Tellus (1996), 48A, 672–683
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TELLUS
ISSN 0280–6495

Main characteristics of the long-term sea level variability in the Baltic sea

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(Manuscript received 16 October 1995; in final form 15 April 1996)

ABSTRACT

The horizontal variation of the sea level variability for periods between a few days and several years has been investigated using daily means of sea level records obtained along the coasts of Sweden in the period 1977–1987. Motions on these periods are forced, either "externally" by the varying sea level outside the mouth and the freshwater supply, or "internally" by varying air pressure, wind and density in the Baltic Sea. Free, natural oscillations (seiches) of the Baltic Sea are generally considered to have periods from two days and shorter, and may thus contribute some variance to the daily means of the sea level and by that to the studied motions. The externally and internally forced contributions to the sea level records in the Baltic Sea are separated using a model for the externally forced contribution. The externally forced sea level variations explain most of the variance for periods longer than one month, and between 50 and 80% of the total sea level variance in the Baltic Sea with maximum in the central parts (the Stockholm area). It is also found that for periods shorter than about one month the internally forced oscillations are kinematically similar to those occurring in the first natural seiche mode in a closed Baltic Sea, with maximal variability in the extreme north and south, and minimum in the Stockholm area. For longer periods, however, the internally forced oscillations are kinematically similar to those occurring in an open bay with increasing amplitudes from the mouth and inwards. The shift in the kinematics of the internally forced oscillations is explained by the limited transport capacity of the straits in the mouth for "high frequency" motion.

1. Introduction

Massive sea level recording started in the Baltic Sea in the second part of the nineteenth century, mainly in order to make possible estimates of the rate of post-glacial rebound. As a result of this, a large portion of the longest sea level records in the world have been obtained along the coasts of the Baltic Sea. A lot of analyses of the apparent land uplift, i.e., the sea level trend relative to an earth-fix point, and the variability at certain frequencies have been published, see Lisitzin (1974) for a summary of earlier work. From disparate measurements in Stockholm, Ekman (1988) put together the world's longest continuing sea level record which starts in 1774. Dividing this series in two parts he could show that the eustatic sea level rise during the last century is about 1 mm yr^{-1} greater than in the previous century. The Stockholm sea level record has also been used to show the presence of large secular changes of the amplitudes of the annual, semi-annual and pole-tide periods (Ekman and Stigebrandt, 1990). It was argued that the changes of the amplitudes of these long periods were imported from the North Sea by the co-oscillating Baltic Sea.

Early in the present century, scientists began to use sea level records to study variations in the volume of the Baltic Sea. The studies showed that most of the low-frequency variability of the Baltic

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Sea volume may be explained by water exchange with the Kattegat and the North Sea, e.g., Bergsten (1933) and Hela (1944). It is nowadays well-known that instantaneous in- and out-flows through the Danish Straits in the mouth of the Baltic Sea, forced by the difference in sea level between the Kattegat and the Baltic Sea, may be a factor of 20 greater than the mean rate of freshwater supply, e.g., Stigebrandt (1980) and Omstedt (1987). Thus, the volume changes of the Baltic Sea are essentially due to water exchange with the Kattegat, but freshwater supply by runoff and precipitation minus evaporation on the sea surface of the Baltic have some effect.

In addition to the sea level variability imposed by the varying sea level in the Kattegat, there is also variability imposed by direct atmospheric impact on the Baltic. Analysing initial oscillations in a 2-dimensional numerical model, Krauss (1974) found that the Baltic Sea has barotropic eigen-oscillations of period lengths 32 and 22 h, periods that show up in most sea-level spectra together with periods in the range 50–60 h, c.f. Kullenberg (1981). In the Bothnian Bay, periods of about 2 days are commonly observed, which is close to the appropriate seiche period according to, e.g., Lisitzin (1967). Wind-forced barotropic oscillations of the Baltic Sea have been modelled by Svansson (1972), and Holmström and Stoke (1978) constructed a purely empirical, statistical forecasting model.

Ekman and Mäkinen (1991, 1996) calculated the topography of the long-term mean sea level relative to the mean geoid in the Baltic Sea using geodetic methods. They found that the mean sea level drops by about 20 cm from the upper Bothnian Bay to the southwestern Baltic Sea which was mainly due to the horizontal variation of salinity.

