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Storm-surges Indicator for the Polish Baltic Coast

I. Stanislawczyk
Institute of Meteorology and Water Management, Maritime Branch in Gdynia, Poland

ABSTRACT: Storm surges appear in the coastal zone of the Baltic Sea and, depending on row of factors, have different sizes, specifically characteristic for each region of the sea-coast. Observed climate changes are characterized with greater dynamics of weather phenomena. To compare the risk of storm surges to different areas, a new method had to be developed. Storm-surges indicator is used to compare the risks to the South Baltic water areas, varied along with conditions therein and the hydro meteorological and local conditions. The studies on the relations between the parameters and the occurrence of storm surges were carried out as well. The storm surges indicator "W" is related to the number of storm surges observed at the stations in the particular regions, the maximal wind velocity and the max sea level occurring during the same storm surges. The storm surges indicator was calculated for the period of 1955-2008 for the Polish coastal zone. The intention is to use this indicator for research and forecasting purposes. Assessment of the tendencies and variability of the regional phenomena indicators in timescale prove occurrence of certain regional changes of hydrometeorological conditions.

1 INTRODUCTION

Storm surges, as water level extremes, have been investigated quite extensively as they represent a major threat to the coastal population. Considerable technical and scientific effort has been invested worldwide to reduce the impacts of such phenomena, which may reach catastrophic proportions. Storm surges do occur within the Baltic coastal zone where, in addition to causing a direct threat to the seashore and inundation of the coastal area, they affect safety of navigation and operation of the ports. Climate change and sea-level rise will increase the frequency and severity of storm surges (based on the SRES scenarios in range 0.2-0,8 m/century). Observed climate changes are characterized with greater dynamics of weather phenomena. A number of weather and hydrological phenomena already now characterized by the increase in the prevalence of their presence and intensity of natural disasters.

Translocating storms induce surges, characteristic for specific seashore regions and, depending on a row of factors, the surges reach various sizes. To compare the risk of the storm surges at various water areas the new methods had to be worked out. Taking the above into consideration, there had been undertaken the works focused on classification of the storm surges sizes and developing a concept of the storm surge indicator, including analyzing the indicator values in relation to the South Baltic coast. The identification of the hydro-meteorological factors and the height of storm surges were done.

Thus the storm surge indicator is used to compare the storm surges related risks, occurring at various water areas. In the above studies there were analyzed the data gathered within a period of over 50 years, it means from 1955 to 2008 at stations of Świnoujście, Ustka and Hel. It was accepted (in accordance with the definition given by A. Majewski) that any hydrological situation, when the sea level is reaching or extending 570 cm, stands for a storm surge. (thus for Hel the alarm level was decided to be at 570 cm, for Ustka 600 cm and for Świnoujście - 580 cm).

2 METHODS

Sea level changes along the coasts are generated in connection with several factors, however mainly with the wind impact. Affecting sea surface by wind results in changes of the sea surface which appear in a form of storm surges of water. Within a time from November till March the largest number of storms used to occur; they generate extreme changes of sea

levels. The most intensive deterioration of the seashore occurs in a time of severe storms. The sea coastal zone is an area covering both – on-shore part (coastal zone) as the off-shore one. The storm surges are threatening about 500 km of the coastline. The variable route of the coastline results in differentiated exposure of individual sections to wind conditions. In spite of considerable equalization of our coastline, there exist sections of different exposition to wind directions, characterized with diverse regime in meteorology and hydrodynamics.

Storm surges occur in the coastal zone of the Baltic Sea and, depending on a row of factors, have different sizes, characteristic for each region of the seacoast. Of essential influence are however, the local conditions. The magnitude and the character of the changes depend on the coast line configuration, on the bathymetry of the adjacent sea basin, on the exposition of a particular coast part to the actual wind etc. However the 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.

