Seasonal forcing of Baltic water volumes by the meteorological fields over the basin from 1896 to 1970*

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Baltic Sea level
Atmospheric pressure
Seasonal oscillations

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Abstract

This paper discusses the seasonal oscillations of the meteorological fields influencing the seasonal changes in the Baltic water balance. Mean monthly atmospheric pressure data (1896–1970) from eight stations located around the Baltic were taken to be the basis for the computations. Six horizontal components of the atmospheric pressure gradients were selected for use in the subsequent computations. The mean monthly water volumes in the Baltic were computed by the method presented by the author in an earlier publication (Wróblewski, 1992a). In the next step, the selected horizontal components of atmospheric pressure gradients were expanded into EOFs. The first three amplitude expansion functions of the wind field had more significant coherences with changes in the Baltic water volumes than the corresponding EOF functions of the atmospheric pressure field. The spectral and statistical analysis of these functions and gradients was computed in order to detect their periodic structure and statistical characteristics. The multiple input stochastic dynamic system was used in the analysis. The most important result is the demonstration that the solar annual period is distinct in the wind-field components influencing the sea's seasonal dynamics. The solar semi-annual period is not well marked. The mean atmospheric pressure over the Baltic has a weak seasonal structure and practically does not force the water volume changes.

1. Introduction

Seasonal sea-level oscillations in the Baltic Sea and the resulting variations in its water volume and water balance have already been analysed in the oceanographic literature. The principal factors giving rise to this kind of

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phenomenon are known in general: they include the level of the North Sea, the wind and atmospheric pressure fields, and the steric effect. The effect of the wind field, connected with water exchange through the Danish Straits, is clear-cut and frequently determines synoptic and shorter periods in water volume oscillations. However, it requires precise definition in the case of seasonal oscillations: these are computed from mean monthly values corresponding to data applications following low-pass filtration. The fact that the influence of atmospheric pressure at high latitudes does not necessarily obey the inverted barometer rule is well-known. A precise explanation of the generation of seasonal oscillations in Baltic water dynamics is all the more complicated, because the factors generating them can be divided into local Baltic ones, and large-scale ones that also affect the Atlantic and the North Sea, which have an open border with each other. The collinearity existing among these factors is a significant difficulty in the stochastic analysis of the problem.
The aim of the present work was to present the seasonal oscillations in the atmospheric pressure and wind fields over the Baltic together with their influence on Baltic water volumes. The meteorological forcing factors chosen in the computations concurrently affect other aspects of Baltic Sea dynamics.

2. Measurement data

Baltic monthly mean sea levels (BMMSL) and Baltic water monthly mean volumes (BWMMV) were used in the computations as the basis for selecting elements of the wind and pressure fields correlated with them. The measurement series for the period 1896–1970 consisted of N = 900 data items. In order to determine the BMMSL time series and then to calculate the BWMMV, the method of empirical orthogonal functions (EOF) was applied (Wróblewski, 1992a). Oscillations of the basin water volume were expressed as cubic km values. A one-cm difference in BMMSL yields a 3.92 km^3 difference in BWMMV. The area of the basin is 392 228 km^2 excluding the Danish Straits (Ehlin and Mattisson, 1976). Sea level data were gathered from the Permanent Service for Mean Sea Level collection (Spencer and Woodworth, 1993).

The characteristics of the wind and atmospheric pressure fields were computed from point measurements (Vose *et al.*, 1992). In areas where no point measurements were available, data averaged at the nodes of the geographical coordinates were introduced (Jones *et al.*, 1987). All atmospheric pressure data were converted to sea-level pressure (SLP). The geographical locations of the SLP points used in the computations are shown in Fig. 1.

