Papers

Analysis and long-term forecast of sea levels along the Polish Baltic Sea coast Part II. Annual mean sea levels – forecast to the year 2100

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Sea level rise
Southern Baltic
Probabilistic forecast

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Abstract

This is the second part of the analysis and long-term forecast of sea levels along the Polish Baltic Sea coast. The first dealt with annual sea level maxima; the present paper covers mean annual sea levels. The computations were based on measurements made at Świnoujście, Kołobrzeg and Gdańsk from 1901 to 1990. The statistical characteristics of the time series examined are presented and the occurrence of a trend and variations in its statistical significance in the course of measurements are analysed. The periodic structure is described and the data is analysed by means of empirical orthogonal functions (EOF). Mean sea level forecasts to the year 2100 were computed by extrapolating the linear trend and applying variable confidence limits. The height of the quantiles 0.01 and 0.001 of the maximum sea level distribution computed in the first paper is determined on the assumption that the mean sea level will continue to rise to the year 2100.

1. Introduction

As far as Baltic Sea level changes are concerned, it is basin filling, the local wind tangential stress effect and glacial isostatic movements of the Earth's crust that are the principal factors to be taken into account in explanations of the oscillation in annual mean sea level (AMSL). The long-term sea level structure, described in this paper, is of much lesser significance.

Computing AMSL as the arithmetic mean of measurement data with a step of a few hours is equivalent to applying low-pass filtration. The maximum aliasing error is assessed at 0.035 per cent of the M_2 amplitude (Pugh, 1987). Along the Polish coast, the Baltic is practically tideless, so the aliasing error is ignored in further computations.

Owing to the fundamental significance of rising sea levels to the safety of hydraulic engineering structures and low-lying coastal areas, forecasts of such rises in the 21st century have been the subject of many papers *e.g.* (Bird, 1993; Houghton *et al.*, 1990; Mercer, 1978; Peltier and Tushingham, 1989; Cubasch *et al.*, 1992). Sea level rises along the Polish coast have also been computed (Wróblewski, 1992a, 1993; Zeidler, 1992; Zeidler and Toms, 1992; Zeidler *et al.*, 1994).

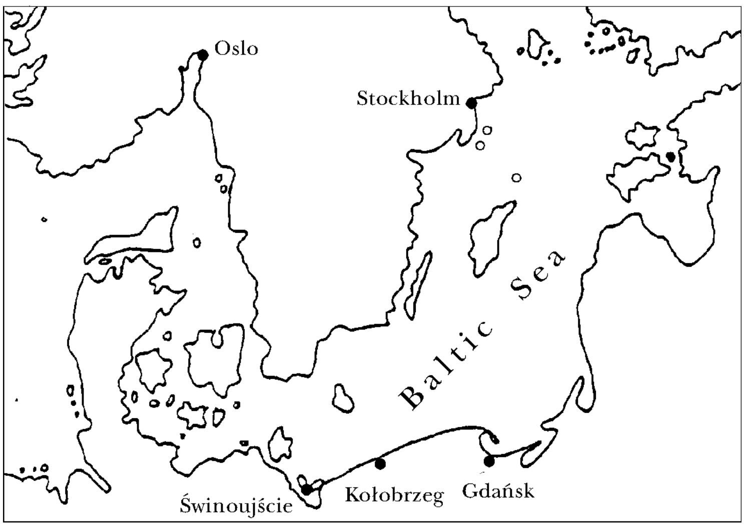

Fig. 1. Geographical position of AMSL measurement stations

The continuity of the data series was interrupted by the Second World War. These gaps are indicated in the brackets, following the overall measurement period: Świnoujście (1901–1990, 1945–1947), Kołobrzeg (1901–1990, 1944–1945), Gdańsk[1] (1901–1990, 1940–1945). The missing wartime data were filled in on the basis of AMSL from Baltic stations with uninterrupted measurement sequences, all levels being referred to –500 cm $N.N._{55}$ (Dziadziuszko, 1994). Because the results are comparable and the data published

[1]The records of the tide gauge at Gdańsk include historical data recorded at Gdańsk–Nowy Port. Although this tide gauge has since been moved to the North Port, it still preserves the original zero level.

since 1901 are reliable (Preussische Landesanstalt, 1901), the same measurement period has been assumed for all three sets of data. This has meant curtailing the Gdańsk and Kołobrzeg series. However, it was considered that N = 90 years was a period of measurements sufficiently long to provide reliable characteristics for their analysis. As local factors exert a substantial influence on AMSL, the forecasts were computed separately for each tide gauge. The location of measurement stations is shown on Fig. 1.

