TRANSNAV International Journal on Marine Navigation and Safety of Sea Transportation
Volume 4 Number 2 June 2010

Low Sea Level Occurrence of the Southern Baltic Sea Coast

I. Stanisławczyk, B. Kowalska & M. Mykita
Instytut Meteorologii i Gospodarki Wodnej, Oddział Morski, Gdynia, Poland

ABSTRACT: The level of 440 cm is defined as the upper limit of low sea level. This value is also accepted as the warning level for navigation, according to the NAVTEX. The low sea levels along the southern Baltic Sea coast were analyzed in the years 1955 – 2005. Lowest values recorded ranged from 309 cm in Wismar to 370 cm in Kołobrzeg. The phenomenon was chiefly generated by hurricane like offshore winds. Extremely low levels were not frequent, their occurrence did not exceed more than 0,3% in Świnoujście and not more than 1% in Warnemünde. In summer months these phenomena occurred extremely seldom, they were more frequent in the western, than in the eastern part of the coast. Long-term variation and statistical analysis was presented. Probability of low sea levels occurrence was calculated by Gumbel method and percentile distribution for 4 gauge stations was analyzed. The calculations revealed that, for instance, in Warnemünde once in 20 years the minimum sea level can be as low as 358 cm.

1 INTRODUCTION

The mean sea level in the Baltic Sea has visibly increased during the last century. The global generators of this increase may be supported or reduced by local influences. Routinely measured level values are the result of all the affecting causes. As some of these impacts appear irregularly in time, the resulting sea level changes are irregular, too. Daily oscillations of the levels at the southern coast may reach even 2,5 – 3 m in extreme cases.

Very low water levels may cause small harbours to fall dry and may cause obstructions to navigation. To ensure the safety of navigation in the difficult waters of the Southern Baltic Sea, reliable data on water levels, particularly low water levels, are highly important.

Low sea levels are one of the most important factors of the navigation safety. The practical importance of water level for shipping and harbour engineering was recognized early. Representatives of shipping are always deeply interested in safe passages of their vessels through the Baltic Sea, where at particular coasts significant differences in the water level are known to occur, in spite of negligible tides, nearly lacking in this sea.

Analyzed were the low sea level events at the southern Baltic Sea coast, basing on 50 years long series of sea level data from 1955 – 2005. The mareographic records were obtained from the water gauges in Wismar, Warnemünde, Sassnitz, Świnoujście and Kołobrzeg. The investigation was realized by Instytut Meteorologii i Gospodarki Wodnej - Oddział Morski (IMGW OM) from the Polish side and by Bundesamt für Seeschiffahrt und Hydrographie (BSH) from the German side. Used were the hydrological and meteorological data stored in the BSH and the IMGW archives.

This study on low sea levels occurring at the southern Baltic Sea coasts was realized as an internal IMGW and SEAMAN projects.

2 NATURAL CONDITIONS

The here considered section of the South-western Baltic Sea coast comprises, going east, three German water gauges, Wismar, Warnemünde and Sassnitz, and two Polish ones, Świnoujście and Kołobrzeg. The westernmost part of the southern Baltic coast between Wismar, on the Mecklenburg Bay, and Cape Arkona on the island of Rugia extends roughly from southwest to northeast. This part of the coast has a highly variable topography: it is shallow and rich in creeks, shoals, and sandbanks. Also the coastal section extending from the high cliffs of Cape Arkona to Świnoujście and the Odra estuary, oriented from northwest to southeast, has an intricate topography: it is rich in small sandy coastal islets, narrows, and sandbanks. In the adjacent Pomeranian

Bay, the seabed also is highly variable, with shallow depths below 10 m prevailing. A particularly wide belt of shoals exists off the island of Uznam in the waters close to Świnoujście and around the island of Wolin. Farther to the east, between Wolin and Kołobrzeg, the 10-m isobath runs as close as one nautical mile from the shore. The coastline in this area, running from west-southwest to east-northeast, is rather smooth, and the isobath 50 m is not more distant than about 15 NM off the shore.

3 DEFINITION OF LOW SEA LEVEL

No obligatory definition of "low sea level" is in force in the hydrological forecasting and warning service and no obligatory warnings on expected occurrence of this phenomenon are issued. For this investigation the level 440 cm has been accepted for the southern coast of the Baltic Sea as the warning level for navigation, according to the NAVTEX.