In this paper we will investigate the horizontal variation of the sea level variability, from Kattegat, through the Baltic proper and up to the Bothnian Bay, for periods from a few days to several years. We will also investigate how the sea levels in the different parts are correlated. To this end we use daily means of sea level during the period 1977–1987 in 6 locations, 5 within the Baltic Sea and 1 in the Kattegat. Using the model in Stigebrandt (1980) we separate the externally and the internally forced contributions to the sea level variability. Here, the external forcings are the in-outflows to the Baltic Sea as well as the fresh-water supply, and the internal forcings are due to varying air pressure, wind and density in the Baltic Sea. Freshwater supply acts both as external and internal forcing, since it affects the volume flow between the Kattegat and the Baltic as well as the distribution of density (salinity) inside the Baltic. However, the internal effect is here considered only implicitly through observed changes in the salinity. A simple model for the internally forced sea level variability that includes effects of varying horizontal gradients in air pressure and density distribution within the Baltic Sea is formulated and compared to the internally forced sea level. The internally forced sea level variability due to local winds, however, is the subject of a forthcoming paper, and is not included in the present model.

The data sets are described in Section 2. In Section 3, the variance of the series is partitioned among different period bands. The model for externally and internally forced oscillations is presented in Section 4, and the results are discussed in Section 5. The paper ends with some conclusions in Section 6.

2. Data

The data consist of daily mean values of the sea level from 6 stations from the period 1977–1987. One station, Viken, is situated in the Kattegat, and the other in the Baltic Sea. The latter stations are, going from south to north, Klagshamn, Stockholm, Forsmark, Spikarna and Ratan (c.f. Fig. 1). As an example the Klagshamn series is plotted in Fig. 2, and the annual variations can be seen with high sea levels in late autumn and early winter.

The model for the externally forced sea level variations in the Baltic Sea is driven by the sea level at Viken and the freshwater supply (i.e., river run-off) to the Baltic Sea while the model for the internally forced variations is driven by horizontal daily gradients of air pressure and monthly density variations. Monthly mean values of the river runoff from the period 1950–1990 are given by Bergström and Carlsson (1993). Air pressure data are taken from a meteorological database produced by SMHI (the Swedish Meteorological and Hydrological Institute) with horizontal resolution $1^\circ \times 1^\circ$ and a time step of three hours. The database