2. Periodic structure and empirical orthogonal functions (EOF)

The periodic structure of AMSL for these data has been analysed by spectral and other methods (Kowalik and Wróblewski, 1973; Wróblewski, 1974), (Dziadziuszko and Jednorał, 1988). There was found to be a weak 11–year period due to changes in solar activity and slight 3 and 5–6 year periods previously analysed during the computation of annual sea level maxima (ASLM). The Chandler effect and lunar nodal tide were not detected.

The data series were expanded in accordance with the EOF scheme in order to demonstrate the sea-level fluctuation characteristics common to M = 3 measurement stations. Following these computations, AMSL can be determined from the basic formula of this method

$$\mathbf{H} = \mathbf{E}\,\mathbf{F}, \tag{1}$$

where

H – AMSL matrix at three measurement stations with elements $H_i(t)$, $i = 1, ...M, \quad t = 1, ..., N$;

E – matrix of local transformation functions with elements e_{ji}, $j = 1, ..., M, \quad i = 1, ..., M$;

F – amplitude expansion function matrix with elements, $f_j(t), \quad j = 1, ...M, \quad t = 1, ..., N$.

Fig. 2 shows the local transformation functions, to which have been appended the percentage of the total variance, given by function $f_j(t)$, corresponding to the respective layouts of level e_{ji}. The layout of sea-level oscillation given by e_{1i} shows that 94.7% of AMSL along the Polish coast involves the simultaneous rise and fall of the level at the measurement stations in question. This function is linked directly with AMSL rise. The e_{2i} system represents the sea-level fall oscillations from Gdańsk to Świnoujście with a variance of 3.7% and through correlation with e_{1i} affects the mean level computations in the region by the EOF method. The function e_{1i} and e_{2i} are typical of EOF computations based on data from measurement stations located along the longitudinal axis of the Baltic (Wróblewski,

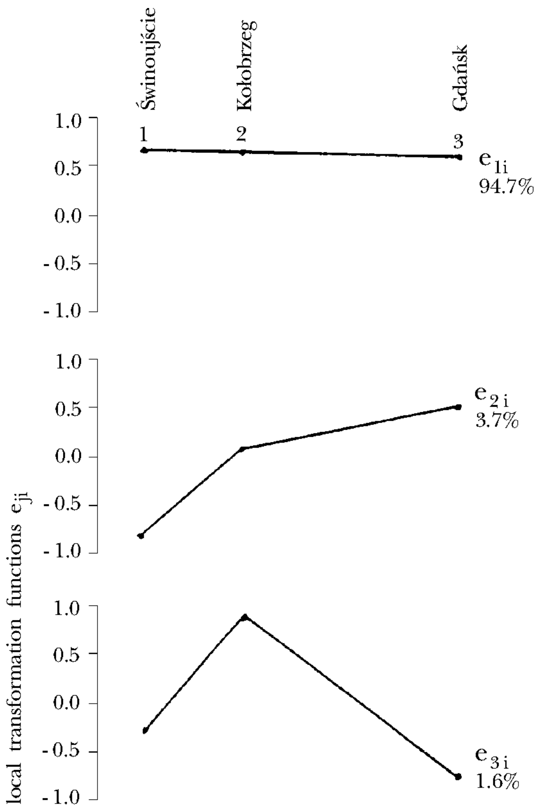

Fig. 2. Local EOF transformation functions of AMSL series

1992b). The characteristics of function e_{3i} (variance 1.6%) are highly atypical and do not make any significant contribution to resolving the problem of sea-level rise. The computations show that 98.4% of the AMSL variance at the three measurement stations is interconnected in a known level layout in accordance with the general oscillation of the mean Baltic Sea level.