Mostly active depressions with the fronts systems move eastwards from over the Atlantic Ocean. Well developed low-pressure troughs and their frontal systems moving across the coast are accompanied by gale-force backing winds as the fronts approach, and by veering winds after they have passed. The pressure gradient becomes very steep and the wind, initially gale-force, increases in severity and finally reaches hurricane force. In the forefield of a depression winds prevail of a strong southern component, behind the fronts usually veering. The winds in the forefield of a depression are offshore in relation to the southern coasts of the North and Baltic Seas. This situation normally causes sea level oscillations.

The mean sea level and a number of storm surges in the southern Baltic Sea have visibly increased during the last century. Figure 1 shows the number of storm surges in Świnoujście in 1950-2008, from 1950/1951 (from August 1950 to July 1951) to 2007/2008, when maximum occurrence of storm surges is for the autumn – winter months, from November to January – February.

The storm surges are not a regular annual event. Their number may vary as in the case of Świnoujście - from no occurrence at all to as many as twelve. The linear trend of this parameter values indicates an increasing tendency of the storm surges number (linear trend in Świnoujście is described as follows: $y = 1{,}6407+0{,}0619*x$). Also a threat of storm surges got increased towards the end of the 20 century nearly twice as compared to the middle of 20 century in the Southern Baltic Sea. Within 1950-1979 (almost half the entire period) 72 storm surges occurred, whereas in 1980-2008 as many as 129.

Distribution of the annual sea level maxima on the Polish coast (Świnoujście - on the western part and Gdańsk - on the eastern part of the Polish coast) changed also within 1955-2008. The annual sea level maxima frequency distribution (for 10 cm intervals) in Gdańsk (Fig. 2) in two periods - of 1955-1981 and of 1982-2008 illustrates the changes occurred in the period of issue.

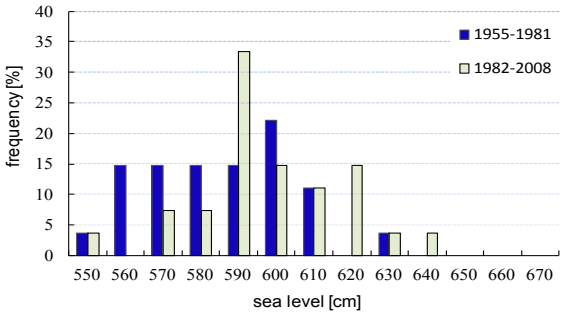

Figure 2. Frequency distribution of annual sea level maxima (for 10 cm intervals, e.g. 550-559, ect.), Gdańsk, 1955-1981 and 1982-2008

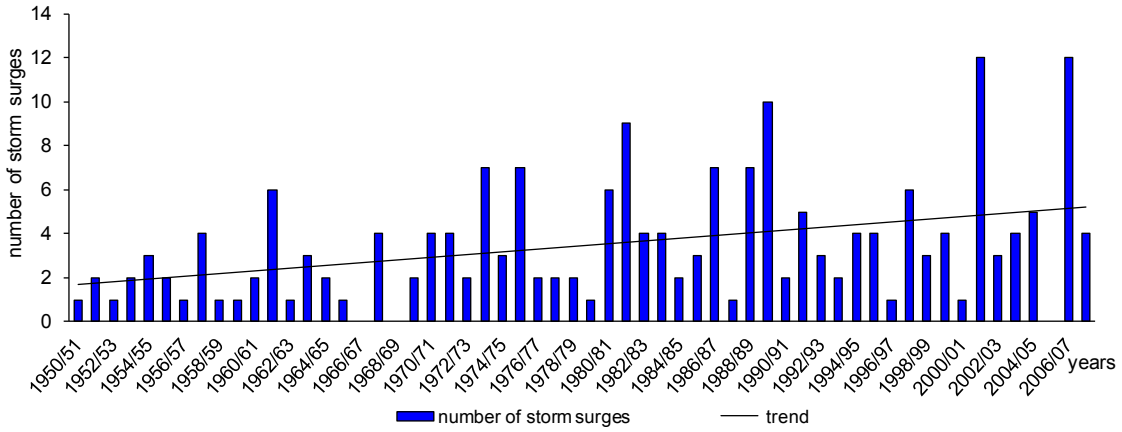

Figure 1. Long term variation of number of storm surges in Świnoujście, 1955-2008 (from 1950/1951 to 2007/2008).