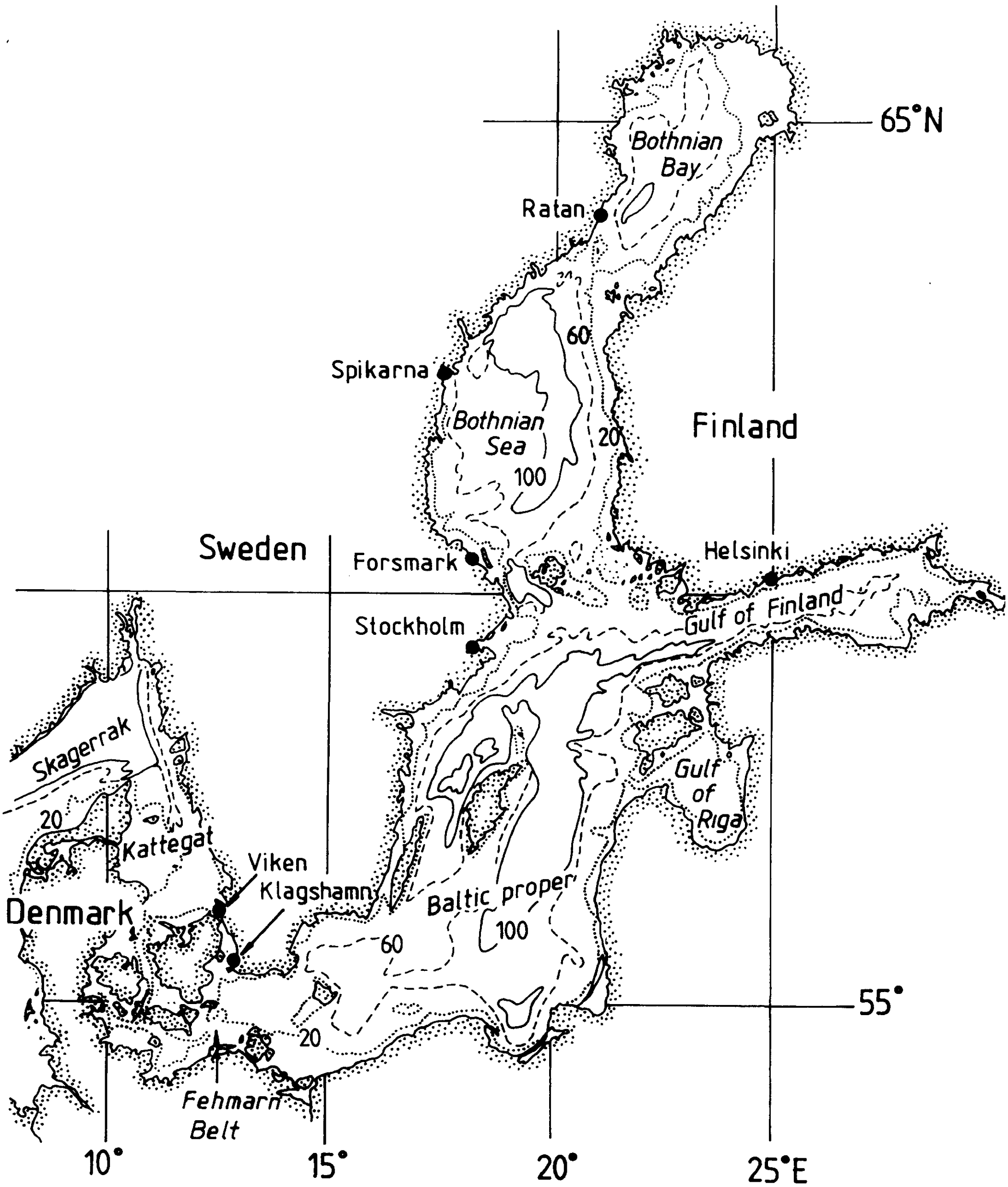

Fig. 1. A map of the Baltic Sea, with the sea level stations marked.

starts in 1979 so the model is only run for nine years, 1979–1987. From this database the daily mean air pressure for the different sub-basins (Bornholm Basin, Gulf of Finland, Baltic proper minus the Bornholm basin and the Gulf of Finland, Bothnian Sea and Bothnian Bay) are calculated. The density data are monthly mean values for the different basins calculated from salt and temperature data from a cruise database obtained from SMHI.

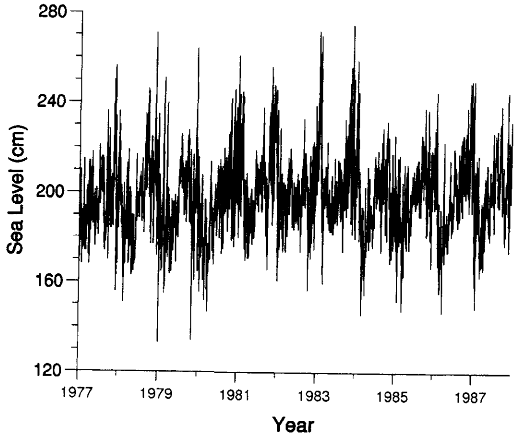

Fig. 2. The sea level at Klagshamn during the period 1977–1987.

3. Variance calculations

A sea level time series obtains contributions from a continuous spectrum of frequencies. Through appropriate averaging, the contributions to the variance from different period bands and discrete periods may be obtained. The idea of the analysis in this section is to get a first robust description of the partition among wide period bands of the variability of the time series. From the horizontal distribution of variance we intend to obtain a crude picture of the kinematics of the sea level motions in the Baltic Sea for different period bands. This in turn will give some insight into the dynamical response of the Baltic Sea to different types of forcing.

3.1. Annual sea level variations

The annual mean sea level, h_j, as well as the variance around this level, Var_j, (the annual variance) are calculated as

$$h_j = \frac{1}{N_j} \sum_{ni} h_{nij}, \tag{1}$$

and

$$\mathrm{Var}_j = \frac{1}{N_j} \sum_{ni} (h_{nij} - h_j)^2, \tag{2}$$

where h_{nij} is defined as the mean sea level at day n, month i and year j. N_j is the number of days during year j.

In Fig. 3, the annual mean sea levels during the investigated period are shown, arranged from south to north to increase the readability. It can be seen that all mean sea levels varies with 10–15 cm, and the larger variations at Viken occur in the Baltic as well. Within the Baltic all the 5 stations show a similar pattern, but the sea level at Klagshamn appears to be a little more influenced by the sea level at Viken than the other stations. In 1986 for instance, there is a week maximum in the sea level of the Baltic Sea stations but this is hardly detectable at Klagshamn, and at Viken there is a steady decrease. Thus Fig. 3 suggests that the sea level in the Baltic is very much influenced by (co-oscillates with) the Kattegat, at least for time scales from a few years and longer.

