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Analysis of Storm Surges, Sea Level and Atmospheric Pressure for the Polish Baltic Coast

Andrzej Wróblewski, Ryszard B. Zeidler, Jarosława Kaczmarek

Polish Academy of Sciences, Institute of Hydro-Engineering, Kościerska 7, 80–953 Gdańsk, Poland

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Abstract

Probabilistic linkage between significant sea level increments in 4-hourly intervals and the absolute sea level due to storm surges has been shown to exist upon comparison of the ranges of values of both quantities with the same probability of exceedance complying with the Pearson type III distribution. Hence the possible effect of the Baltic fill-up on considerable short-term surges has been eliminated and wind friction has been taken as the major forcing factor of short-term sea level growth. Finding trends in substantial sea level increments series is assumed to be equivalent to trend analysis for strong winds controlling coastal surges. The computations carried out for the period 1955–1990 at the stations Świnoujście, Ustka and Gdańsk have confirmed the existence of a statistically significant linear trend in the growth of sea level increments. EOF computations for 22 storm surge situations have been centered around numerical characteristics of atmospheric pressure fields. It can be concluded that the first EOF amplitude function $a_1(t)$ contains almost 90% of the overall variance of the atmospheric pressure fields; hence it can be a significant predictor of storm surges. An average field of atmospheric pressures controlling storm surges has also been identified, along with isolines of the first vector of local transfer functions. The behaviour of the two latter quantities confirms the linkage between onshore winds and the storm surge-induced sea level along the Polish coast. The collected data for sea level, wind and atmospheric pressure, together with results of the present analysis, provide insight into the major phenomena affecting the Polish coast and can be regarded as a sound background in formulation of the hydrodynamic input for models of coastal climate and coast evolution in decadal time scales.

1. Introduction

The research on climate change in the Polish coastal zone undertaken under the Polish programme KBN 6P 202 004 04 has aimed at analyzing the long-term variability of sea level (SL) and other elements of sea dynamics and meteorological fields. Kaczmarek et al. (1997) described some results obtained under that programme wherein emphasis has been placed on identification of the mechanisms and components of storm surges, along with the techniques supporting the description for prognostic purposes. In turn, the present analysis is centered around examination of sea level increments, denoting increasing storminess if the annual occurrence of SL increments increases over a certain time span. Of interest is also the linkage to high sea levels of the storminess so identified.

An increasing frequency of high sea level events has been noted in Polish oceanographic literature (Jednorał and Dziadziuszko 1993). A rising trend of annual sea level maxima in the Gulf of Gdańsk has been pointed out by Wróblewski (1992). A question arises if there is a coupling between the frequencies of high sea levels and of the winds occurring with those sea levels at the Polish coast. Such a coupling, based on meteorological data, has been postulated by Miętus (1994).

The analysis presented herein employs both absolute values of sea level and their short-term increments in the years 1955–1990 measured at the stations Świnoujście, Ustka and Gdańsk-Nowy Port, thus covering a fairly representative segment of the Polish coast. Detailed probabilistic testing of sea levels has been arranged for the years 1961–1970. For the ranges of sea level increments identified by that probabilistic analysis, one can draw conclusions on the statistical similarities of SL and SL increments. Subsequently one arrives at a linear, statistically significant, growing trend of high sea level increments during the investigated period of 1955–1990. Further, a similar trend can be postulated for strong wind events responsible for storm surges. A closer examination of such winds has been based on an analysis of 22 anemobaric situations associated with storm surges, done by empirical orthogonal functions (EOF). By this means one can confirm the earlier hypothesis that strong onshore winds are responsible for growing occurrence of storm surges at the Polish coast.

2. Analysis of Storm Surges and High Levels

The present practice identifies as storm surges the events at which high sea levels occur. Such an assumption is insufficient for an analysis of sea level increments and their linkage to strong winds because it is evident that such high and rapid sea level rises occurring at low sea levels in the Baltic basin are not included in the database so generated. In order to determine the correlations between high sea levels and significant sea level increments, an analysis of the two quantities has been carried out on the basis of the data collected for the period 1961–1970. The primary objective of that analysis has been established as the derivation of statistical and probabilistic characteristics for both datasets and subsequent identification of their common features.