The annual sea level maxima in Gdańsk varied from 570 cm (as in the definition - for Gdańsk the alarm level was 570 cm, although the lowest value of the annual sea level maxima is 557 cm) to 644 cm and the most frequent were values ranging between 590 and 600 cm in 1955-2008 (intervals are left-closed). In 1955-1981 period the most frequent were the peak values of the annual sea level maxima ranging between 600 and 610 cm (22%), then followed the values between 560 and 600 cm (the same values). The maximal values of the sea level ranged between 630 and 640 cm. In 1982-2008 the frequencies of the annual sea level maxima have been shifted to the higher values. However, the most frequent were the peak values between 590 and 600 cm, but the maximal annual sea level was in the higher range of 640-650 cm.

The frequency distribution of the annual sea level maxima (for 10 cm intervals) in Świnoujście within two periods - of 1955-1981 and of 1982-2008 is shown in the Figures 3. The distribution of the sea level maxima in Świnoujście differs from that of Gdańsk, but the frequencies of the annual sea level maxima in 1982-2008 haves been shifted also to the higher values.

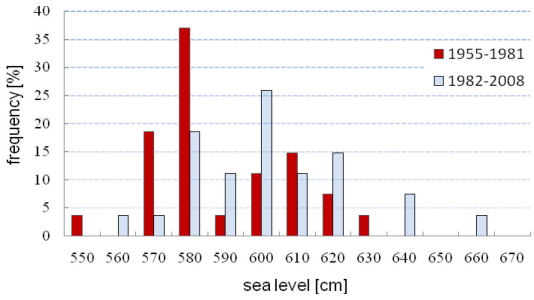

Figure 3. Frequency distribution of annual sea level maxima (for 10 cm intervals, e.g. 550-559 ect.), Świnoujście, 1955-1981 and 1982-2008

In Świnoujście the annual sea level maxima varied from 580 cm (as in the definition - for Świnoujście the alarm level was 580 cm) to 669 cm, and in 1955-2008, maximum was between 580-590 cm (intervals are left-closed). Thus the maximal annual values of sea level were shifted from a range of 630-640 cm to 660-670 cm. Distribution of the annual mean sea level (frequencies) indicates also an increase in their amount in a last period and trend of changes is also growing.

On base these of results one can ascertain, that in nearest period threat of storm surges on sea-coast will grow, what will influence on necessity of more precise forecasts and of information on theme of storm surges, flooding and coastal erosion hazard.

2.1 *Storm surges indicator for the Polish coast*

Proper classification is in terms of conditions of storm surges occurrence, gives the opportunity to compare and assess the risks of different and often separated areas. The storm surges indicator ”W” indicator has been worked out to satisfy researches on climate, weather forecasting, navigation and sea ports operation planning. General aim is the development of innovative methods for mitigation of hazard in the context of increasing storminess and sea level rise. In addition, the research works were aimed at assessment of the storm surges threat to various water areas of the Polish Baltic coastal zone and correlativeness of the regional indicators and climate variability. The appropriate classification of regions in respect of surge occurrence conditions offers a possibility of comparison and assessment of the threat to differential, located often at quite a distance apart water areas and in future, a possibility of seasonal storm surges forecasting.

There has been preformed identification of factors, conditioning and determining storm surges occurrence at the Polish sea coast. The meteorological and hydrological factors have been indicated, analysis of the selected parameters carried out. There has been examined correlativeness of the maximal surge height and other parameters and magnitudes: atmospheric circulation, atmospheric pressure, wind velocity and direction, differences in water and air temperatures, also the mean monthly temperature of air within the specific years of the period in question in Świnoujście. The obtained considerable values of the correlation coefficients were used to select the parameters conditioning a storm surge size. On such a basis the concept of the storm surges indicator “W” has been worked out.

