is important to analyze the longest observational series and not the intervals of a few years decadal intervals.

The values of the trends presented here complement and confirm the evaluation of the trend of annual sea level changes documented in the previous studies of the

Table 1. The calculated trends in the annual maximum sea levels for the period of 1889–2006 and in the second half of the observational series, the period of 1948–2006 (trends are statistically significant at the significance level $\alpha = 0.05$)

	1889–2006			1948–2006		
Station	the trend value		mean increase (cm)	the trend value		mean increase (cm)
	cm/year	cm/100 years		cm/year	cm /100 years	
Ystad	0.00***	0	89.4 → 89.9	0.22 ± 0.13	22	82.8 → 95.8
Stockholm	0.06 ± 0.03	6	57.6 → 64.8	0.09 ± 0.03	9	60.9 → 66.3
Furuögrund*	0.43 ± 0.07	43	65.6 → 104.4	0.51 ± 0.16	51	77.3 → 106.8
Świnoujście**	0.13 ± 0.07	13	88.2 → 101.8	0.39 ± 0.15	39	86.7 → 109.3
Kołobrzeg	0.13 ± 0.06	13	89.3 → 104.0	0.39 ± 0.15	39	89.3 → 111.8
Gdańsk	0.20 ± 0.05	20	76.3 → 99.7	0.54 ± 0.14	54	78.3 →109.3

* period 1916–2006, ** period 1901–2006, *** no statistical significance.

Source: Authors' own calculations

Table 2. The results of some evaluations of trends of average sea level on the Polish coast

Authors	The observation period	Trend (mm/year)		
		Świnoujście	Kołobrzeg	Gdańsk
Z. Dziadziuszko, T. Jednorał 1988	1811–1985 a 1868–1985 b 1886–1985 c	0.7 (a)	1.1 (b)	1.2 (c)
	1951–1985	1.4	0.8	2.9
K. Rotnicki, W. Borzyszkowska 1999	1951–1990	2.19	2.19	4.02
Jakusik et al. 2010	1951–2008	1.8	1.8	2.9
B. Wiśniewski, T. Wolski 2011	1811–2006 a 1901–2006 b 1886–2006 c	0.45 (a)	0.53 (b)	1.57 (c)
	1947–2006	1.0	1.4	2.5

Source: Authors' own calculations

Baltic Sea. According T. Hammarklint[12] the average water level along the Swedish coast has increased from 1898 until today by about 20 cm, that is at an average rate of 1.5 mm per year. The author also notes that for the last 30 years (period 1980–2009) the rate of sea level rise in the Swedish coast has increased markedly rising by 3 mm per year. This effect is explained by the climate change (global warming). According the authors 30 years is too short a period for such definitive statements.

Similar tendencies of rapid mean sea level rise of the southern Baltic in the last few years has been noticed by other authors,[13] The values of the average sea level rise for the Polish coast in the last few years hover over 2 mm/year (Table 2).

3. Significant cycles in sea level changes on the Polish and Swedish coast

The course of the maximum sea levels on the Swedish and Polish coast in the period of 1889–2006 (Figure 3) shows their oscillatory character with the marked periodicity. To study periodical fluctuations in sea level we applied the Fourier spectral analysis. Significant cycles are the highest values of periodogram, clearly different from the level of white noise. Significant fluctuations of sea level cycles for gauge station on the Polish and Swedish coast determined from the observation period 1889–2006 are shown in Table 3.

The spectral analysis in sea levels shows that at the gauge stations on the Polish and Swedish coasts a cycle of about ~3 years is evident. Other minor cycles which are more or less marked in the various stations: ~ with periods of 4.5-year and 8-year, respectively. These results indicate fluctuations in the long course of sea level that are superimposed on the long-term trend. The periods of these cycles are in the range

[12] T. Hammarklint, *The Swedish Sea Level Network*, GLOSS Experts 11th Meeting, 2009, pp. 1–5; *idem*, *Swedish Sea Level Series – A Climate Indicator*, Swedish Meteorological and Hydrological Institute (SMHI), 2009.