3. The occurrence of a trend

The computations, preceded by a visual analysis of the trend line and measurement data, vindicated the assumption of a linear trend. For the linear function, the absolute increments $\Delta h = h_t - h_{t-1}$ are constant except for possible random deviations. In this case, the linear regression function parameter of the increments should not differ significantly from zero. Student's test applied at the 0.05 significance level showed that the zero regression parameter hypothesis was not rejected for the three data sets. The previously described periodic structure is too weakly pronounced to change the general nature of the trend. Moreover, the fundamental periodic oscillations are superimposed on one another and occur many times during the measurement period; the linear approximation of the sea-level rise is thus the best approximation of the phenomenon. Snedecor and Cochran's (1967) test was used to check agreement with the normal distribution of data dispersion with respect to the trend line. At a probability of $\alpha = 0.10$ all the series were distributed normally. The autocorrelation coefficients test (Anderson, 1942) showed that at the 0.95 probability level, the series of the differences between the trend lines and the measurement data were independent. Likewise, Bartlett's cumulative spectrum test (Box and Jenkins, 1976) demonstrated the independence of the series for limits $\varepsilon = 0.25$.

The occurrence of a trend was further investigated at the 0.05 significance level by means of the Mann-Kendall test (Bendat and Piersol, 1986). These computations showed that the existing trend hypothesis could not be rejected for any of the three AMSL series. The number of inversions A, the characteristic feature of this test, is a function of both the measurement time t and the number of series N. What is significant is the placement of t with respect to long-term sea level changes. To discover whether the trend was stable, values of $A(t, N)$ were calculated for $N > 29$; the results are shown in Fig. 3. The plot shows that only in the periods and their neighbourhood where data had to be inserted by interpolation was the trend at all three stations statistically insignificant. The linear trend of AMSL rise was calculated by the least squares method; the results are given in Tab. 1. The results presented in Tab. 1 are comparable to the global sea level rise, which without glacial isostatic adjustment is in excess of 1 mm per year (Peltier and Tushingham, 1989).

Table 1. Linear trend of annual mean sea level (AMSL) rise at Świnoujście, Kołobrzeg and Gdańsk from 1901 to 1990

Measurement station	Trend [cm year^{-1}]	Regression line increment [cm]	RMS error of data *vs.* regression line [cm]
Świnoujście	0.12 ± 0.02	11.0	4.3
Kołobrzeg	0.12 ± 0.02	10.8	4.7
Gdańsk	0.16 ± 0.02	14.3	5.4