2.1.1 *Storm surges indicator “W”*

The indicator “W” is related to the number of storm surges observed at stations in the particular region and the maximal wind velocity and the maximal sea level occurring in a time of the same storm surge.

The storm surges indicator “W” comprises the parameters specified below; thus:

$$W = \frac{1}{i}\sum\left(\frac{V^2}{H \times 0.1}\right)_i$$

where i = number of observing storm surges in month, year or season; V = maximal wind velocity [m/s] observed within a time of a singular surge; H = maximal high of sea level [m] within a time of a singular surge; and 0.1 = numerical coefficient [m/s^2].

Thus; the storm surges indicator ”W” is used to compare a threat with storm to different areas. It also displays a potential risk which may occur in circumstances of changing the meteorological conditions –

a path of low, which is a random phenomenon, and, what is followed therewith, eventual wind force and direction changes to more unfavorable and more danger. The suggested formula of calculation of the indicator enables to assess estimatively a threat with high surges even basing on non-homogenous values and analyzed periods.

3 RESULTS

To estimate (potential risk) the threat of storm surges on the Polish sea coast, selected were the data from 3 sea areas, representatives of different kind of hydrographic conditions. In storm surges occurrence there can be seen regional differentiation, reflected in regional diversification of the storm surge indicator.

To determine the South Baltic storm surges indicator (seashore of Poland) there have been selected stations, representing dissimilar types of hydrographic conditions: Świnoujście (the Pomeranian Bay), Ustka (open waters of central seaside) and Hel (area of the open sea) In the analysis there were applied the homogeneous sequences of data collected by the mentioned stations within a period of over 50 years (1955 – 2008). Distribution of the indicator's values is different in specific regions of Polish sea coast. The results are presented in Table 1.

Table 1 Statistical parameters of the storm surges indicator "W" on the Polish coast, 1955-2008 and 1971-1990.

Area	Storm surges indicator					
	1955-2008			1971-1990		
	Max	Min	Mean	Max	Min	Mean
Świnoujście	7.4	0.2	2.8	6.3	0.8	3.1
Ustka	7.5	0.2	2.6	5.4	0.2	1.8
Hel	6.8	0.2	2.2	5.2	0.3	2.2

The values of the regional storm surges indicator range from 7.5 to 0.2, but in substance to zero (zero value proves that no storm surge occurred in a given time period). A number of years with no storm surge occurrence is as follows: within the mentioned period in Świnoujście - 5 years with no storm surges, in Ustka - 9 years and in Hel 12 years. The highest storm surges indicator "W" values within the whole period, i.e. 1955-2008, is related to Ustka (7,5), slightly lower in Świnoujście (7.4), and even in Hel (6.8), anyhow the mean indicator values are highest for Świnoujście (2.8), then for Ustka (2.6); the lowest for Hel (2.2). The storm surges indicator values for the period of 1971-1990 (period of reference is 30 years) for all the stations - Świnoujście, Ustka and Hel, were lower than the values for the whole period in question. Then, the mean values were higher in Świnoujście, but lower in Ustka, whereas for the Hel locality the mean value of the indicator was the same for the whole period of the investigations.

For Świnoujście the indicator value's standard deviation is 1.35, variance 1.8. The value of median, the average, it means such a value, of which 50% of surges were sever and 50% were mild is 2.7. The 90th percentile, it means a value, above which 10% of all the cases fall in, was equal to 4.8. For the Hel locality in turn, a value of the storm surges indicator is of standard deviation equal to 1.2, the variance is 1.4. The value of median is 1.8, the 90th percentile was equal to 3.9. For Ustka, the standard deviation is 1.5, the variance 2.2. The value of median is 2.4, 90th percentile was equal to 4.5.