The basic data employed in the analysis consists of the sea level data measured every four hours at the sea level stations Świnoujście, Ustka and Gdańsk-Nowy Port (PIHM, 1961–1970). The location of those stations is presented in Figure 1. The total number of the SL data used is 21912. The ten years selected for the analysis have been felt representative because the measured data has been thoroughly verified prior to publication. Before the computations all increments not smaller than 10 cm ($\Delta h \geq 10$ cm) were also checked so as to eliminate major errors at the stages of recording and computer editing. Characteristics of the sea levels and their 4-h increments, for the analysed period of ten years, are presented in Table 1.

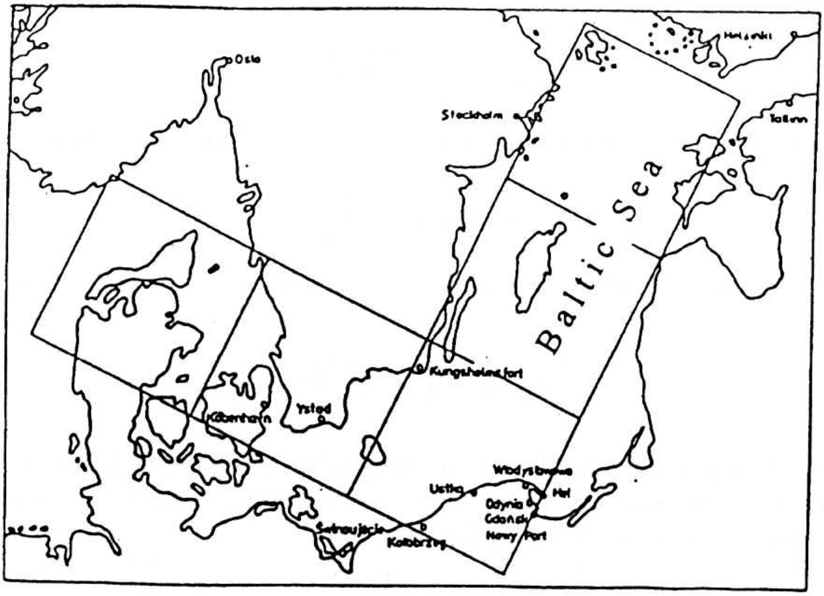

Fig. 1. Grid of atmospheric pressure in EOF computations and location of sea level stations

Local storm surges depend on many factors, among which the degree of basin fill-up x and the wind friction y are most crucial for the Baltic Sea. Assume that the absolute storm surge h (referred to sea level station zero) at a given point of the water body depends on the above variables, without specifying the form of the relationship $h = h(x, y)$. For synoptic time scales the random variables x and y can be assumed independent, so that the joint probability density $f(x, y)$ is a product of their densities. Hence the probability density of storm surge reads $f(h) = f(x)f(y)$. The probabilistic characteristics of a sea level thus depend on the two-dimensional characteristics of random variables.

The variable x is difficult to determine, for it requires the sea level data spread all over the entire sea. Even if the analysis is restricted to the central and southern basins of the Baltic Sea, the computations are difficult since unique levelling has not been done for every station and not all necessary data has been collected. In order to eliminate the effect of the variable x one can consider sea level increments at four-hourly intervals, i.e. $\Delta h(t) = h(t) - h(t-4)$. In this case the variable x

plays a secondary role and can be neglected, while $\Delta h(t)$ depends primarily on respective features of the variable y.

Upon consideration of wind effect alone for the joint distribution of two continuous variables Δh and y it is clear that the function of the conditional probability density for Δh and known y is given by Equation 1, given that appropriate assumptions are satisfied (e.g. Fisz 1967). The formula provides a probabilistic background permitting conclusions on the trend of surge-inducing wind on the basis of SL increments:

$$f\,(\Delta h|y) = \frac{f(y, \Delta h)}{f'(y)}. \tag{1}$$

Assuming that very high sea levels depend on wind (thus sea level increments) one can write

$$f\,(h|\Delta h) = \frac{f(\Delta h, h)}{f'(\Delta h)} \tag{1a}$$

in which $f'(\Delta h)$ denotes the marginal density function for Δh given by the formula

$$f'(\Delta h) = \int_{-\infty}^{\infty} f(\Delta h, h)dh. \tag{2}$$

The exceedance function $P_F(h|\Delta h)$ in Equation 1a is given by Equation 3, representing the fundamental conditional dependence of high sea level on significant sea level increments due to wind friction:

$$P_F(h|\Delta h) = 1 - \frac{\int_{-\infty}^{h} f(\Delta h, h)dh}{f'(\Delta h)}. \tag{3}$$

The empirical probabilistic relationships between high sea levels and sea level increments have been found upon the initial assumption that the numbers of occurrences of both quantities (SL and SL increments) are nearly equal. From that criterion for the series of both variables it has been concluded that considerable increments Δh should be analysed if greater than 21 cm for Ustka and Nowy Port or 26 cm for Świnoujście. Then the counts of respective data were established about 90 for the series measured (Table 1). The same counts have been reached for sea levels if $h \geq 563$ cm (Świnoujście and Nowy Port) and $h \geq 560$ cm (Ustka).