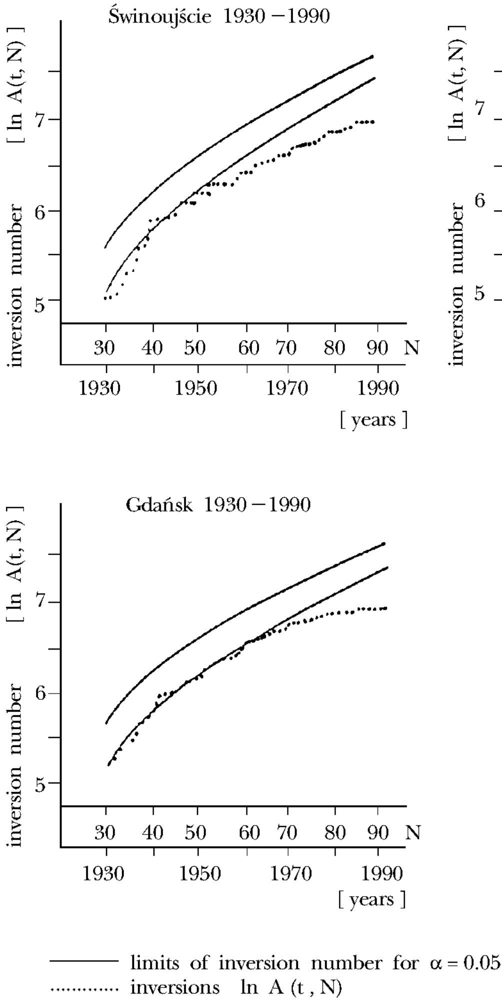

Fig. 3. Number of $A(t, N)$ inversions in the Mann-Kendall test for AMSL series

4. Forecast of sea-level rise to the year 2100

The forces inducing sea-level rise over the past 100 years have been the subject of many hypotheses. The complex factors bringing this about, of which we still have only superficial knowledge, are usually lumped together under the heading 'greenhouse effect'. A description of the complex problems involved there would, however, go beyond the bounds of this paper. The probabilistic method has been used in further computations; as in the case of ASLM, this enables the risk to be combined with the corresponding probability that sea levels will rise. It was assumed that the forces inducing such a rise and the vertical movements of the Earth's crust in the measurement region will not change significantly; the present trend can therefore be extrapolated. The risk involved in forecasting the set of factors responsible for the sea trend and determining the stability of its parameters – a difficult task – is taken into account by introducing appropriate confidence limits.

For the series in question the AMSL forecast for a time T can be given by the formula

$$\widehat{H}_T = \mathbf{c}'\,\hat{\mathbf{a}}, \tag{2}$$

where

$$T = N + 1, \quad N + 2, \quad N + ...,$$

$\mathbf{a}$ – vector of the trend parameters,
$\mathbf{c}$ – vector of the time variable.

The real AMSL for a time T can be given as

$$H_T = \mathbf{c}'\,\mathbf{a} + u_T, \tag{3}$$

where u_T is the forecast random component. The forecast error D_T for time T is

$$D_T = \mathbf{c}'(\hat{\mathbf{a}} - \mathbf{a}) - u_T. \tag{4}$$

It should be stressed that $\mathbf{E}\,(\mathbf{a}) = \mathbf{a}$, $E(u_T = 0)$ and $E(D_T) = 0$. The variance D_T is given by (Zelias, 1984)

$$\mathrm{var}\,(D_T) = \sigma^2_{uT}[1 + \mathbf{c}'(\mathbf{X}'\,\mathbf{X})^{-1}\mathbf{c}], \tag{5}$$

$$\mathbf{X}'\,\mathbf{X} = \begin{bmatrix} N & \sum\limits_1^N t \\ \sum\limits_1^N t & \sum\limits_1^N t^2 \end{bmatrix}. \tag{6}$$

It is clear from eq. (5) that the D_T variance is computed by multiplying the variance of the random component u_T by the matrix component of the right-hand side of the equation. The matrix component is dependent on the forecast lead. The u_T is accepted on the assumption that the normal confidence interval containing the random component for a large sample has a probability of $s = 0.683$. In these computations the matrix component in eq. (5) has yielded low values, which are of no use in view of the considerable risk involved in making very long-term forecasts. In further computations s must be assumed to be greater than 0.683 in order to take into consideration the possibility of changes in the set of factors inducing the trend in sea-level rise. With a forecast lead of $T_{\max} = N +$ 110 years, *i.e.* for the year 2100, it would seem to make sense to compute the sea level for various s. The choice of probability level of s depends on the risk involved in overstepping the limits of the confidence interval. In hydrology the confidence intervals were primarily used as a measure of the accuracy of the probable flood flows in rivers *e.g.* (Kaczmarek, 1960). Later they were introduced into ASLM computations. In this work they are used in AMSL and ASLM forecast. Using the confidence limits in making a probabilistic forecast of AMSL rise is similar to taking the quantile of the ASLM probability distribution. To avoid the jump from ongoing trend computations to a long-term forecast, eqs. (7) and (8) are introduced. These link the increase in the variable u_T with the increase in risk due to the extension of the forecast lead.

$$u_{Ts_z} = \sigma_u + \left[\frac{(u_s - \sigma_u)}{(T_{\max} - N)} \right] (T - N), \tag{7}$$

$$\operatorname{var}(D_{Ts_z}) = \sigma^2_{u_{Ts_z}} \left[1 + \mathbf{c}'(\mathbf{X}'\,\mathbf{X})^{-1}\mathbf{c} \right], \tag{8}$$

where

σ_u – standard deviation of the u differences between the measurements and regression line,

u_{Ts_z} – u_T positive value for probability s_z and forecast lead T,

u_s – u_T positive value for the maximum forecast lead time $T_{\max}$ with an assumed probability s.