The annual storm surges indicator within 1955-2008 period at the stations of Świnoujście, Ustka and Hel is presented respectively in Figures 4, 5 and 6. In Świnoujście the indicator is definitely of higher frequency, also its mean values are higher. The annual storm surges indicator changes within a range from zero to values above 5.

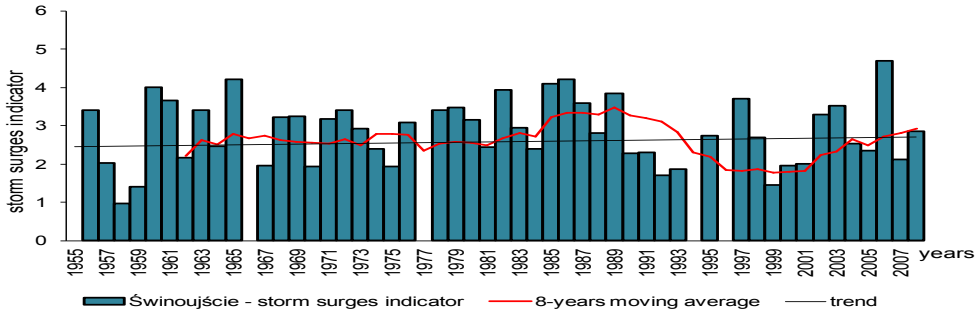

Figure 4. Variability of annual storm surges indicator, Świnoujście, 1955-2008.

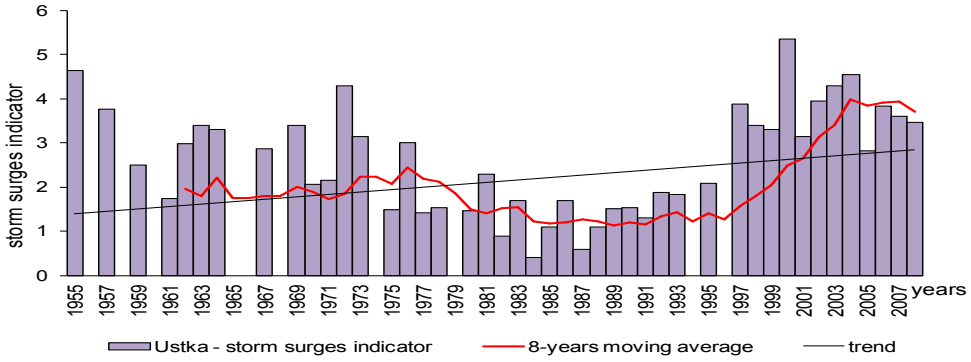

Figure 5. Variability of annual storm surges indicator, Ustka, 1955-2008.

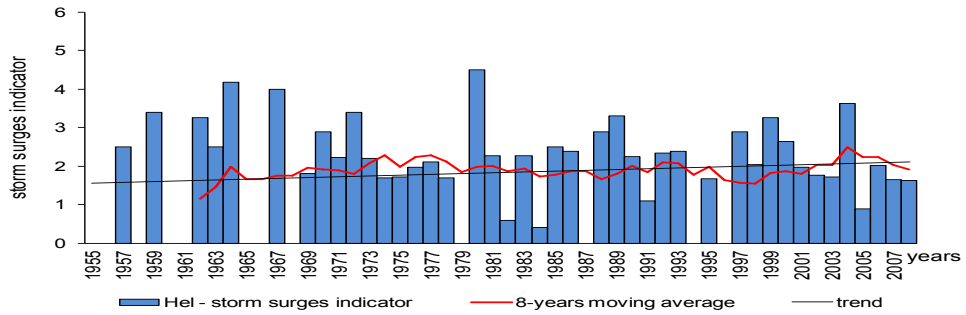

Figure 6. Variability of annual storm surges indicator, Hel, 1955-2008.