4 LOW SEA LEVELS GENERATORS

Sea level changes along the coasts are generated by several factors, mainly by the wind impact on the sea surface and, to some extent, by the actual water volume of the sea. Most spectacular deformation of the water surface at the Baltic Sea shores can occur due to the already mentioned off- or on-shore, stormy, sometimes hurricane-like winds, veering or backing, accordingly to the weather system actually passing along or across the coast. The force of the wind against the water surface causes deformations which become the greater, the shallower is the area of the sea.

Of essential influence are however, the local conditions. In shallow areas, such as the Baltic Sea, the wind exerts dominating influence on the water level. The magnitude and the character of the sea level changes depends thus on the coast line configuration, on the exposition of particular coast part to the actual wind, on the bathymetry of the adjacent sea basin, the currents, etc. Sometimes, even in the same time the opposed water level tendencies can be observed along a comparatively short section of the same coast. The grounds for this differences lie mainly in the morphology and in the peculiar hydrographic character of this coast. In some cases, however, these opposed tendencies are due to a rapid changes of the storm direction within a limited area of the wind field.

5 METEOROLOGICAL INFLUENCES

Strong wind is the dominant factor, which forces the water surface oscillations in the Baltic Sea. An offshore wind depressing the water surface at the shore is usually less vehement over the land than on the sea, and, depending on the character of the coast line, can have more or less deflected direction. Much stronger effect than the wind measured at the shores exert the storms, which accompany the low pressure systems moving across the Baltic Sea, affecting considerable areas of water. A rather seldom, though noteworthy cause of low levels is a long lasting gale connected with an anticyclone over Scandinavia and Russia and influencing a vast area of the whole Baltic basin. Each of the mentioned wind systems, though transforming and very much influenced on their way, develops in accordance with the actual specific pressure pattern over Europe and the adjacent Atlantic Ocean.

The Norwegian and North Seas, the Scandinavia and the Baltic Sea, are situated in the west wind zone. They are an area over which the atmospheric disturbances, mostly active depressions with the fronts systems, move eastwards from over the Atlantic Ocean. In the fore field of a depression winds of a strong southern component prevail, behind the fronts usually veering. The winds in the fore field of a depression are offshore in relation to the southern coasts of the North and Baltic Seas. The depressions are common here.

Some depressions, on their way eastwards, when entering Scandinavia, slow down, though continue to deepen. The pressure gradient gets very steep and the initially stormy wind grows to hurricane force. At the southern coasts the offshore-wind-driven-level-decrease begins and holds on, until the wind calms, or veers. Typical reaction of the levels to such wind forcing is, at first, a gradual decrease along a big part of the coast, then, pretty often, a sharply accelerated sinking when the storm grows to maximum force and finally a prolonged minimum which lasts as long as the hurricane force hold on, without changing the direction. When the wind veers, the levels begin a more or less rapid increase (often supported by the now along or onshore wind).

Another type of low sea level variation can be observed when a strong, stationary anticyclone covers, or oscillates over the Fennoscandia and the northwestern parts of Russia. In such atmospheric situation two main factors strive to diminish the water levels. The first one is the considerably increased hydrostatic pressure in the powerful high. The other one is the wind system, which develops at the southwestern outskirts of the high: over the northernmost areas of the Baltic Sea prevail light to moderate winds of a high northern component; going south the

winds veer to easterly and south-easterly and grow in force, sometimes to storm in places. In the westernmost part of the Baltic Sea, in the Sound and in the south-east of the North Sea dominate the south-easterly and southerly winds. If such configuration of pressure systems persists for long enough – a week, two or even more, the surface water not only is pushed away from the shores, but is also forced out of the sea basin through the Belts and the Sound. All the coastal water gauges in the Baltic Sea (except, perhaps, those in the Sounds) should then record decreased levels.

6 SOME PARAMETERS OF THE DECREASING LEVELS

The process of sea level decrease begins, as already said, forced by the impact of a strong wind. Depending on the wind character, the decrease can be rapid and short lasting, or smooth and need a longer time to develope. The acting force (wind) can cover the whole area in the same time or, what is more frequent, can progress from west to east, only in rare cases - from east to west. Sometimes it can influence only a part of the coast. It must be also kept in mind that a decrease sea level is only a phase of the sea surface oscillation, followed (or preceded) by a rise of sea level – the other phase of this wind driven oscillation. An illustration of a sea level decrease can give the variation curves of the falling sea surface at the southwestern coast of the Baltic Sea.