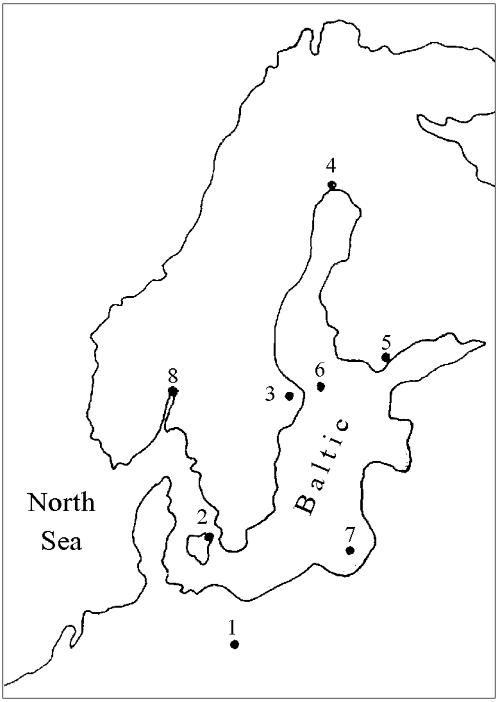

Fig. 1. Geographical location of the atmospheric pressure measurement points; 1 – Berlin, 2 – Copenhagen, 3 – Uppsala, 4 – Haparanda, 5 – Helsinki, 6, 7 – geographical grid points, 8 – Oslo

3. Computations

Initially, all possible horizontal components of the atmospheric pressure gradients (HCAPG) were computed for the eight SLP points shown in Fig. 1. Then, from the matrix correlating gradients *vs* water volumes, six gradients with a correlation coefficient of $r \geq 0.50$ were selected. Gradient vectors were computed by subtracting the atmospheric pressures given in the lower line of Tab. 1 from those in the upper line.

Table 1. Horizontal components of atmospheric pressure gradients correlated with changes in Baltic water volume at the $r \geq 0.50$ level for the period 1896–1970

Gradients between measurement points	Berlin Copenhagen	Berlin Haparanda	Berlin Helsinki	Copenhagen Uppsala	Point 7 Uppsala	Point 7 Point 6

As can be seen from the data in Tab. 1, seven point SLPs determined by the above correlation criterion were used in the subsequent computations.

In order to define the interaction of all the HCAPGs on a sea basin, the EOFs were introduced. Gradient matrix expanded in EOF is given in abbreviated form by eq. (1) and obtained by applying the results in Tab. 2. Similar computations were done using eq. (2) for the 7 SLP points and applying the results in Tab. 3.

$$\mathbf{G} = \mathbf{EA}, \tag{1}$$

where

G – HCAPG matrix with elements $g_i(t)$;
$i = 1,..., 6; \quad t = 1,..., N$,

E – local transition function matrix with elements e_{ji};
$j = 1,..., 6; \quad i = 1,..., 6$,

A – amplitude function matrix with elements $\alpha_j(t)$;
$j = 1,..., 6; \quad t = 1,..., N$.

Table 2. EOF expansion of mean monthly horizontal components of atmospheric pressure gradients acting on changes in Baltic water volume in the period 1896–1970

	Amplitude functions $\alpha_j(t)$					
	$\alpha_1(t)$	$\alpha_2(t)$	$\alpha_3(t)$	$\alpha_4(t)$	$\alpha_5(t)$	$\alpha_6(t)$
percentage of overall variance determined by $\alpha_j(t)$	79.0	9.5	7.1	2.4	1.4	0.6
summarised percentage determined by $\alpha_j(t)$	79.0	88.5	95.6	98.0	99.4	100.0
correlation coefficient $\alpha_j(t)$ *vs* Baltic water volumes	0.66	–0.25	–0.07	–0.05	–0.06	0.13

$$\mathbf{P} = \mathbf{F\Phi}, \tag{2}$$

where

P – atmospheric pressure matrix with elements $p_i(t)$;
$i = 1,..., 7; \quad t = 1,..., N$,

F – local transition function matrix with elements f_{ji};
$j = 1,..., 7; \quad i = 1,..., 7$,

Φ – amplitude expansion function matrix with elements $\varphi_j(t)$;
$j = 1,..., 7; \quad t = 1,..., N$.