The annual variances, Var_j, vary a lot from year to year and the greatest variability occurs at Ratan, (Fig. 4). The year to year variations of the

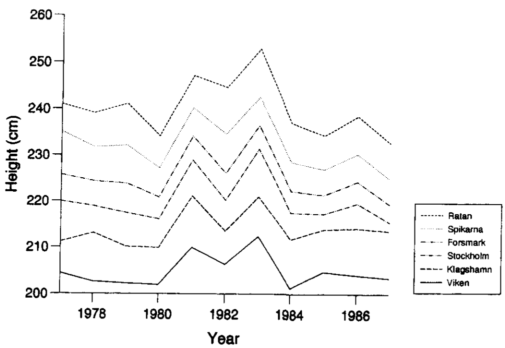

Fig. 3. The annual mean sea level at the six stations arranged from south to north, arbitrarily with respect to the local height.

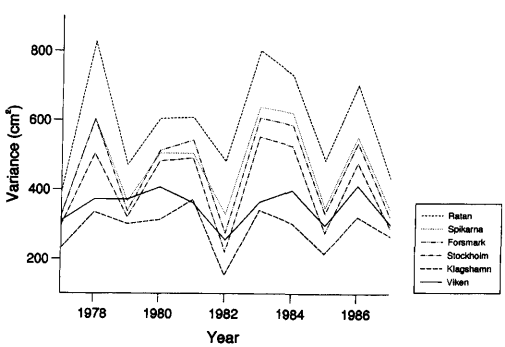

Fig. 4. The annual variances at the six stations.

annual variance are in phase for all locations so the forcing appears to be common for the whole system. In the figure can also be seen the horizontal distribution. The sea level variability at Viken appears to be transmitted a little damped to Klagshamn. Within the Baltic the variability is increasing from south to north. The variance, Var_j, contains contributions from a very wide period band ranging from two days (the Nyquist period) to 2 years (there will be influences by longer periods i.e., as trends). However, due to aliasing from, e.g., seiches, even shorter periods than 2 days may contribute.

3.2. *The seasonal cycle of the variance*

The monthly variance of the sea level, Var_i, relative to the monthly mean sea level h_{ij}, is defined by:

$$\mathrm{Var}_i = \frac{1}{M}\sum_j \mathrm{Var}_{ij} = \frac{1}{M}\sum_j \frac{1}{N_{ij}}\sum_n (h_{nij}-h_{ij})^2\,, \tag{3}$$

where M is the number of years in the time series. N_{ij} is the number of days in month i and year j.

The monthly variance, Var_i, has a very pronounced annual cycle at all locations with minimum in early summer and maximum in late autumn-early winter, (Fig. 5). This is certainly due to the annual weather cycle with large air pressure variations and accompanying strong winds in late autumn — early winter. The amplitude of the annual cycle is greatest at Viken and Ratan and smallest at Stockholm. Quite similar results as those for Viken were obtained for Varberg, about 100 km north of Viken, using an 89 years long sea level record (Stigebrandt 1984). This indicates that

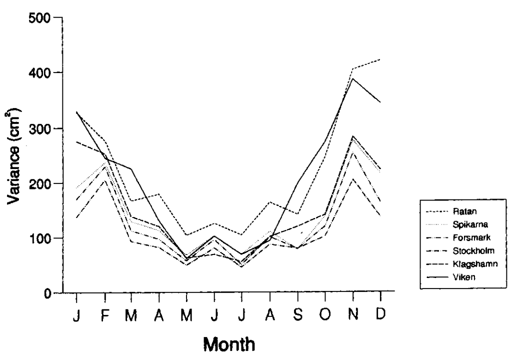

Fig. 5. The mean monthly variances at the 6 stations.

our time-series are long enough to be representative of the system. The weekly variances (not plotted) have the same seasonal cycle but the amplitude is of course lower.