In the afternoon and night of 17 October, a deep meteorological depression was almost stationary over the Kattegat and southern Sweden. A very strong westerly to southwesterly storm of 8-9 Bft, and of 10 Bft in places, developed over the eastern North Sea and the southwestern basins of the Baltic Sea. Behind the occluded front, the storm veered northwest in the early hours of 18 October, without calming during the next several hours.

On 17 October 1967, sea levels on the southwestern Baltic Sea coast oscillated slightly above the mean value. Around noon, they dropped first in the Wismar Bay, which is the area most sensitive to the impact of gale-force offshore winds. Water levels began to fall steadily, initially at a rate of about 10 cm / hour, later 10-15 cm/hour. A less regular rate of decrease was recorded at the other water level gauges. Kołobrzeg, the easternmost of the considered water gauges, was the last station to record falling water levels on this part of the coast. The values there remained above 500 cm until the westerly (alongshore) winds had backed SW, partly S, at about 21 UTC. This forced a rapid drop of sea levels in this area. Minimum levels were recorded just after midnight on 18 October, between 01 and 04 UTC. The storm however, still came from southerly directions, causing water levels to drop particularly rapidly (Fig.1).

Rates of decrease were as high as about 40 cm/h in Sassnitz, and about 50 cm/h in Kołobrzeg and Świnoujście. The lowest minima were as follows: Warnemünde 332 cm, Wismar 334 cm, Świnoujście 362 cm, Sassnitz 381 cm, and Kołobrzeg 435 cm. During that storm levels below 440 cm remained for 17 hour in Wismar, while in Kołobrzeg only for 2 hours. The severity of the storm, which veered NW - N, caused the sea levels to start rise again, immediately at high rates, to compensate the difference of more than 1.5 m in 5-7 hours.

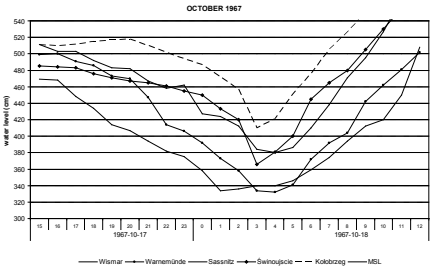

Figure 1 Fragment of sea level decrease during the storm on 17-19th Oct, 1967

During a series of another three successive storms, between 29 November and 7 December 1999, one of them caused a particular deep sinking of the sea levels, particularly on 4 December. The intensity of the storm raging in the whole southwestern area of the Baltic Sea, from the Sounds to the coasts of Kołobrzeg, reached and at times exceeded 9 to 10 Bft. The highest rates of decrease oscillated about 25-15 cm / hour, while the absolute minima were as low as 309 cm in Wismar and 333 cm in Warnemünde. In Wismar the water stayed below 440 cm for 19 hours.

7 FREQUENCIES

Extremely low sea level values recorded along the southern coast of the Baltic were as high as 370 cm in Kołobrzeg (1979-11-04), 366 cm in Świnoujście (1967-10-18), 357 cm in Sassnitz (1939-12-22), 332 cm in Warnemünde (1967-10-18) and 309 cm in Wismar (1999-12-04).

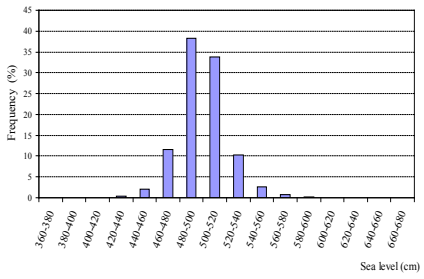

Figure 2. Frequency distribution of sea level values, Świnoujście, 1955-2005.

In Świnoujście, for example, most frequent values of the levels were closest to the mean sea level, that means to H= 500 cm (Fig.2). About 90 % of the measured levels were included in the intervals between 520 cm to 480 cm only about 0,3 % of the levels were lower than 440 cm and in the months from May to August such low values were not recorded at all. In the same years in Warnemünde the frequencies of particular sea level values were as follows: between 520 cm and 480 cm included were about 70 % of the values. Only scarcely smaller than 1 % were the levels below 440 cm.