Following the determination of the EOF, the amplitude spectra of the first three amplitude functions of $\alpha_j(t)$ and $\varphi_j(t)$ were computed using a Fourier finite series model, where the Sa and Ssa frequencies were harmonics of the fundamental frequency. The proportions of $\alpha_j(t)$ and $\varphi_j(t)$ in the overall data variance and their correlation with the water volumes were

Table 3. EOF expansion of mean monthly point atmospheric pressures in the Baltic region for the period 1896–1970

	Amplitude functions $\varphi_j(t)$						
	$\varphi_1(t)$	$\varphi_2(t)$	$\varphi_3(t)$	$\varphi_4(t)$	$\varphi_5(t)$	$\varphi_6(t)$	$\varphi_7(t)$
percentage of overall variance determined by $\varphi_j(t)$	77.1	17.7	2.5	1.2	0.7	0.6	0.2
summarised percentage determined by $\varphi_j(t)$	77.1	94.8	97.3	98.5	99.2	99.8	100.0
correlation coefficient $\varphi_j(t)$ *vs* Baltic water volumes	–0.46	–0.49	0.08	–0.11	0.16	0.14	–0.09

taken into consideration. All the amplitude functions were correlated with BWMMV at the 0.05 significance level. The results of the spectral computations are given in Fig. 2.

By means of the Fourier finite series model the Sa and Ssa amplitudes of $\alpha_j(t)$ were verified for three 25–year periods in order to demonstrate the long-term variability of these oscillations. The relevant data are given in Tab. 4. To demonstrate the overall effect of all HCAPGs on the water volume changes of the basin using a dynamic approach, their influence was computed by the introduction of the three first $\alpha_j(t)$ as correlated inputs

Table 4. The variability in amplitudes $A(f)$ of functions $\alpha_j(t)$ computed from horizontal components of atmospheric pressure gradients over the Baltic. Computations for 25–year periods

	Function					
	$\alpha_1(t)$		$\alpha_2(t)$		$\alpha_3(t)$	
Measurement period	Sa [hPa]	Ssa [hPa]	Sa [hPa]	Ssa [hPa]	Sa [hPa]	Ssa [hPa]
$A(f)$ for the period 1896–1970	0.772	0.349	0.317	0.132	0.190	0.093
$A(f)$ for the period 1896–1920	0.918	0.691	0.298	0.090	0.201	0.135
$A(f)$ for the period 1921–1945	0.709	0.284	0.298	0.156	0.237	0.077
$A(f)$ for the period 1946–1970	0.771	0.168	0.370	0.162	0.144	0.142
min. $A(f)$/max. $A(f)$ for three 25–year periods	0.77	0.24	0.81	0.56	0.61	0.54