Within the above approach, one could establish regressional relationships between the time series for Δh and h. However, another method of computations has been harnessed. The ordered series have been smoothed with respect to the exceedance function for extremes, and the smoothed curves have been employed to single out 10-cm ranges of Δh and their counterpart for h. Such procedure avoids generalisation of data necessary in the regression technique and permits elimination of the unavoidable yet small differences in counts of the series.

Table 1. Occurrence of sea level h and sea level increments Δh in four-hourly measurements at Świnoujście, Ustka and Gdańsk-Nowy Port in the years 1961–1970

Świnoujście		Ustka		Gdańsk-Nowy Port	
Quantity [cm]	# Occurrences	Quantity [cm]	# Occurrences	Quantity [cm]	# Occurrences
$\Delta h \geq 1$	9513	$\Delta h \geq 1$	9524	$\Delta h \geq 1$	9329
$1 \leq \Delta h \leq 10$	8637	$1 \leq \Delta h \leq 10$	8933	$1 \leq \Delta h \leq 10$	8806
$11 \leq \Delta h \leq 25$	783	$11 \leq \Delta h \leq 20$	505	$11 \leq \Delta h \leq 20$	428
$\Delta h \geq 26$	93	$\Delta h \geq 21$	86	$\Delta h \geq 21$	95
$h \geq 563$	92	$h \geq 560$	90	$h \geq 563$	91
	[cm]		[cm]		[cm]
$\max \Delta h$	99	$\max \Delta h$	56	$\max \Delta h$	78
$\max h$	639	$\max h$	619	$\max h$	611
$\min h$	381	$\min h$	430	$\min h$	435

Computations with the smoothed probabilistic distribution of extremes have been carried out by using the general formula for three distributions put forth by Jenkinson (1955). After the computations it turned out that using only one curve type would be inadequate. The Gumbell distribution (Gumbell 1958) estimated by the method of best likelihood (Kimball 1949) was adequate for most ordered series. Yet the Gumbell method cannot be applied to all distributions because of the high asymmetry of Δh series due to some highest data. An application of other curves given by Jenkinson in the generalised distribution was not recommendable upon the assumption that the relationship between Δh and h should follow the same distribution. The computations have shown that the Euler distribution (Jednorał 1983) would require differentiated transformation of data, separate for each of the two types of series, Δh and h.

In the end, the computations were conducted by the use of Pearson III type distribution with estimation by the method of moments (e.g. Kaczmarek 1970). The technique yields good compatibility of the measured data and the theoretical distributions used for all analysed series. It is noteworthy that Pearson type III distribution has been suggested in Poland for computations of the probability of maximum river stages (CUGW 1969). This probability density reads

$$f(h) = \frac{\alpha^{\lambda}}{\Gamma(\lambda)} e^{-\alpha(h-\varepsilon)} (h-\varepsilon)^{\lambda-1} \tag{4}$$

in which

ε – lower limit of the distribution,
α – parameter ($\alpha > 0$),
λ – parameter ($\lambda > 0$).

In the estimation by the method of moments, the parameters α and λ can be found from the well-known formula, depending on the standard deviation σ, the coefficient C_V and the skewness factor C_S, the latter providing some degre of freedom in the computations. The basic parameters of the distributions so computed are given in Table 2, while the relationship between the smoothed values of Δh and h is presented in Table 3.

Table 2. Basic parameters of Pearson type III distribution employed in computations of probabilities for high sea levels and sea level increments at Świnoujście, Ustka and Gdańsk-Nowy Port.