[13] Z. Dziadziuszko, T. Jednorał, *Wahania poziomów morza na polskim wybrzeżu Bałtyku*, "Studia i Materiały Oceanologiczne" 1988, nr 52, pp. 215–238; K. Rotnicki, W. Borzyszkowska, *Przyspieszony wzrost poziomu morza i jego składowe na polskim wybrzeżu Bałtyku w latach 1951–1990*, in: *Ewolucja systemów nadmorskich Południowego Bałtyku*, ed. R.K. Borówka, Bogucki Wyd. Naukowe, Poznań–Szczecin 1999, pp. 141–160; J. Jakusik, R. Wójcik, D. Biernacik, M. Pilarski, M. Miętus, R. Wójcik, *Zmiany poziomu morza wzdłuż polskiego wybrzeża Morza Bałtyckiego. Rezultaty projektu KLIMAT. Klimat Polski na tle klimatów Europy. Zmiany i ich konsekwencje*, Seria: Studia i Prace z Geografii i Geologia 2010, 16, pp. 219–234, Bogucki Wydawnictwo Naukowe; B. Wiśniewski, T. Wolski, *A long-term trend, fluctuations and probability of the sea level at the southern Baltic coast*, "Journal of Coastal Research" 2011, Special Issue 64. ICS2011 (Proceedings) pp. 255–259.

Table 3. Significant cycles in maximum sea level changes at the Polish and Swedish gauge stations, as determined for the 1889–2006 observation series

Station	Cycles	Station	Cycles
Ystad	2.6 4.3	Świnoujście	2.7 4.4 8.1 17.7
Stockholm	4.5 7.9	Kołobrzeg	3.6 4.7
Furuögrund	2.0	Gdańsk	3.1

Source: Authors' own calculations

found by other evaluations of periodical changes in the Baltic Sea made by other authors.[14]

4. Results of probability distribution of the annual maximum sea levels and their return periods for the selected Polish and Swedish gauge stations

The analyses of the time series of sea level is important when we need to determine long-term probabilistic forecasts of the annual maximum sea levels. They are called theoretical sea levels that may occur once a certain number of years such as once every 200 years, 100 years or 50 years. In the paper we determine the theoretical value of sea levels on the Swedish and Polish coast based on the Gumbel distribution with parameters estimated by the maximum likelihood method (Table 4, Figure 5).

Table 4 shows that the height of the extreme sea level with return period of 100 years (probability of 1%, once per century) is the lowest in Stockholm (108 cm above zero local gauge). This results from the location of this gauge station away from the open sea.[15] For the remaining gauge stations the 100-year annual maximum

[14] Z. Kowalik, A. Wróblewski, *Okresowe wahania stanów wody przy polskich wybrzeżach południowego Bałtyku*, Archiwum Hydrotechniki 1973, t. 20, z. 2, pp. 203–211; B. Wiśniewski, *Sezonowe i wieloletnie wahania poziomu wód Morza Bałtyckiego*, Studia. Wydawnictwo WSM Szczecin 1978; Z. Dziadziuszko, *op.cit.*, pp. 215–238; B. Wiśniewski, T. Wolski, *A long-term trend...*

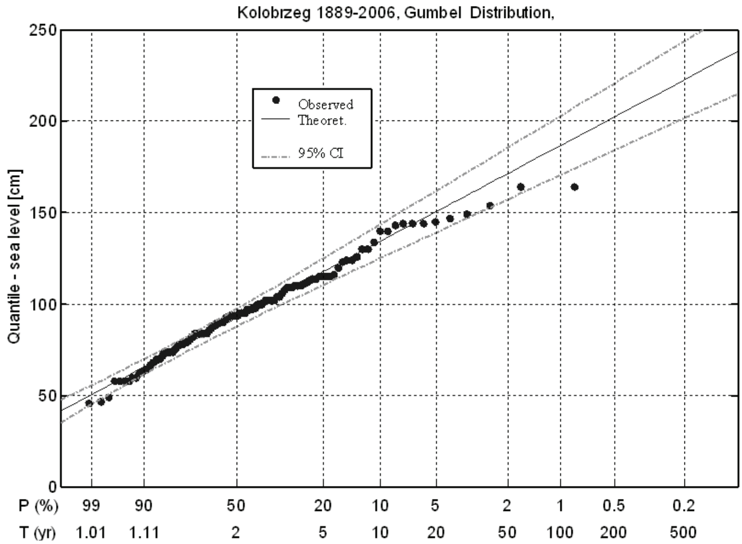
[15] T. Hammarklint, *Swedish Sea...*; M. Ekman, *The Changing Level of the Baltic Sea Turing 300 Years: A Clue to Understanding the Earth*. Summer Institute for Historical Geophysics, Aland Islands 2009.