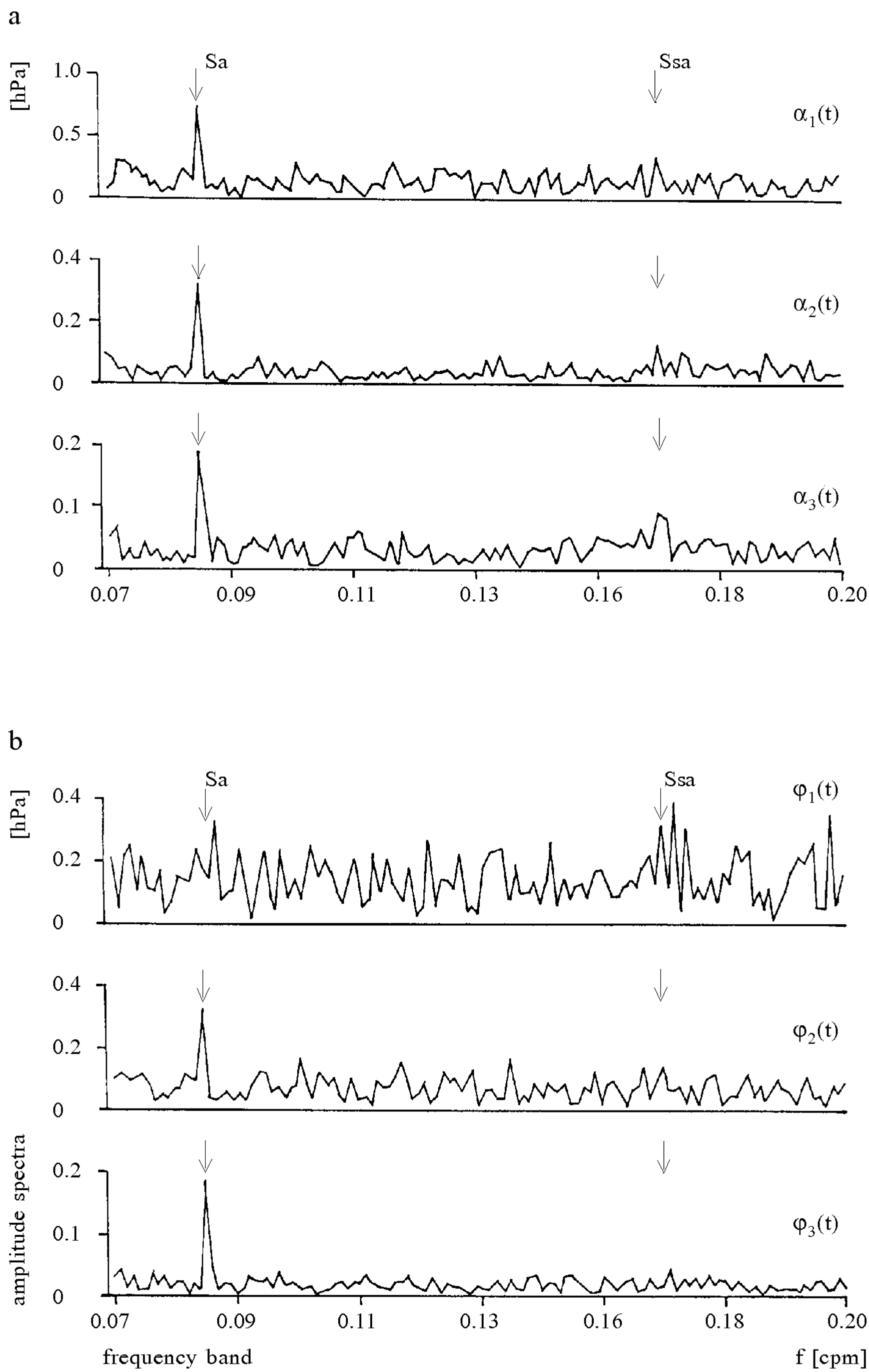

Fig. 2. Amplitude spectra of the EOF functions of the horizontal components of the atmospheric pressure gradients (a) and atmospheric pressures (b) over the Baltic. Computations for mean monthly data 1896–1970