Station	Mean value of the series	C_V	C_S
Świnoujście			
h	579 cm	0.028	1.533
Δh	37 cm	0.387	2.416
Ustka			
h	574 cm	0.025	1.284
Δh	27 cm	0.252	1.898
Nowy Port			
h	575 cm	0.021	1.234
Δh	30 cm	0.388	2.447

Table 3. Relationships between high sea levels and sea level increments at Świnoujście, Ustka and Gdańsk-Nowy Port derived from 4-hourly increments measured from 1st January 1961 till 31st Decemebr 1970

Station	Range of occurrence [cm]	Range of occurrence [cm]	Range of occurrence [cm]	Range of occurrence [cm]
Świnoujście	$563 \leq h \leq 577$	$578 \leq h \leq 597$	$598 \leq h$	$628 \leq h$
	$26 \leq \Delta h \leq 35$	$36 \leq \Delta h \leq 45$	$46 \leq \Delta h$	$86 \leq \Delta h$
Ustka	$560 \leq h \leq 586$	$587 \leq h \leq 603$	$605 \leq h$	$620 \leq h$
	$21 \leq \Delta h \leq 30$	$31 \leq \Delta h \leq 40$	$41 \leq \Delta h$	$56 \leq \Delta h$
Gdańsk-Nowy Port	$563 \leq h \leq 57$	$578 \leq h \leq 587$	$588 \leq h$	$618 \leq h$
	$21 \leq \Delta h \leq 30$	$31 \leq \Delta h \leq 40$	$41 \leq \Delta h$	$76 \leq \Delta h$

From Table 3 it is evident that high sea levels and sea level increments are probabilistically 'matched' in the ranges given above. For instance, high sea levels in the enclosed range of 578–597 cm at Świnoujście are probabilistically equivalent, in the above sense, with sea level increments occurring in the range 36–45 cm. However, it should be stressed that the conclusions drawn from Table 3 are confined to those stemming from properties of the technique used in derivation of the relationship. Table 3 results from empirical relationships fitting Equation 3 for selected ranges of the exccedance function. Hence the table cannot be employed for general conclusions as to the increments, on the basis of *h* for time periods shorter than 10 years. The ranges given above for the two random variables, Δh and *h*, should also be not narrower than the indicated ones.

3. Storm Surges in the Years 1955–1990 and Occurrence Trend of Storm Winds

One of the objectives of this study has been to determine the trend of storm winds on the basis of sea level increments measured in the period 1955–1990. The database for Świnoujście, Ustka and Gdańsk-Nowy Port (PIHM 1955–1970, IMGW 1971–1990) has been used to reach the above goal.

A detailed analysis of statistical characteristics of storm winds and identification of their trend would require processing of thousands of synoptic maps (e.g. above 100,000 maps taken every 3 hours in the investigated time span of 1955–1990). Instead, one can undertake an attempt of a less accurate but sufficient assessment of the trend by relying on Δh in some regions, thus at the same time reducing the number of data. The general probabilistic assumptions applicable in this case are reflected in Equation 1. Identified in Chapter 2 are sea level increments linked to storm winds materialising as high sea levels. It should be recalled that high sea levels are caused not only by wind effects but also the fill-up of the Baltic Sea and, to a lesser extent, seiches and other forcing agents. Examination of the data, i.e. SL increments taken at time steps $\Delta t = 4h$, eliminates almost completely the effect of the Baltic fill-up, the wind forcing being still present, while all other secondary causes of sea level rise are basically filtered out. The computations with such 4-hourly increments are thus equivalent to high-pass filtering of sea level series measured. An in-depth investigation of all forcing agents responsible for storm surges would require a separate analysis, far beyond the scope of the programme outlined in Introduction.

Hence the trend analysis was confined to the sea level increments Δh in the three ranges given in Table 3, in the years 1955–1990. The variables in this analysis are the numbers of occurrences in the above ranges computed consecutively for each year. Every station has thus three variables which assume different numbers during 36 years in Gdańsk and Świnoujście and 31 years at Ustka. The data counts representing the occurrences of the variables are sufficient for statistical reasoning. The random sample taken in this way covers a relatively short time but, because of the accuracy of the measurements, adequate data would require more decades of measurements. The total number of data in respective ranges is shown in Table 4.