In one month of the year namely in June no levels lower than 440 cm occurred.

8 LONG-TERM VARIATION OF LOW SEA LEVEL OCCURRENCES

The long-term variation of low sea level occurrence and annual frequency distribution provides important information on this hydrological effect.

Very low sea levels in the Baltic Sea occur very irregularly and are extremely rare in summer. At the declared low level limit of 440 cm they are a marginal phenomenon. At the southern coast their frequency and deviation of magnitude decrease, when moving east. For instance, while in Wismar and Warnemünde, in each of the years between 1955 and 2005 the values of absolute minima fell lower than 440 cm or even lower than 420 cm, so already in Sassnitz and Świnoujście they remained above the threshold value in three of these years (1989, 1998 and 2000), and in Kołobrzeg ten of the absolute annual minima in this 50 years stayed above 440 cm.

The range of variability of the absolute annual minima reached to about 1 m in those 50 years: in Wismar from 420 cm to 309 cm, in Warnemünde from 431 to 331cm, in Sassnitz from 444 to 364 cm, in Świnoujście from 445 to 366 cm and in

The 5 extremely deep minima of the time considered (1956, 1967, 1981, 1989, 1999) were the effect of the same hurricane like storms. So was also the case in the year 1979, when the decrease was exceptionally deep in Kołobrzeg, where the water fell nearly as low as in Wismar and Warnemünde, what usually is not the case (Fig.3). Those events were due to very deep depressions with accompanying hurricane like winds, passing across the Baltic Sea.

The long term variability of low sea level (H≤440) shows much more low levels occurrences in the western part of the coast than in the east. However, in some years low levels were not recorded at all, e.g. in 1989, 1998 in Sassnitz, Świnoujście, Kołobrzeg (Figs 4a, b). Maximum number of low sea level events (H≤440) had the year 1993 in the whole southern cost, from Wismar to Kołobrzeg, similarly was in 1979 and 1959. The number of low level events varies from year to year, changing by as much as two or three times. In general an increase of low level events was observed at the turn of nineteen fifties to sixties, in the seventies to mid-eighties and also in the nineteen nineties. The behavior of the general low sea level variation is given in Figures 4a and 4b, by bars and by curves of 8 years moving averages, calculated for Wismar and Świnoujście.

9 PROBABILITY

The Gumbel method is well suitable for evaluating the probability of low sea levels. In Gumbel distribution, the extreme-value events are distributed asymmetrically.

The following probability of non-exceedance W(x) has been used as design basis for the occurrence of a low sea water event with the value x:

$$W(x) = e^{-e^{-y}}$$

and: $y = a(x - b)$

where: *W(x)* = probability of non-exceedance;
x = annual water level minima
from where it follows:

$$W(x) = e^{-e^{-a(x-b)}}$$

Probabilities according to the Gumbel method are computed by means of the above conditional equations using annual extreme water levels.

They are updated annually.

The recurrence intervals were calculated using the absolute annual sea level minima in Wismar, Warnemünde, Świnoujście and Kołobrzeg from the years 1955-2005 and the above mentioned Gumbel probability method. From the calculations it follows that, for instance every 50 years a sea level slightly below 330cm would occur in Wismar, which in Kołobrzeg a 50 years value is as low as 390 cm.

A 20 years value in Wismar is as low as about 335 cm , while in Kołobrzeg is scarcely falls below 400 cm (Fig.5). The probability of occurrence of low sea level on the southern coast decreases from west to east.

The percentile is a measure which gives information on the per cent of observations found below a definite value. Figure 6 shows the percentile distribution of monthly minimum sea levels for the southern coast of the Baltic Sea.