Table 4. Theoretical maximum sea levels [cm] and the probability of their occurrence at Swedish and Polish gauge stations

T (years)	P (%)	Gauge station					
		Ystad	Stockholm	Furuögrund	Świnoujście	Kołobrzeg	Gdańsk
1000	0.1	183.0	134.7	215.0	223.5	238.2	214.8
500	0.2	172.8	126.7	200.8	209.5	222.7	201.0
200	0.5	159.4	116.0	182.1	190.9	202.3	182.7
100	1	149.1	108.0	167.9	176.8	186.8	168.8
50	2	138.9	99.9	153.6	162.6	171.3	154.9
20	5	125.2	89.1	134.63	143.7	150.6	136.3
10	10	114.6	80.8	119.9	129.1	134.5	122.0
5	20	103.6	72.1	104.6	113.9	117.8	107.0
4	25	99.8	69.1	99.4	108.8	112.2	101.9
3.33	30	96.7	66.6	95.1	104.4	107.4	97.6
2	50	86.9	58.9	81.5	90.9	92.6	84.4
1.33	75	76.6	50.8	67.2	76.8	77.1	70.5
1. 25	80	74.5	49.2	64.3	73.9	73.9	67.6
1.11	90	69.2	45.0	56.9	66.5	65.8	60.4
1.01	99	59.1	37.0	42.9	52.5	50.1	47.0

Source: Authors' own calculations

Figure 5. The theoretical and observed sea levels in Kołobrzeg in the years 1889–2006



Source: Authors' own calculations

sea level is significantly higher: 149 cm in Ystad, 168 cm in Furuögrund, 169 cm in Gdańsk, 177 cm in Świnoujście and 187 cm in Kolobrzeg. These estimations did not differ significantly from the values calculated for the Southern Baltic Sea by other authors.[16] The occurrence probability of the extreme sea levels determined in this work for the Polish and Swedish stations (ports) can be used in the design of coastal hydro-engineering buildings, in the costal zone management and inudation areas during storm and flood events.

5. Number of storm surges on the Polish and Swedish Baltic coast

In the present work we have analysed the number of storm surges on the Polish and Swedish coasts in the period of 1947–2006. The results are presented in Figure 6.

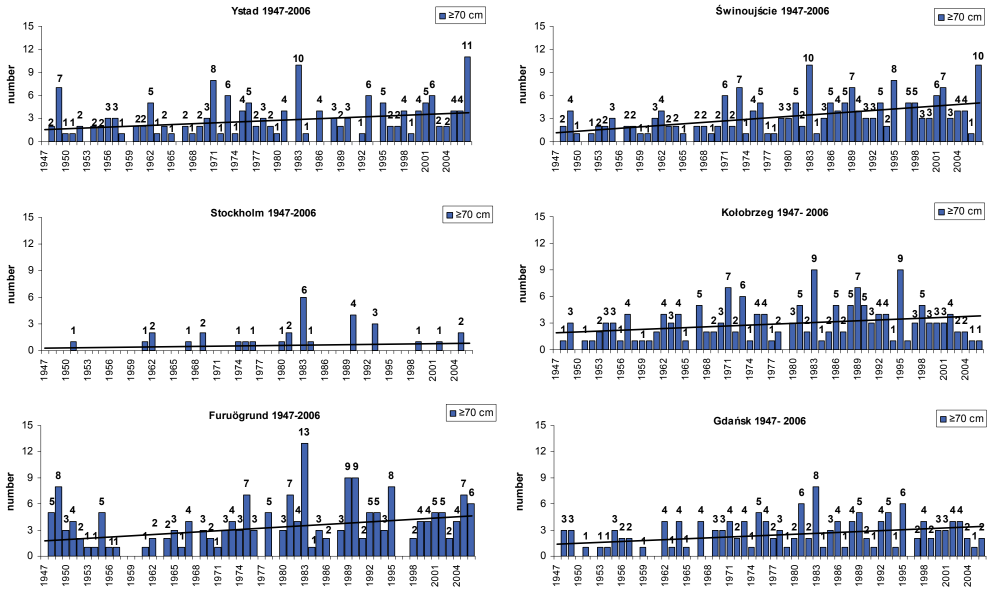
To define storm surges, a value of sea level ≥ 70 cm from the local gauge zero was prescribed, as A. Majewski et al.[17] and B. Wiśniewski, T. Wolski.[18] As shown in Figure 6, the number of storm surges in the past 60 years, both on the Polish and Swedish coast, has been growing steadily. In the period of 1947–2006 the number of storm surges increased in Świnoujście: from the average of 1 to 5 storms annually; in Ystad and in Kołobrzeg: from the average of 2 to 4 storms annually, in Furuögrund: from the average of 2 to 5 storms annually; and in Gdańsk: from the average of 1.5 to 3.5 storms annually. Because of its partly inland location, in the Stockholm gauge station the number of storm surges is small. A significant increase in the amount of storm surges on the Swedish and Polish Baltic coast during the period of 1947–2006 may be the evidence of increased intensity of the low-pressue systems from the North Atlantic. These low-pressure areas passing through the Baltic Sea intensify the flow of air masses towards the Polish and Swedish coasts. This direction of flow