The hypothesis on the trend linearity, dealing with increments of annual Δh occurrences, was verified by the Student test at the significance level of 5%. For a linear trend (and also a straight line displaying a zero trend), the hypothesis on

Table 4. Properties of sea level increments Δh at Świnoujście, Ustka and Gdańsk in the years 1955–1990

Station	Period n[years]	Δh [cm]	# Occurrences	$A_{n;1-\alpha/2} - A_{n;\alpha/2}$ $\alpha = 5\%$	A_p	(Lin)	(Reg)
Świnoujście	1955-90	$26 \leq \Delta h \leq 35$	296	248 – 398	202	+	4.8
	36	$36 \leq \Delta h \leq 45$	103	248 – 398	190	+	2.3
		46 Δh	55	248 – 393	189	+	1.5
Ustka	1960–90	$21 \leq \Delta h \leq 30$	244	176 – 291	175	+	2.0
	31	$31 \leq \Delta h \leq 40$	55	176 – 292	135	+	1.0
		41 Δh	18	176 – 292	100	+	0.5
Gdańsk	1955–90	$21 \leq \Delta h \leq 30$	283	248 – 393	213	+	4.1
	36	$31 \leq \Delta h \leq 40$	69	248 – 393	249	+	-0.1
		41 Δh	39	248 – 393	250	+	0.0

(Lin) = trend linearity test at significance level of 0.05,
(Reg) = data count growth by regression,
A_p = parameter.

the zero value of the parameter in the regression relationship for the increments Δh should not be rejected in any of the tested series.

The significance of the linear trend has been tested by reverse arrangements (Bendat and Piersol 1986) at the given significance level $\alpha = 5\%$. The results of those computations are presented in Table 4.

An analysis of the daat depicted in Table 4 shows that the trend is not significant at the level 0.05 for Gdańsk in the range of Δh above 31 cm. The remaining values of A_p are beyond the theoretical boundaries, although only slightly in some cases. For the most numerous series in the first ranges of Δh it is of interest if the latter follow the normal distribution; the skewness factor can be employed as an indicator in this case (Snedecor and Cochran 1967). The skewness factors turn out to be 1.34, 0.09 and 0.68 respectively for Świnoujście, Ustka and Gdańsk. At the significance level of 2% the test shows positive results only for Gdańsk and Ustka. Storms at Świnoujście are characterised by vigorous dynamics of sea level rise and high values of absolute sea level. Hence the divergence of data from the normal distribution seems to be justified for the period of measurements taken in the computations.

The results of the computations for the linear regression of the counts $L\Delta h_t = B_0 + B_1 t$ as a function of the variable t (denoting years) are presented in Table 5, for the series with significant trends and the two lower ranges.

The trends of annual counts of Δh occurrences in the ampliest ranges from 21 (26) to 30 (35) cm are depicted in Figure 2.

Spatial characteristics of the occurrences of sea level increments along the Polish coast have been investigated by expansion in EOF series. The same count of

Table 5. Regression parameters for annual occurrences of Δht (defined as $L\Delta ht = B_0 + B_1 t$) at three Polish sea level stations

Station	Δh range	B_0	B_1
Świnoujście	26 – 35	5.737	0.134
	36 – 45	1.659	0.065
Ustka	31 – 40	1.265	0.032
Gdańsk-N. Port	21 – 30	5.744	0.114

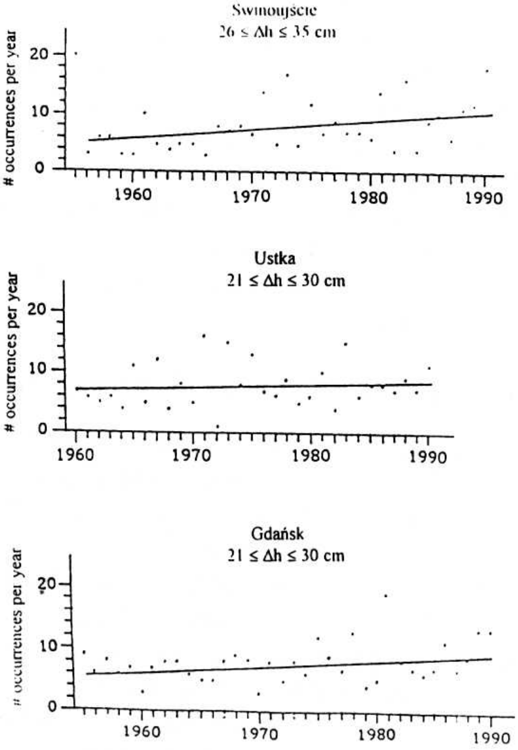

Fig. 2. Trend lines for annual occurrences of Δh at Świnoujscie, Ustka and Gdansk in the years 1955–1990