The probability s_z can be determined from the table of normal distribution when variable u_{Ts_z} has been computed from eq. (7).

What is striking about these computations is the rise in sea level at Gdańsk. This has been due to local factors raising the tide-gauge readings and a faster rise in sea level along the Polish coast during the last 40 years. These changes in sea level are explained by the increased frequency of westerly circulations (Dziadziuszko and Jednorał, 1993; Zeidler *et al.*, 1994). However, as meteorological and tide-gauge records have been made over a relatively short period, this rise cannot be assessed in the context of the long-term oscillations of the mean sea level. It must be stressed that on a global scale, the acceleration in sea-level rise assessed on the basis of 37 time series with an average measurement period of 92 years between 1850 and 1991 was found to be 0.001 ± 0.008 mm/y^2 (Douglas, 1992). A more local computation for the MSL of the Baltic was provided by Woodworth (1990), who assessed the acceleration in sea-level rise in this basin at 0.4 mm/y^2/century. The Student's tests performed prior to this computation at the 0.05 significance level in no way invalidated the trend linearity hypothesis. These tests were allowed a very wide margin of safety in computations. Taking these results into consideration, an AMSL forecast was made on the assumption that the trend is linear. The computations of

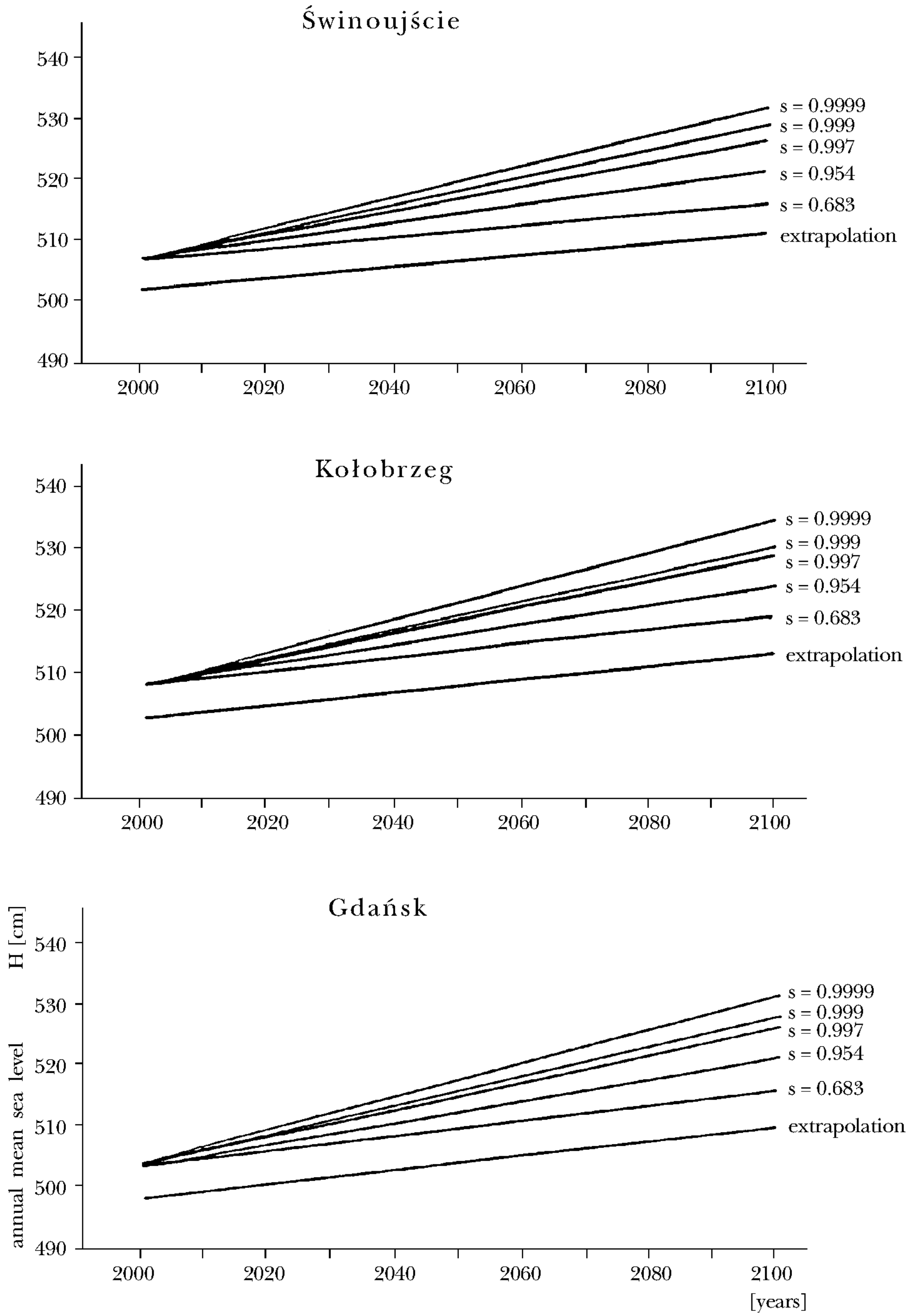

Fig. 4. Probabilistic AMSL forecast to the year 2100 at Świnoujście, Kołobrzeg and Gdańsk for different confidence limits

Table 2. The forecast rise in mean sea level at Świnoujście, Kołobrzeg and Gdańsk up to the year 2100 (based on measurements 1901–1990).
Tide-gauge zero level –500 N.N.$_{55}$

Measurement station	[year]	H_T $s = 0.683$ [cm]	H_T $s = 0.954$ [cm]	H_T $s = 0.997$ [cm]	H_T $s = 0.999$ [cm]	H_T $s = 0.9999$ [cm]
	2000	506	507	507	507	507
	2020	509	510	511	512	512
	2040	511	513	515	516	517
Świnoujście	2060	514	517	520	521	523
	2080	516	520	525	526	528
	2100	519	524	529	531	534
	2000	508	508	509	509	509
	2020	510	512	513	513	514
	2040	513	515	517	518	519
Kołobrzeg	2060	515	519	522	523	525
	2080	518	522	527	528	531
	2100	521	526	532	533	537
	2000	516	516	517	517	517
	2020	519	521	522	523	524
	2040	522	525	528	529	530
Gdańsk	2060	526	530	533	535	537
	2080	529	534	539	541	544