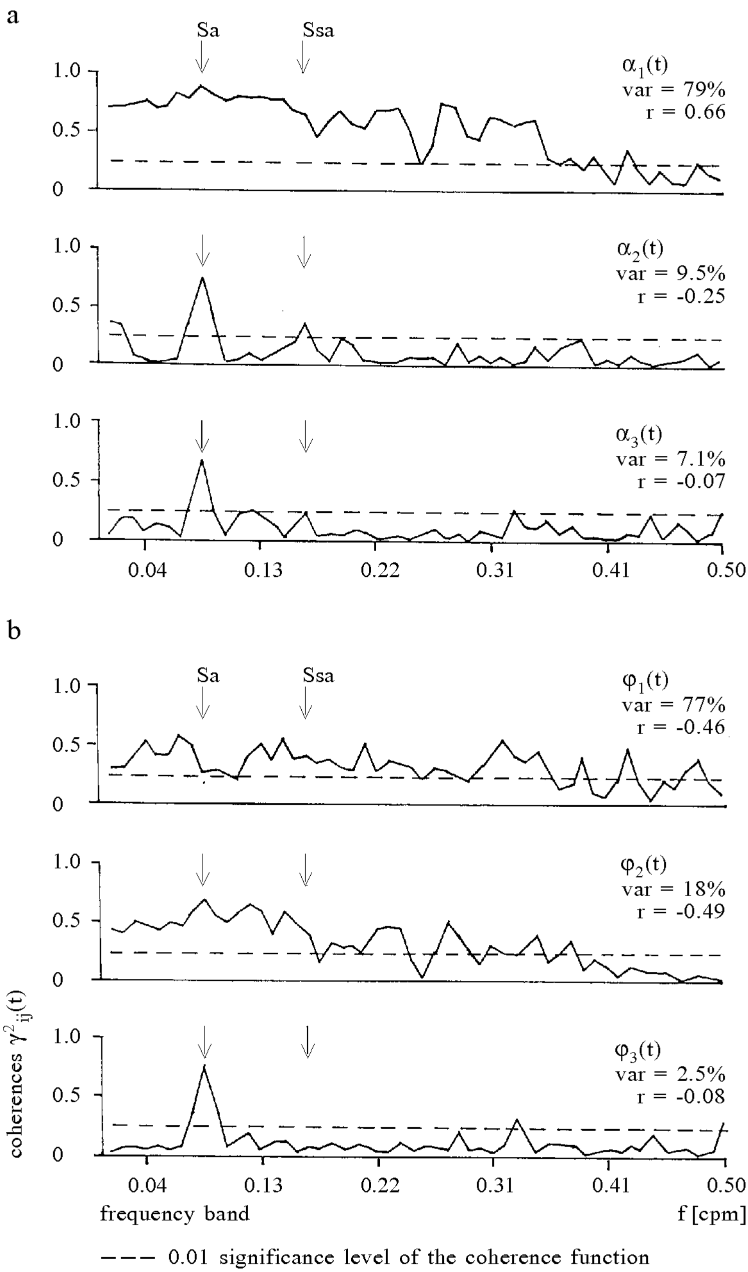

Fig. 3. Coherences of the EOF amplitude functions of the horizontal components of the atmospheric pressure gradients (a) and atmospheric pressures (b) over the Baltic *vs* Baltic water volumes; var – percentage of the total variance represented by the EOF amplitude function, r – correlation coefficient of the amplitude functions *vs* monthly mean water volumes of the Baltic basin. Computations for mean monthly data 1896–1970