[16] A. Wróblewski, *Prawdopodobieństwo maksymalnych rocznych poziomów Morza Bałtyckiego w Nowym Porcie, Kołobrzegu i Świnoujściu*, "Oceanology" 1975, No. 6, pp. 37–53; *idem*, *Analisys and forecast of long-term sea level changes along the Polish Baltic Sea coast, Part I. Annual sea level maxima*, "Oceanologia" 1992, No. 33, pp. 65–85; T. Jednorał, M. Sztobryn, M. Miłkowska, *Zastosowanie modelu statystyk pozycyjnych do prognozowania ekstremalnych poziomów Morza Bałtyckiego w polskiej strefie brzegowej*, "Inżynieria Morska i Geotechnika" 2008, nr 5, pp. 257–263; B. Wiśniewski, T. Wolski, *Katalogi wezbrań...*, p. 158.

[17] A. Majewski, Z. Dziadziuszko, A. Wiśniewska, *Monografia powodzi sztormowych 1951–1975*, Wydawnictwa Komunikacji i Łączności, Warszawa 1983.

[18] B. Wiśniewski, T. Wolski, *Katalogi wezbrań...*

Figure 6. Number of storm surges on the Polish and Swedish Baltic coast
(defined as sea level ≥ 70 cm from the reference gauge)



Source: Authors' own calculations

causes a significant and rapid accumulation of water and then a rapid decrease of water levels together with the passage of the depression and with growing winds from the coast. This is the influence of the so called the pressure wave described in detail in: *Catalogues of sea level storm surges and falls…*[19] Increasing number of storm surges in the Baltic Sea may be due to climate change, the NAO index or local wind conditions.[20]

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[19] *Ibidem*.

[20] M. Ekman, *op.cit.*; M. Johansson, K. Kahma, H. Boman, J. Launiainen, *Scenarios for sea level on the Finnish coast*, "Boreal Environment Research" 2004, No. 9, pp. 153–166; Ü. Suursaar, J. Sõõr, *Decadal variations in mean and extreme sea level values along the Estonian coast of the Baltic Sea*, Tellus 2007, 59A, pp. 249–260; Ü. Suursaar, T. Kullas, T. Kuusik, *Possible changes in hydrodynamic regime in the Estonian coastal waters (the Baltic Sea) as a result of changes in wind climate*, "Journal of Coastal Research" 2007, SI 50, pp. 247–252.