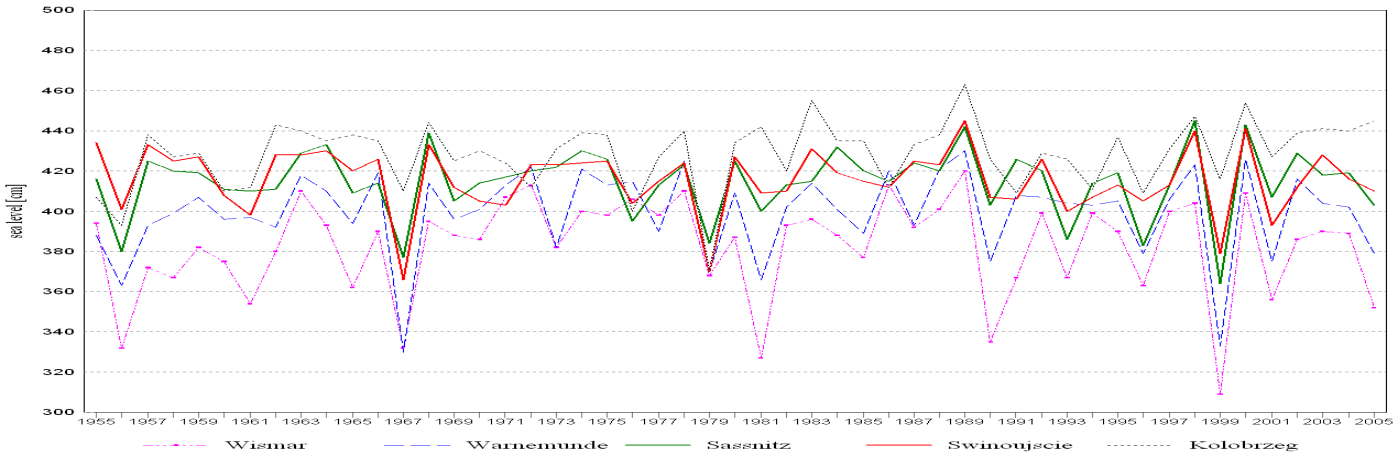

Figure 3. Long term variation of absolute annual sea level minima in Warnemünde, Wismar Sassnitz, Świnoujście and Kołobrzeg, 1955-2005

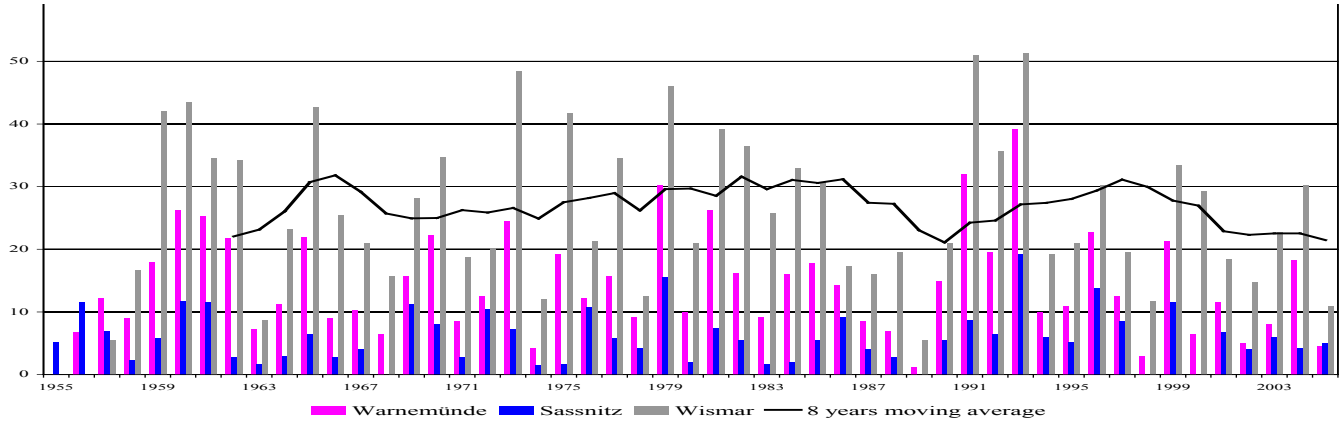

Figure 4a. Long term variation of low sea level events H≤440 cm in Warnemünde, Sassnitz and Wismar, 1955-2005.