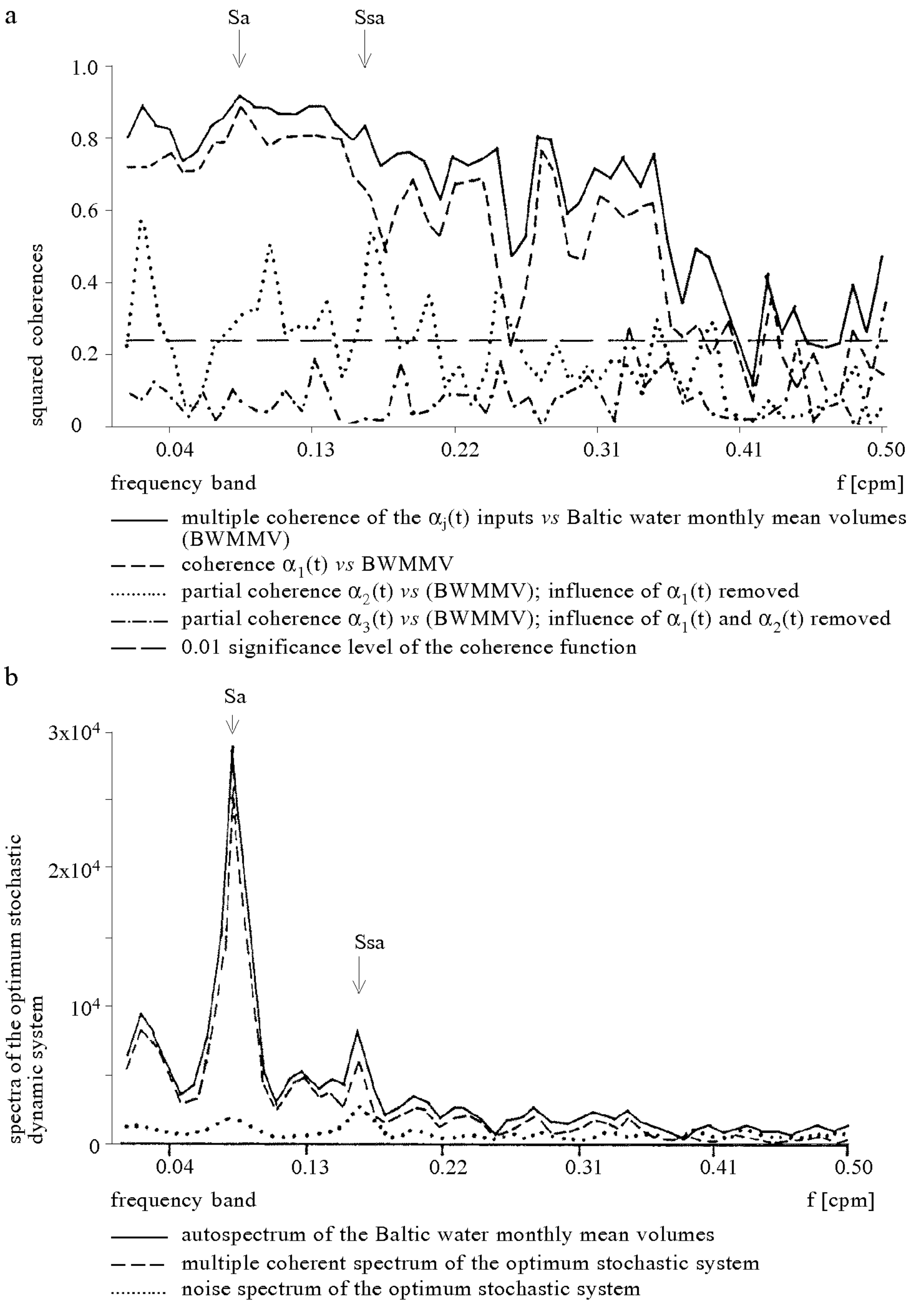

Fig. 4. Influence of the horizontal components of the atmospheric pressure gradients expanded into EOF on Baltic water monthly mean volumes. Computations by the optimum multiple dynamic stochastic system for mean monthly data 1896–1970; coherences of the system (a), spectra of the system (b)

to the multiple stochastic dynamic system (Bendat and Piersol, 1986), the output of which are BMMSLs and BWMMVs. Computations were also carried out by the Fourier finite series model and ensemble averaging. As in the previous computations the Sa and Ssa frequencies were harmonics of the fundamental frequency. Fig. 3 shows the coherences of the first three functions of $\alpha_j(t)$ and $\varphi_j(t)$ computed within the framework of the dynamic system applied. Fig. 4 shows the connection between HCAPG characteristics and BWMMV for the computation of the multiple coherence function, the coherence of $\alpha_1(t)$ and the partial coherences of the individual $\alpha_j(t)$. The overall influence of particular inputs into the optimum conditioned model is presented by a computation of the multiple coherent spectrum and the noise spectrum of the system plotted in Fig. 4. The computations were done with the aid of eqs. (3)–(8).

$$G_{jj.r!} = \frac{2}{T} E[X^*_{j.r!}\, X_{j.r!}], \tag{3}$$

where

$G_{jj.r!}$ – one-sided conditioned autospectrum (frequency notation omitted),
$X_{j.r!}$ – Fourier transform of process $x_j(t)$ with the exclusion of $r!$ processes,
$X^*_{j.r!}$ – complex conjugate value of $X_{j.r!}$,
T – measurement period of realisation series.

$$G_{ij.r!} = \frac{2}{T} E[X^*_{i.r!}\, X_{j.r!}], \tag{4}$$

where

$G_{ij.r!}$ – one-sided conditioned cross-spectral density function of processes $x_i(t)$ and $x_j(t)$ with the exclusion of $r!$ processes.