3.3. *Spectral distribution of the sea level variance*

The variance, Var, from the mean sea level for the hole period, z_0, is calculated as

$$\mathrm{Var} = \frac{1}{12M}\sum_{ij}\frac{1}{N_{ij}}\sum_n (h_{nij}-z_0)^2\,. \tag{4}$$

Following Stigebrandt (1984) this equation can be rewritten

$$\begin{aligned}\mathrm{Var} &= \frac{1}{12M}\sum_{ij}\frac{1}{N_{ij}} \\ &\quad\times\sum_n \{(h_{nij}-h_{ij})^2+2h_{nij}h_{ij}-h_{ij}^2+z_0^2-2h_{nij}z_0\} \\ &= \frac{1}{12M}\sum_{ij}\frac{1}{N_{ij}} \\ &\quad\times\sum_n \{(h_{nij}-h_{ij})^2+(z_0-h_{ij})^2 \\ &\quad+2(h_{ij}-h_{nij})(z_0-h_{ij})\}\,.\end{aligned} \tag{5}$$

The first term is the monthly variance from the monthly mean value so

$$\mathrm{Var} = \frac{1}{12M}\sum_{ij}\{\mathrm{Var}_{ij}+(z_0-h_{ij})^2+\mathrm{Res}_{ij}\}\,, \tag{6}$$

where

$$\mathrm{Res}_{ij} = \frac{2}{N_{ij}}(z_0-h_{ij})\sum_n (h_{ij}-h_{nij}) \tag{7}$$

is of $O(10^{-3}\ \mathrm{cm}^2)$ and can, to a good approximation, be neglected. The spectral distribution of the sea level variance can thus easily be divided into 2 groups. In the present example Var_{ij} is the variance due to sea level fluctuations with periods between a few days and two months, and $(z_0-h_{ij})^2$ is the variance contribution due to periods greater than two months. Through successive averaging of a time series over longer and longer periods this method may be used to determine the distribution of the variance among arbitrarily chosen period bands. Using this method (eq. (5)), we partitioned the total sea level variance at the different stations in the following period bands: 2 days–2 weeks, 2 weeks–2 months, 2 months–8 months, 8 months–2 years and 2 years–9 years.

Table 1. *Contributions to the sea level variances (cm^2) from different period bands; Var is the variance around the mean sea level for the whole period*

Station	Var	2 years– 9 years	8 months– 2 years	2 months– 8 months	2 weeks– 2 months	2 days– 2 weeks
Viken	365.5	13.5	79.5	66.4	79.6	126.5
Klagshamn	303.7	16.1	57.2	77.4	74.2	78.9
Stockholm	434.1	28.9	136.8	160.1	84.1	24.2
Forsmark	482.6	29.8	153.0	171.0	89.8	39.1
Spikarna	500.2	28.6	158.8	164.6	97.0	51.1
Ratan	630.8	35.4	186.9	181.2	122.7	104.6

The results are displayed in Table 1. For periods shorter than about two weeks the highest amplitudes within the Baltic Sea are found at Klagshamn and Ratan. This suggests that the sea level in the Baltic, for these relatively short periods, oscillates kinematically like the first fundamental seiche mode in a closed basin (a half-wave-length oscillator with 180° phase shift between the northern and southern coasts), with highest amplitudes close to the bellies in the Bothnian Bay and the southwestern Baltic proper and smaller amplitudes in between. For longer periods (i.e. >2 weeks), however, the amplitudes of the oscillations increase monotonously towards the Bothnian Bay. Kinematically, this is analogous to the fundamental mode of oscillation in an open system like a bay or fjord where the nodal line is at the mouth (a quarter-wave-length oscillator). The explanation of the shift in the nature of the kinematics of the forced oscillations at periods of about 2 weeks will be discussed later in this paper. The relative contribution of variance from the different period bands at the different stations is shown in Fig. 6. This figure, based upon the results in Table 1, shows that the relative importance of longer periods is largest at Stockholm, though the longer periods also dominate in the Bothnian Sea and Bay.

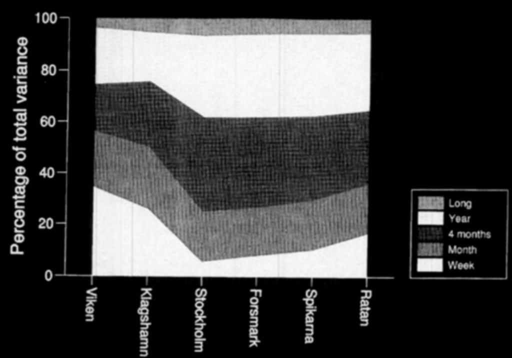

Fig. 6. The % of the total variance from different period bands, see Table 1.