	2100	533	539	545	547	551

sea-level rise with the upper confidence limits for various T and s are given in Fig. 4 and Tab. 2.

The rise in sea level for the year 2100 was referred to the AMSL determined by regression line for Świnoujście, Kołobrzeg and Gdańsk in 1990. The results, obtained on the assumption of a normal distribution of the random component, are comparable with other forecasts of global sea-level rise. Depending on the value of s used in the forecasting, by 2100 the sea-level in these three ports will have risen by 14–29 cm, 14–30 cm and 19–37 cm respectively.

The literature contains a large number of papers determining the mean global sea-level rise during the 21st century. The earliest of these predicted a catastrophic rise in sea level caused by the melting of the Western Antarctic ice-cap (Mercer, 1978). In time, such forecasts have moderated. The IPCC forecast, based on the expected global warming, shows that the sea level of the oceans will most likely have risen about 60 cm by 2100 (Houghton *et al.*, 1990). The smallest forecast rise is ca 30 cm. The same paper also states, however, that the forecast of the extent and effects of local climatic changes determined by the GCM are very uncertain. Summarising the results of all the forecasts, most workers have predicted a rise of between 25 and 60 cm by 2100 (Titus and Narayanan, 1992). According to the latest computations ($2 \times CO_2$ scenario) the sea level will have risen 16 cm by 2090 as a result of the warming up of the water masses which is the only cause of greater importance (Cubasch *et al.*, 1992).

Having computed the AMSL forecast, it is possible to predict annual sea level maxima (ASLM) for rising sea levels in time T. To do this one can utilise the equations presented in earlier publications on this subject (Wróblewski, 1992a, 1993)

$$h_{Tp} = h_p + \mathbf{c}' \, \hat{\mathbf{a}} \pm \varepsilon_s, \tag{9}$$

$$\varepsilon_s = \sqrt{h_{ps}^2 + D_{Ts}^2}, \tag{10}$$

where

h_{tp} – maximum sea level at time T with an exceeding probability p, $T = N + 1, \quad N + 2, \ldots\ldots\ldots,$

h_p – sea level for probability p in the ASLM forecast with the trend eliminated (Wróblewski, 1992a),

ε_s – mean error in determining h_{Tp} at probability level s,

h_{ps} – mean error in determining the quantile h_p at probability level s,

D_{Ts} – error in determining the H_T at probability level s.