$$\gamma^2_{ij.r!} = \frac{|G_{ij.r!}|^2}{G_{ii.r!} G_{jj.r!}}, \tag{5}$$

where

$\gamma^2_{ij.r!}$ – partial coherence function of processes $x_i(t)$ *vs* $x_j(t)$ with the exclusion of $r!$ processes.

$$\gamma^2_{y:q!} = 1 - \Pi^q_{i=1} \left(1 - \gamma^2_{iy.(i-1)!}\right), \tag{6}$$

where

$\gamma^2_{y:q!}$ – multiple coherence function of the output process $y(t)$ and q input processes.

$$G_{vv} = G_{yy} \left[1 - \Pi^q_{i=1}(1 - \gamma^2_{iy(i-1)!})\right], \tag{7}$$

where

G_{vv} – one-sided multiple coherent spectrum.

$$G_{nn} = G_{yy} - G_{yy} \left[1 - \Pi^q_{i=1}(1 - \gamma^2_{iy(i-1)!})\right], \tag{8}$$

where

G_{nn} – one-sided noise spectrum of the system.

4. Analysis of computation results

Taking into account the noise characteristic of $\varphi_1(t)$ shown in Fig. 2, the coherence plots of $\varphi_j(t)$ functions *vs* BWMMV shown in Fig. 3, and the comparison of atmospheric pressure spectra with the Baltic volume spectrum by means of the equivalence test, the atmospheric pressure characteristics over the Baltic were not used in the subsequent computations. These indicate that the geostrophic wind field components, *i.e.* the HCAPGs, are the best meteorological predictors of seasonal changes in BWMMV and BMMSL.

The general rejection of a local atmospheric pressure field as an important predictor of sea-level oscillation has been mentioned in general in the Baltic oceanographic literature (Ekman and Stigebrandt, 1990; Wróblewski, 1992b). These computation results clearly excluded its significant static influence on the Sa and Ssa periods in the BWMMV dynamics. It is generally true that at high latitudes, and especially at shore stations and in semi-open basins, the tangential friction of the wind is crucial and can, depending on local conditions, exceed the influence of atmospheric pressure. The effect of atmospheric pressure on seasonal oscillations world-wide has been demonstrated in basic works (Pattullo *et al.*, 1955; Gill and Niiler, 1973). The EOF local transition functions expanded from SLP measured at particular points, present atmospheric pressure patterns. Amplitude functions reflect their changes with time. The noise aspect and seasonal frequency irregularities (see Fig. 2) in the amplitude spectrum of $\varphi_1(t)$, which makes up 77% of the field variance, is indicative of the random nature of the variations in the averaged pressure field. The Sa amplitudes of the $\varphi_2(t)$ and $\varphi_3(t)$ take small values and Ssa periods lie within the noise band. It seems that the pressure field over the Baltic is a poor reflection of the large-scale seasonal atmospheric processes in the northern hemisphere, *e.g.* (Rogers, 1990). The spatial averaging in these computations often concerned distant measurement SLP points under the influence of different atmospheric pressure systems or at the variable boundary between such systems. The seasonal characteristics of pressure systems over the Baltic have been published for the period 1961–1990 (Miętus, 1994). This paper also discusses the differentiation during a year of mean monthly SLP ranges at different measurement points. The general trend is associated with the increase in seasonal pressure range along the horizontal longitudinal axis of the basin with distance from the Danish Straits.