Values above 4 confirms frequent occurrence of high surges in storms of significant strength. A value close to 1 indicates a majority of storms, with slightly exceeded state of emergency. There also happen years with no high surges at all. A values of the indicator may change significantly even from year to year. The highest values of the annual storm surges indicator have been observed in Świnoujście in 2006, 1965 and 1986, in Ustka in 2000, 1955 and 2004 and in Hel in 1980, 1964 and 1967.

In Hel and Świnoujście localities there remains a stable value of the annual storm surge indicator (only in the nineties in Świnoujście there are of the considerably lower values), whereas in Ustka there occurred a high growth thereof since the middle of nineties, what confirms a course of anomalies of the annual storm surge indicator. The differences in the indicator variability course, fairly equal before (8 - years moving averages) is observed from the beginning of the eighties.

The indicator's value reflects not only the risk caused by surge, which occurs with very high sea level. It shows a possibility of much higher risk in case of wind direction changing to less favorable, also in case of a lower surge and very strong wind of not as much danger direction. For example: in Hel in 1999 the indicator value was 5.0, sea level was 580cm, the mean wind velocity 17m/s, but the wind direction only 260 grades, it means from the west directions. If only the wind direction had changed to less favorable, the north one, a potentiality of a very high surge would be much higher.

Anomalies of the storm surge indicator for Świnoujście, Ustka and Hel localities also confirm its regional character (Fig.7, 8 and 9). The results for various stations (areas) differ considerably from each other. Only for Ustka (in the central coast region) there is observed a clearly growing tendency in the storm surge course and the increased values thereof in recent years (approximately last ten years period).

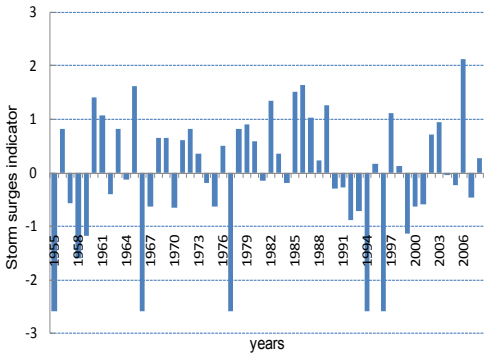

Figure 7. Anomalies of annual storm surges indicator „W_a", Świnoujście, 1955-2008 (mean W_a =2,58).

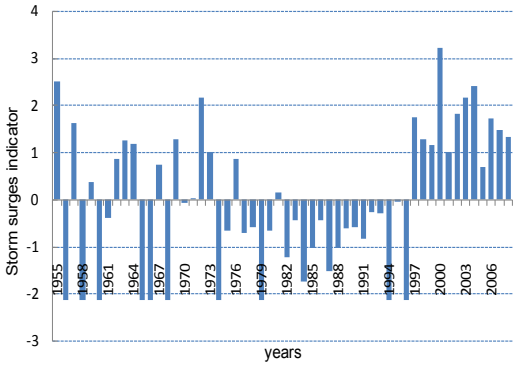

Figure 8. Anomalies of annual storm surges indicator „W_a", Ustka, 1955-2008 (mean W_a =2,12).

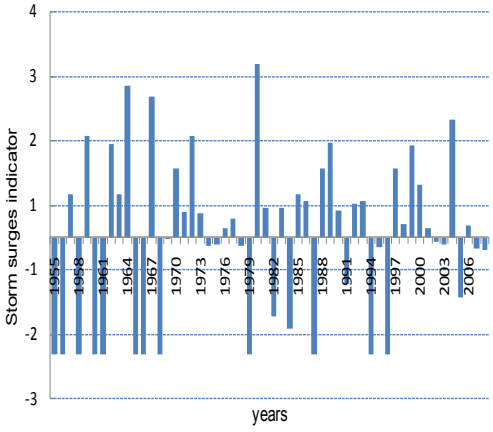

Figure 9 Anomalies of annual storm surges indicator „W_a", Hel, 1955-2008 (mean W_a=1,82).