Conclusions

In the present work we characterise the changes and the course of maximum sea levels on the Polish and Swedish coasts on the basis of long-term observational series. The analysis of long series of data has allowed us to show the impact of climate change on the course of fluctuations in the levels of the Baltic Sea. From our analysis the following conclusions can be drawn:

1. The longest observation series of gauges stations on the Swedish and Polish Baltic coasts showed a slight positive trend of maximum sea levels. The values of linear trends estimated for the period of 1889–2006 ranged from 0.06 cm/year in Stockholm to 0.20 cm/year in Gdansk. In the gauge station Furuögrund, which was observed for the shortest period (1916–2006), the trend of sea levels displayed a larger value of 0.43 cm/year (Table 1).
2. The trend of maximum water levels on both the Polish and Swedish Baltic coasts for the last 60 years has been much higher than in the whole period of 1889–2006. The values of trends have been in the range of 0.09 cm/year in Stockholm to 0.51 cm/year in Furuögrund and 0.54 cm/year in Gdansk. The gauge stations closest to the Danish Straits, i.e. Ystad and Świnoujscie are characterized by intermediate values of the trends of maximum water (0.22 cm/year Ystad, 0.39 cm/year in Świnoujście and Kołobrzeg). These results are complementary and confirm the works by other authors who partially explain the positive rate of sea levels by climate changes, or NAO index.[21]
3. The spectral analysis of the maximum sea levels shows that in the gauge stations on the Polish and Swedish coasts there has been an evident cycle with periods of about ~3 years and some minor cycles which are more or less marked in the various series of sea level, which are superimposed on the long-term trend.
4. In the period of 1947–2006 the number of storm surges increased in Świnoujście: from the average of 1 to 5 storms annually; in Ystad and in Kołobrzeg: from the average of 2 to 4 storms annually; in Furuögrund: from

[21] D. Chen, A. Omstedt, *Climate-Induced Variability of Sea Level in Stockholm: Influence of Air Temperature and Atmospheric Circulation*, "Advances in Atmospheric Sciences" 2005, Vol. 22, No. 5, pp. 655–664; M. Ekman, *op.cit.*; J. Jakusik, R. Wójcik, D. Biernacik, M. Pilarski, M. Miętus, R. Wójcik, *op.cit.*; M. Johansson, K. Kahma, H. Boman, J. Launiainen, *op.cit.*

the average of 2 to 5 storms annually, and in Gdańsk: from the average of 1.5 to 3.5 storm annually.

5. The height of the extreme annual sea-level with 100-year return period on the Polish and Swedish coast depends on the location. In Stockholm, the 100-year annual maximum is 108 cm above the zero local gauge. This results from the fact that this gauge station is located away from the open sea. For the remaining gauge stations the 100-year extreme sea level is significantly higher: 149 cm in Ystad, 168 cm in Furuögrund, 169 cm in Gdańsk, 177 cm in Świnoujście and 187 cm in Kolobrzeg. The probability of occurrence of high sea levels estimated in this work for Polish and Swedish stations (ports) can be used in designing the coastal hydro-engineering infrastructure, in coastal zone managing, and the planning of the inundation areas during storm and flood events.

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ZMIANY MAKSYMALNYCH POZIOMÓW MORZA NA WYBRANYCH STACJACH POLSKIEGO I SZWEDZKIEGO WYBRZEŻA BAŁTYKU

Streszczenie

Celem badań jest pokazanie zmienności poziomów wód M. Bałtyckiego na podstawie wieloletnich serii maksymalnych poziomów wód na polskim i szwedzkim wybrzeżu. Analizowane stacje to Świnoujście, Kołobrzeg, Gdańsk a także Stockholm, Ystad i Furuögrund. W pracy wyznaczono trendy wieloletnich wahań poziomu morza dla wspólnego okresu 1889–2006 jak również dla drugiej połowy serii obserwacyjnej czyli okresu 1948–2006. Okres 1948–2006 charakteryzuje się wzrostem poziomu morza dla wszystkich stacji W pracy wyznaczono także ilość wezbrań sztormowych w okresie 1947–2006. Ilość wezbrań sztormowych zarówno na polskim i szwedzkim wybrzeżu wyraźnie wzrasta. Inne analizy zawarte w pracy dotyczą obliczeń teoretycznych maksymalnych poziomów wód czyli takich, które mogą wystąpić raz na 1000 lat, 100 lat czy 50 lat. Wzrostowa tendencja maksymalnych poziomów morza oraz zwiększająca się ilość wezbrań sztormowych w ostatnich kilkudziesięciu latach można częściowo tłumaczyć zmianami klimatycznymi, indeksem NAO oraz lokalnymi warunkami wiatrowymi.

Słowa kluczowe: poziom morza, polskie i szwedzkie wybrzeże, trend, wezbranie sztormowe.