It should be noted that h_{ps} errors are asymptotically normal for the ASLM distribution according to Gumbel's method and the estimates of parameters by the highest likelihood method (Kimball, 1949). The hypothesis that u differences are normal is not rejected in these computations during the investigation of the trend. For $N = 90$ and the series under consideration, both formula (10) errors and ε_s can be assumed to have a normal distribution. The forecast for the 0.01 and 0.001 quantiles with upper confidence limits, is presented in Tab. 3. Forecasting of the ASLM distribution quantiles not shown in Tab. 3 is possible on the basis of eqs. (7), (8), (9) and (10). The AMSL trend for the computations presented in Tab. 3 were determined for the same periods in which ASLM were recorded. The same computation methodology was used as before.

The AMSL and ASLM computations were performed on the assumption of a normal distribution of confidence limits. However, this assumption restricts the forecast rise in sea level. But the assumption of any other distribution is ambiguous in the computations and analyses performed so far. If a very large rise in AMSL is assumed, considerable changes in probability correspond to small increments in the normal distribution variable. One can

Table 3. Forecast of the 0.01 and 0.001 quantiles of Gumbel's ASLM distribution for rising sea levels up to the year 2100 based on measurements at Świnoujście (1901–1990), Kołobrzeg (1867–1990) and Gdańsk (1886–1990).
Tide-gauge zero level –500 cm N.N.$_{55}$

Measurement station and period	T [years]	$h_{T\,0.01}$ Linear extra-polation [cm]	$\varepsilon_{0.997}$ [cm]	$\varepsilon_{0.9999}$ [cm]	$h_{T\,0.001}$ Linear extra-polation [cm]	$\varepsilon_{0.997}$ [cm]	$\varepsilon_{0.9999}$ [cm]
Świnoujście 1901–1990	2000	677	11	12	720	15	16
	2020	680	14	16	723	20	23
	2040	682	18	21	725	25	30
	2060	685	21	26	728	29	37
	2080	687	25	32	730	34	44
	2100	690	28	37	733	39	51
Kołobrzeg 1867–1990	2000	696	11	12	749	15	16
	2020	699	14	17	752	20	23
	2040	701	18	22	754	25	30
	2060	704	21	27	757	29	37
	2080	706	25	32	759	34	44
	2100	709	28	37	762	39	51
Gdańsk 1886–190	2000	668	11	11	711	15	16
	2020	671	14	16	714	19	22
	2040	674	17	21	717	24	29
	2060	677	21	26	720	28	35
	2080	680	24	31	723	33	42
	2100	683	28	36	726	38	49

then take a suitable multiple for values of the σ_u to obtain a comparative index of computations for different time series.

5. Conclusions

Analysis of AMSL time series has proved the existence of a trend in sea-level rise at Świnoujście, Kołobrzeg and Gdańsk. At none of the the three ports was the hypothesis that the trend is linear rejected at the 0.05 significance level. At the same level of significance, the hypothesis that occurence of a trend is statistically significant was not rejected either. EOF analysis of the series under investigation showed that the layout of the first two local transformation functions and the corresponding EOF characteristics of the mean Baltic Sea level were in agreement. AMSL were forecast to the year 2100 by extrapolating the trend and introducing variable confidence limits for the random component in the forecast formula. As local factors are important for sea-level rise, the forecasts were computed separately for every tide-gauge station.

Forecasts of the 0.01 and 0.001 quantiles of the ASLM distributions were computed for the same lead time. In these computations, variable confidence limits of the error in quantile estimation and AMSL forecast were taken into consideration.

These computations enable AMSL and ASLM to be predicted for the 21st century if probabilistic assumptions are made corresponding to the expected effects of a rise in mean sea level.

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