Were analyzed the reasons for this increase, the differences between the periods 1955-2008 and 1997-2008 are connected with an increased mean wind velocity which occurred in Ustka in the last period, assuming the not changed wind directions distribution. A growth of the mean wind velocity is the most intense in case of the north directions, especially N (north) and NE (north-east) (Fig.10).

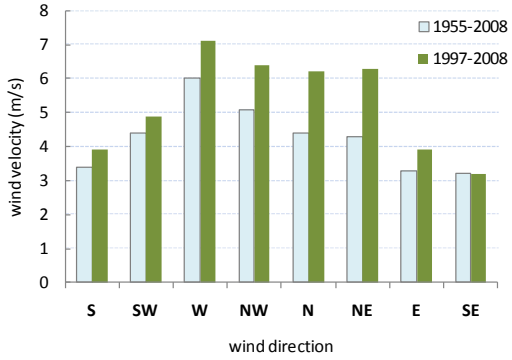

Figure 10. Frequency distribution of the mean wind velocity in Ustka, 1955-2008 and 1997-2008

This increase for mean wind velocity is 2 m/s for NE (north-east) direction and 1.8 m/s for N (north) direction. At the remaining stations are not observed any such changes, on the contrary, the mean wind velocity for north directions, is lower in recent years compared with the previous period: slight decrease in Świnoujście and greater lowering in Hel. The increase of the mean wind velocity is an important indicator, because reflected into an increase of the strong or stormy winds and higher storm surges. Assessment of the tendencies and variation in timescale of the regional phenomena indicators shows certain regional changes of climate conditions.

The seasonal storm surge indicators values enable assessment of its intensiveness within specific year seasons; it means autumn, winter and springtime, for the selected stations within a period of 1955-2008, assuming that autumn comprises months from September to November, winter – December to February and spring – March till May. In summertime the storm surges usually do not occur, however two cases happened in July 1989 and August 1995 in Świnoujście. Different seasons vary considerably in terms of value storm surge indicator for each part of the Polish coast. The seasonal storm surge indicator values are highest at all the stations in autumn and among them the highest value in Świnoujście - 3,1 (Table 2). Next in the order of the season, is winter and slightly lower values define the severity of the storm surges conditions during the spring season (but only in Świnoujście in springtime is higher indicator than in winter - 3,0).

Table 2. Seasonal storm surges indicator on the Polish coast, 1955-2008.

Area	Storm surges indicator		
	Autumn	Winter	Spring
Świnoujście	3.1	2.6	3.0
Ustka	2.8	2.6	2.4
Hel	2.5	2.1	2.1

A very large influence of local factors, resulting in large differences in storm surges conditions and value of storm surges indicator of each areas. In Świnoujście area storms conditions cause much more threat than in the other part of the coast.

4 CONCLUSIONS

To compare the risk of the storm surges at various sea areas, the new methods had to be developed. The storm surges indicator has been worked out to satisfy researches on climate, weather forecasting, navigation and sea ports operation planning. Weather and hydrological phenomena characterized now by the increase in their presence and intensity.The pre-

sented storm surge indicator allows for satisfactorily characterising the conditions of threat with surges to Polish coastal zone and changes thereof in timescale. The comparative analysis of the indicator has confirmed its regional character. Moreover, the observed conditions variability in the last years proves that there occurs an increased threat with large surges in storms of considerable severity for a given area of the coast. In case of Świnoujście the threat is most intense however it remains at stable level. At the central area of the coast (Ustka) there can be observed a clearly growing tendency within a course of the storm surge indicator values (with its increased values in last ten years). The least threat occurs around Hel locality; within the many years course of the annual indicator there is to notice a slightly growing trend only and fairly low values thereof. Assessment of the tendencies and variability of the regional phenomena indicators in timescale prove occurrence of certain regional changes of climate. It is planned to carry out further work on the capabilities of the practical application of the indicator and the relationship between the storm surges indicator and regional processes and scenarios of changes (to 2030).

ACKNOWLEDGEMENTS

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