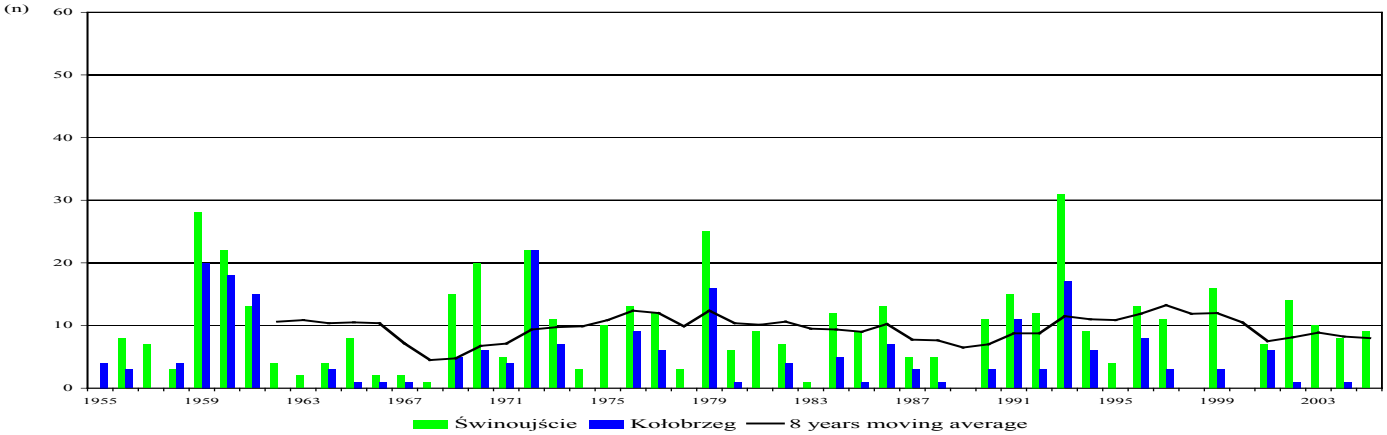

Figure 4b. Long term variation of low sea level events H≤440 cm in Świnoujście, Kołobrzeg, 1955-2005.

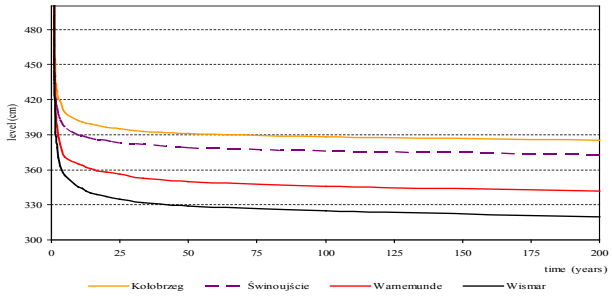

Figure 5. Low sea level as a function of statistical recurrence from 4 gauge stations, 1955-2005.

25th percentile (lower quartile) is the value, below which 25 percent of all observed water levels fall. In Wismar 25% of all values was below 367 cm, in Warnemünde below 392 cm, in Świnoujście below 407 cm and in Kołobrzeg below 414 cm. Upper quartile (75th percentile), often used in statistical characteristics, is the value of variable below which there is 75% of all analyzed values. In the case of all here considered stations, the maximum value of 75th percentile was 439 cm in Kołobrzeg and 427 cm in Świnoujście.

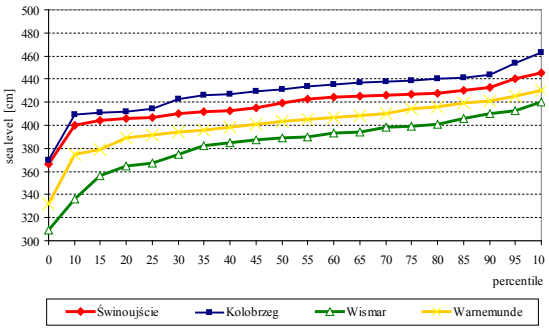

Figure 6. Percentile distribution of monthly lowest sea level at the 4 gauge stations.

This means that in Świnoujście 75% of observations was below 427 cm. In Warnemünde 75% of observations of monthly lowest sea level was below 414 cm and below 399 cm in Wismar. The 50th percentile is an equivalent of the median. In case of the analysed stations the median amounts to: 431 cm in Kołobrzeg, 419 cm in Świnoujście, 403 cm in Warneműnde and 389 cm in Wismar.

10 CONCLUSIONS

Considered was the low sea level at the southern coast of the Baltic Sea as a factor influencing the navigation safety, the off shore engineering and in general the maritime management. The range of the actually met sea level oscillations may grow in face of the expected global warming.