$N = 31$ was assumed for $M = 3$ measuring stations. The expansion into empirical orthogonal functions followed the formula

$$\Delta = \mathbf{EF} \tag{5}$$

in which

- Δ – matrix of Δh series in the ranges of occurrence (Table 4) having the elements $\Delta h_i(t) = 1, ..., M;\ t = 1, ..., N$,
- $\mathbf{E}$ – matrix of local transfer functions with elements e_{ni}, $n = 1, ..., M; i = 1, ..., M$,
- $\mathbf{F}$ – matrix of amplitude functions with elements $f_n(t), n = 1, ..., M; t = 1, ..., N$.

The computations have been executed for the first two ranges of Δh occurrence; this is so because of the small amount of data in the last open interval. The local transfer functions are shown in Figure 3, together with the percentage of the overall variance of Δh coupled with those functions. The drawing shows that, for the entire coast, the highest percentage of the variance is contained in the functions e_{11}, which represent almost similar counts of Δh in both (first and second) ranges of occurrence, that is 69.9% and 61.2% respectively. From the computations it follows that the counts of the occurrence of most storm surges are common for the Polish stations, for the assumed 4-h time step of Δh. The remaining local transfer functions reflect the local conditions of the generation of storm surges. Taking into account the number $N = 31$, one should conclude that the functions can be affected by random factors, which disturb the general regularity of the phenomenon.

4. Storm Surges Versus Fields of Atmospheric Pressure

In the search for characteristics of storm surges and their causes one can resort to atmospheric pressure fields, which are easier to investigate than wind fields. Horizontal gradient components of atmospheric pressures so derived provide insight into the generation and coupling mechanisms.

Hence a set of synoptic maps for storm surges in the years 1960–1983 was analysed. The processed maps were identified by the time of storm surge at Ustka or the time preceding the storm surge if no map of maximum sea level rise was available. The sea level station at Ustka was chosen because of its central location on the Polish coast of the Baltic Sea. It is known that storms do not occur simultaneously at all measuring stations, or to occur in some areas only. The selection of the station at Ustka permits an optimum description of the entire coast.

Table 6 shows the dates of all analysed atmospheric situations. In the analysis, the atmospheric pressure data were expanded into EOF series at the nodes of the

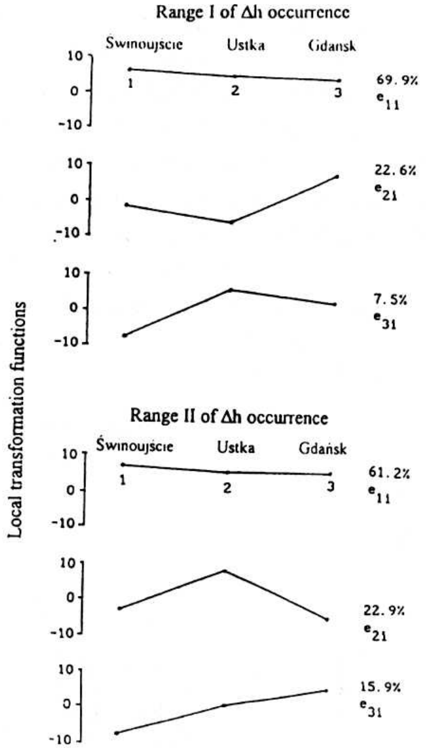

Fig. 3. Local transfer functions for EOF and counts of sea level increments in the years 1955–1990

gridwork shown in Figure 1. If not given directly, the nodal values were found by interpolations.

Table 6. Dates of atmospheric pressure situations linked to storms and analysed by EOF

#	Date	#	Date
1	1960.01.11	12	1971.12.08
2	1961.03.21	13	1972.11.13
3	1963.11.20	14	1973.11.21
4	1964.01.27	15	1973.11.25
5	1964.11.25	16	1973.12.15
6	1967.10.18	17	1974.12.30
7	1968.01.02	18	1975.01.08
8	1968.03.14	19	1976.01.17
9	1969.11.10	20	1981.11.06
10	1970.11.10	21	1983.01.1
11	1971.03.11	22	1983.02.02

Computed as the first step were mean values of the atmospheric pressure at the nodes, for the entire set of situations, so that a typical distributions of isobars given in Figure 4 could be established. The situation so derived depicts a large low with a center to the east of the chosen computational gridwork. The field is characterised by a system of isobars perpendicular to the Polish coast, with a significant horizontal gradient of the atmospheric pressure along the line Świnoujście – Krynica Morska. The difference of atmospheric pressure along that coastal segment is 8 hPa. The field cannot be interpreted accurately in the North Sea area adjacent to the Danish Straits because the number of nodes in that area is too small. The field of atmospheric pressures so averaged generates strong onshore winds along the Polish coast.