4. The sea level model

From the previous calculations 2 conclusions may be drawn. Firstly, on different time scales the Baltic acts either as a an open bay or fjord, or as a closed basin. Secondly, for periods longer than two weeks the variance is increasing within the Baltic Sea, and as argued below this should not be due to resonance to the external forcing provided by the varying sea level in the Kattegat. It is therefore of interest to separate the externally from the internally forced sea level variations to look closer into the latter. As discussed in the introduction, Section 1, the in-outflows to the Baltic Sea as well as the freshwater supply are counted as external forcings, while variations of the air pressure, wind and density are counted to the internal forcings. The separation of externally forced sea level variations from the sea level records from the Baltic Sea is done with the model by Stigebrandt (1980). This is a pumping mode model that only accounts for the dynamics of the entrance straits and the Baltic Sea merely serves as a reservoir. Since the pumping for a large part occurs on longer or much longer time-scales than the internal free oscillations of the Baltic Sea, it is assumed that the pumping mode excites little spatial variation within the Baltic Sea. A simple model for a co-oscillating estuary by Garvine (1985) supports this, provided that the wavelength of the externally forced sea level variation is long compared to the length of the estuary which is the case for periods long compared with the fundamental barotropic seiche.

Briefly, the model for the external forcing can be described as follows: The basins (the Kattegat and the Baltic Sea) are connected by a system of channels, and the flow resistance in the channels has essentially two components: bed friction and singular acceleration/deceleration losses due to flow contraction/expansion mainly at the ends of the channels. Both types of flow resistance are modelled proportional to the velocity squared. The flows through the channels, the Danish Belts and the Öresund, are forced by the sea level difference between the two basins. In the model the complicated systems of channels are replaced by one, dynamically equivalent channel. With the model, the sea level in the interior basin, the Baltic Sea, may be computed from the sea level in the exterior basin, the Kattegat, which thus is assumed to be known. The effect of adding freshwater to the interior basin is also included in the model. Thus the sea level in the Baltic Sea (i.e., the interior basin) is calculated as:

$$\frac{\mathrm{d}h_\mathrm{b}}{\mathrm{d}t} = \frac{(h_\mathrm{k}-h_\mathrm{b})}{\sqrt{|h_\mathrm{k}-h_\mathrm{b}|}}\,\frac{A}{Y}\sqrt{\frac{2g}{(1+\kappa)}} + \frac{Q_\mathrm{f}}{Y}, \tag{8}$$

where h_b is the sea level in the Baltic Sea and h_k is the sea level in the Kattegat. The model channel is characterized by: a constant cross-sectional area, A, and the friction coefficient, κ. The area of the Baltic Sea is Y, g is the acceleration of gravity, and Q_f is the freshwater supply to the Baltic Sea. The friction coefficient κ is tuned (Stigebrandt, 1980) to give best fit between recorded and calculated sea level in the Baltic, see also Omstedt (1987). In the model, the very low frequency variations of the sea level in the Kattegat pass undisturbed into the Baltic Sea. With increasing frequencies the amplitude of the variations are reduced and the phase-shift between the 2 basins is increasing from 0° towards 90°.

In order to calculate the sea levels in the Baltic Sea due to some internal forcings the sea level model is extended to include the sea level adjustment inside the Baltic due to horizontal variations of the daily mean air pressure and the monthly mean density. To resolve the internal horizontal variations we partition the Baltic Sea into the five sub-basins mentioned in Section 2. The wind is certainly very important but not yet included in the model as further discussed later in this paper.

It is commonly assumed that the open ocean adjusts instantaneously to changes in atmospheric pressure according to the so-called inverse barometric law. This law is not, however, valid in shallow seas with large through-flow like the Kattegat, see Stigebrandt (1990). Because of the restricted transport capacity of the straits in the mouth, this law may not be valid for high frequency changes of the integrated air pressure above the Baltic Sea. However, the sea level in the Baltic Sea should adjust internally to even high frequency changes in horizontal gradients of the air pressure, and this effect is included in the model as described below.