In the Baltic region, the most characteristic feature of the movement of the air masses is zonal circulation, and is associated with the exchange of waters through the Danish Straits. The zonal geostrophic circulation can be represented by longitudinally oriented gradient vectors. As the computations showed, all the gradients selected possessed this feature to a greater or lesser extent. The set of gradients in Tab. 1 presents for their positive values a slope of atmospheric pressure fields from a southerly to a northerly and westerly air flow. HCAPGs can be transformed to the monthly mean speeds of the zonal circulation over the region covered by particular vectors. By means of a variety of positive and negative values, the EOF local transformation functions present atmospheric pressure patterns and related wind fields. Amplitude functions give an image of time changes of particular wind field configurations. They can be used as oceanographic predictors, assuming a linear relationship between the geostrophic and local wind as influenced by the local topography. Analysis of the amplitude spectra of the functions shown in Fig. 2 displayed an Sa period occurring in three computed $\alpha_j(t)$ and an Ssa period, far less well-defined in the noise band. The computations of the coherences plotted in Fig. 3 confirm the effect of Sa wind oscillations on the basin's water dynamics; as in the amplitude spectra, the Ssa period is not so well marked. The Fourier transform displayed amplitudinal variability in both periods for particular HCAPGs: for Sa within the 0.5–2.2 hPa interval, and for Ssa in the 0.2–1.0 hPa interval. The computations done with the same method for the three 25–year periods shown in Tab. 4 also display considerable variation. These relatively short computation periods confirm the supposition that the meteorological period Sa affects the 100–year amplitude variations in Sa in the Baltic sea levels (Ekman and Stigebrandt, 1990). The same inferences could probably be applied over a limited range to the slightly marked Ssa period. The coherences of each HCAPG *vs* BWMMV indicated in general that they are significantly diminished in the 0.37–0.5 cpm frequency band interval. The same result is shown by the multiple coherence presented in Fig. 4. Clearly, the BWMMV oscillations in this band are strongly influenced by sources other than meteorological forcing and its collinearities or have random characteristics. It is also possible that both causes act concurrently. The proportions of autospectrum peaks determined by the optimum stochastic dynamic system are 94% for Sa and 68% for Ssa. The reverse arrangement test applied at the 0.05 significance level indicated that there is no evidence of the linear trend in the zonal circulation over the Baltic. A similar result emerged from an analysis of the seasonal averages and annual geostrophic wind speeds over the North Sea for a period of more than a century (Rosenhagen, 1994).

Computations show that the elements of the Baltic geostrophic wind field have a seasonal periodicity structure and can be used as predictors of seasonal variability of the sea's water volumes without recourse to oceanographic characteristics. This does not imply, of course, that oceanographic factors have no influence on BWMMV. Since local Baltic meteorological fields are collinear with the wind and pressure fields over the North Atlantic and North Sea, Baltic and North Sea levels are dependent on the same large-scale meteorological fields. Wind predictors thus present not only local but also far broader meteorological fields, also acting on the Baltic via North Sea levels. Apart from this, the collinearity of other oceanographic forcing factors with meteorological phenomena requires analysis. The same applies to the generation of the Ssa period.

5. Conclusions

Computations have shown that the mean monthly atmospheric pressure fields over the Baltic, characterised by EOF time series, cannot be used to determine the seasonal variability of the water volume or sea level in a basin. The seasonal variability of atmospheric pressure fields is not well defined.

An Sa period and a less well-defined Ssa period occur in the geostrophic wind field over the Baltic. In the computations these are represented by circulation indices, calculated as EOFs of the mean monthly vectors of the horizontal components of the atmospheric pressure gradients. Oriented longitudinally, these vectors are representative of the geostrophic zonal atmospheric circulation. This representation is effective as an oceanographic predictor.

By computing the multiple coherence function and multiple coherent spectrum of an optimum stochastic dynamic system, it has been shown that an accurate computation of the Sa period in the spectrum of water volumes and sea levels in the basin can be based on selected elements of the wind field. The Ssa period cannot be so well determined.

Since the EOF elements of the Baltic wind field are collinear with the large-scale wind and atmospheric pressure fields over the North Atlantic and North Sea, EOFs are also connected with the sea levels in those basins and in this way indirectly influence the sea level in the Baltic. The level of this collinearity and the collinearity with other elements of marine dynamics requires further study.

The seasonal amplitudes of the EOFs representing the wind field in three consecutive 25–year periods display considerable variability and have undoubtedly affected the long-term changes in the water volumes and sea levels in the Baltic.

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