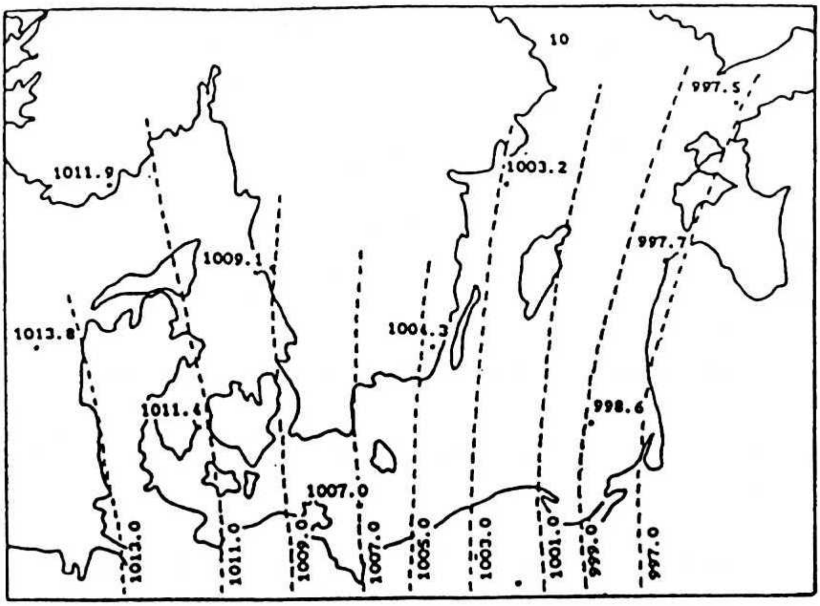

Fig. 4. Mean atmospheric pressure over the Baltic Sea derived from synoptic maps for 22 storm surges recorded at Ustka in the years 1960–1983

The EOF expansion for $M = 12$ and $N = 31$ follows Equation 6 below while the results of the expansion are presented in Table 7.

$$\mathbf{P} = \mathbf{A}\mathbf{\Psi} \tag{6}$$

in which

- $\mathbf{P}$ – matrix of atmospheric pressures at nodes shown in Figure 1 with elements $p_i(t)$; $i = 1, ..., M$; $t = 1, ..., N$,
- $\mathbf{\Psi}$ – matrix of local transfer functions Ψij; $j = 1, ..., M; i = 1, ..., M$,

A – matrix of amplitude functions with elements $\alpha_j(t)$; $j = 1, ..., M$; $t = 1, ..., N$.

Table 7. EOF computations for atmospheric pressure fields in 22 storm surges in the years 1960–1983

	Amplitude functions				
	α_1 [%]	α_2 [%]	α_3 [%]	α_4 [%]	α_5 [%]
Percentage of total field variance for α_1	89.6	7.5	1.9	0.5	0.2
Total field variance $\sum_i^n \alpha_i$	89.6	97.1	99.0	99.5	99.7

The atmospheric pressures fields are represented by the pressures measured at mean sea level and put as isobars on synoptic maps. The fields of local transfer functions Ψ_{ij} are determined for the entire database and do not vary from situation to situation. The gradients between the functions Ψ_{ij} are also constant functions of coordinates. If one assumes a linear relationship between the horizontal component of atmospheric pressure (representing geostrophic wind) and the local wind vector, depending on the site topography, then it becomes obvious that the functions $\alpha_n(t)$ represent the fields of atmospheric pressure and wind. This can be expressed by EOF functions as follows:

$$p_i(t) - \overline{p}_i + \sum_{j=1}^{M} \alpha_j(t)\mathbf{\Psi}_{ji} \tag{7}$$

in which:

$\overline{p}_i$ – local mean atmospheric pressure at node i.

Upon introducing the operator of finite differences for both sides of Equation 7 one obtains

$$\nabla[p_i(t) - \overline{p}_i] = \sum_{j=1}^{M} \alpha_j(t)\nabla\mathbf{\Psi}_{ji} \tag{8}$$

in which

∇ – operator of finite differences.