Extreme values of the lowest sea level met in the presented paper, range from 309 cm in Wismar, in the western area, to 370 cm in Kołobrzeg - central part of the southern coast (that means 191 cm below the mean sea level and 131 cm below the NAVTEX warning level). Extreme rates of decrease can reach 50 cm / hour (or more).

Such conclusions point at the importance of the warnings against very low level. This would be a significant information when the under keel clearance could be critical.

REFERENCES

Baerens, C., Hupfer, P., Nöthel, R.H. & Stigge, H.-J. 1994. Zur Häufigkeit von Extremwasserständen an der deutschen Ostseeküste - Teil I Sturmhochwasser. Spezialarbeiten aus der AG Klimaforschung Nr.8, Humboldt-Universität, Berlin.

Hupfer, P., Baerens, C., Kolax, M. & Tinz, B. 1994. Zur Auswirkung von Klimaschwankungen auf die deutsche Ostseeküste. *Spez. arb. a.d. Arb.gr. Klimaforschung des Meteor. Inst. der Humboldt-Universität zu Berlin:* 12**,** 202 S.

Lisitzin, E. 1974. Sea-level changes, Elsevier Scientific Publishing Company, Amsterdam – Oxford – New York

Majewski, A. 1961. General characteristic of sea level changes on the Southern Baltic Sea, *Bull. PIHM* 4, Warszawa

Majewski, A. 1974. *Hydrological characteristic of the Pomorska Bay* (in Polish). Warszawa: Wyd. Kom. i Łączn.

Majewski, A., Dziadziuszko, Z., Wiśniewska, A. 1983. *The catalogue of storm surges on the Polish coasts in the years 1951-1975* (in Polish). Warszawa: Wyd. Kom. i Łączn.

Majewski. A., Dziadziuszko, Z. 1985. *Low Sea Levels on the Southern Baltic Sea*, Monogr. (in Polish), IMGW.

Neemann, V. 1994. Beschreibung des Sommerhochwasserereignisses an der westlichen Ostseeküste von Schleswig-Holstein am 28.08. 1989. im Vergleich anderer Hochwasser, Dt. Gewässerkdl. Jahrbuch - Küstengebiet der Nord - und Ostsee, Abflußjahr 1989(1994), 135-149

Stanisławczyk, I. 2001. Very Low Sea Levels in Świnoujście, *V Symp. Maritime Safety and Protect of Natural Environment* (in Polish), *NOT Koszalin*, pp 301- 309

Stanisławczyk, I. 2001. Low Sea Levels in Kołobrzeg, *IV Int. Conf. Human Protect in Maritime Environment, Maritime University Szczecin* (in Polish), 213-220

Stanisławczyk, I. 2001. Water changes on the Polish Baltic Coast during heavy storm on Dec. 1999, *Wiadomości IMGW* XXIV: 19 - 25, Warszawa

Stanisławczyk, I. 2002. Meteorological conditions of storm surges on the southern Baltic Coast in period 1976-2000, *Conf. NT Maritime Safety and Protect of Natural Environment*, *NOT Koszalin*, pp 95-102,

Stigge, H-J. 1994. Die Wasserstände an der Küste Mecklenburg -Vorpommerns. Die Küste H 56, 1-24

Sztobryn, M. 2001. Assessment of probability of low sea level occurrence in Świnoujście area, *IV Int. Conf. Human Protect in Maritime Environment, Maritime University Szczecin* (in Polish), pp 221-228

Sztobryn, M. 2001. Low Sea Level Forecasting - Neural Network Model, *V Symp. Maritime Safety and Protect of Natural Environment, NOT Kołobrzeg* (in Polish), pp293 – 300

Sztobryn, M., Stigge, H-J., Wielbińska, D., Weidig, B. & Stanisławczyk, I. et al. 2005. Storm Surges in the Southern Baltic Sea (Western and Central Parts), Monogr., *Bundesamtes für Seeschifffart und Hydrographie*: 39, 51, 3, 51.

Thiel, G. 1953. Die Wirkungen des Luft- und Winddruckes auf den Wassersntand in der Ostsee. *Deutsche Hydrographische Zeitschrift* 6.

Wielbińska, D. 1964. Influence of atmospheric situation on sea level. Bull. PIHM 2.

Wróblewski, A. 1970. Occurrence of annual minimum sea level - Southern Baltic, Przegląd Geofizyczny (in Polish) XV/XXIII.