From Equation 8 and the assumptions for constant functions Ψ_{ij} it follows that wind speed is proportional to the respective functions $\alpha(t)$. The system of

Ψ_{ij} isolines is illustrated in Figure 5. The area covered by the grid encompasses the Central and South Baltic, together with Danish Straits, and the adjacent area of the North Sea. Computations of EOF functions have been done for water bodies involved directly in generation of storm surges at the Polish coast.

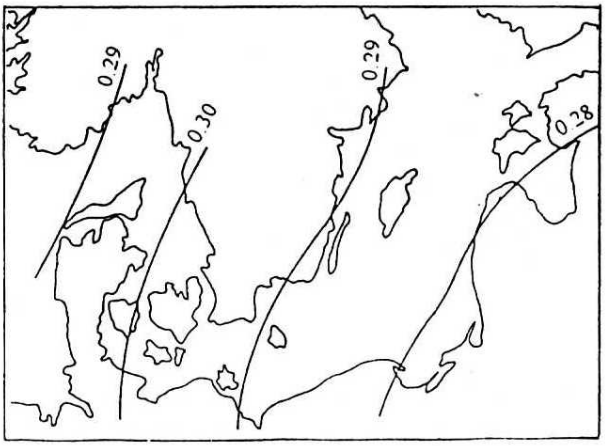

Fig. 5. Isolines of first local EOF transfer function computed from atmospheric pressure maps for 22 storm surges recorded at Ustka in the years 1960–1983.

The first amplitude function $\alpha_i(t)$ presents 89.6% of the total variance for all atmospheric fields. This confirms both the adequacy of the technique employed for selection of synoptic maps and the occurrence itself of such atmospheric pressure fields at the time of storm surges. Yet it should be stressed that computed percentage of variance is a mean value for all atmospheric situations considered. In individual cases the function $\alpha_1(t)$ contributes differently to the entire field. The convergence of the variances presented by individual amplitude functions to the total variance was fast, which stems from the assumptions taken at the stage of map selection. Because of the limited number of synoptic maps selected for the computations, only the first system of local transfer functions was analysed. The remaining systems, contributing much less to the total variance, are not sufficiently representative and can have substantial random components, thus without any general value for field description.

The computations depicted in the drawings show that high storm surges are generated by onshore winds, which was postulated earlier for the Polish coast (Zeidler et al. 1995). Hence the trend indicated for the occurrences of significant sea level increments is caused by more frequent events of onshore winds.

5. Major Findings

The analysis described in this paper has confirmed the existence of a probabilistic linkage between significant sea level increments in 4-hourly intervals and the absolute sea level due to storm surges. The relationship has been shown to exist upon comparison of the ranges of values of both quantities with the same probability of exceedance computed by the Pearson type III distribution.

High-pass filtering of substantial storm surges has been implemented by computation of sea level increments in 4-hour intervals. Hence the possible effect of the Baltic fill-up on considerable short-term surges has been eliminated and wind friction has become the major forcing factor of short-term sea level growth.

Finding trends in substantial sea level increments series is assumed to be equivalent to trend analysis for strong winds controlling coastal surges. Upon this assumption, the computations carried out for the period 1955–1990 have confirmed the existence of a statistically significant linear trend in the growth of sea level increments. The same can be postulated for strong winds at the Polish coast, thus supporting our earlier findings.

EOF computations for 22 storm surge situations have been centered around numerical characteristics of atmospheric pressure fields. It can be concluded that the first EOF amplitude function $\alpha_1(t)$ contains almost 90% of the overall variance of the atmospheric pressure fields; hence it can be a significant predictor of storm surges. An average field of atmospheric pressures controlling storm surges has also been identified, along with isolines of the first vector of local transfer functions. The behaviour of the two latter quantities confirms the linkage between onshore winds and the storm-surge induced sea level along the Polish coast.

The collected data for sea level, wind and atmospheric pressure, together with results of the analysis by the techniques presented herein, provide insight into the major phenomena affecting the Polish coast. At the same time, they can be regarded as a sound background in formulation of the hydrodynamic input for models of coastal climate and coast evolution in decadal time scales. Inter alia, the exploration of extreme events and linkages between their constituents can facilitate the modelling of mesoscale coastal processes in the Polish Baltic (and perhaps elsewhere) and the investigation of chronology effects and other coastal issues.

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