In order to adjust the sea level due to a horizontally varying density distribution, a level of no motion is introduced. At this level there is no horizontal pressure difference. If the density and the air pressure are known at 2 stations, the sea level difference, Δh_b, between the two stations can be calculated from the following equation:

$$\Delta h_\mathrm{b} = -\rho_0^{-1}\int_0^{z_0}(\rho_1(z)-\rho_2(z))\,\mathrm{d}z + \frac{\Delta p_\mathrm{a}}{g\rho_0}, \tag{9}$$

where ρ_0 is a standard density and $\rho_{1,2}$ is the density at station 1 and 2, respectively, Δp_a is the air pressure difference and z_0 is the level of no motion. Between two stations within the same sub-basin the level of no motion is chosen at 60 m depth. The reason for this is that 60 m is below the mixed layer where the main water transport is southwards, out of the Baltic, but it is also above the deeper layers where the saline water from the Kattegat is flowing northwards. When 2 stations are separated by a sill, half the sill depth is chosen as the level of no motion, assuming a two layer flow and a rectangular cross-section.

In the model, the sea level in the 5 sub-basins (5 unknowns) are calculated, and between them four relations can be found. The 5th equation uses the fact that the rate of total volume change must be equal to the sum of the volume flows into the Baltic Sea passing over the sills in the mouth, and coming by runoff respectively. The Gulf of Finland is only used in the internal adjustment due to the horizontal variation in density and air pressure, and no further analysis is carried out for this basin since only recorded sea levels from the Swedish coast are analysed. In the previous analyses there were two sea level stations in the Bothnian Sea, but because of coarse model resolution they will both have the same sea level in these calculations.

5. Model results

The result from the model for the external forcing, eq. (8), is subtracted from the recorded sea levels in the Baltic Sea, leaving the sea level due to the internal forcing. The variance calculations described in Subsection 3.3 are repeated on this sea level, and a table similar to Table 1 is created. Thus, in Table 2 the variances of the sea levels in the Baltic Sea due to internal forcings are displayed. Comparing Tables 1 and 2, it can be seen that the external forcing explains 50 to 80% (no seasonality has been found) of the total sea level variance, Var, in the Baltic Sea. Holmström and Stokes (1978) and Omstedt (1987) obtained similar results. It can also be seen that the variance contributions of the long periods are small for the internally forced sea levels. For the shortest period band (2 days–2 weeks) all variance at Klagshamn, Spikarna and Ratan seems to be due to the internal forcing, while Stockholm and Forsmark are partly externally driven, but the external forcing is weak (only 10 cm^2). The variances in Table 2 are also plotted in Fig. 7. Here it is clearly seen that the Baltic acts like a closed basin for periods shorter than about two months with the node at Stockholm and the bellies at Klagshamn and Ratan. For longer periods the Baltic acts like an open bay with monotonously increasing variance from Klagshamn towards Ratan.

On short time scales (<2 months) the internal forcings are important, and to further elucidate this we have computed the cross spectrum between Klagshamn and Ratan. The squared coherency for both the recorded and the internal (recorded – external) sea levels are shown in Fig. 8, together with the 99%-significance level (Thompson, 1979) and the phase function for the

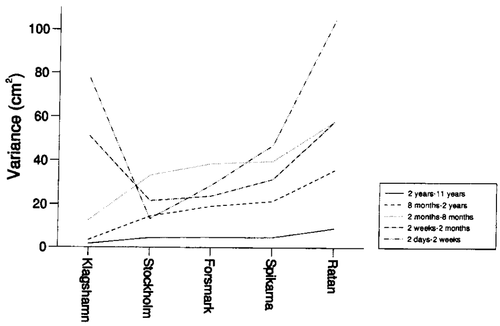

Fig. 7. The variances in Table 2 plotted against the stations, i.e., the variances from different period bands for the internally forced sea levels (recorded minus externally modelled sea levels).

Table 2. *Contributions to the sea level variances from the internally forced sea levels (recorded minus externally forced sea levels) from different period bands; Var is the variance around the mean sea level for the whole period; the % of the internal variance with respect to the total variance is also given*

Station	Var	2 years–9 years	8 months–2 years	2 months–8 months	2 weeks–2 months	2 days–2 weeks
Klagshamn	151.4	1.7	2.8	14.8	56.8	75.4
	49%	11%	5%	19%	77%	96%
Stockholm	97.9	5.1	16.2	36.2	26.1	14.3
	23%	18%	12%	21%	31%	59%
Forsmark	124.4	5.3	21.1	41.4	26.9	29.7
	26%	18%	14%	24%	30%	76%
Spikarna	157.0	5.1	23.8	44.0	36.1	48.0
	31%	18%	15%	27%	37%	94%
Ratan	279.7	9.5	38.7	62.7	62.9	105.8
	44%	27%	21%	35%	51%	100%

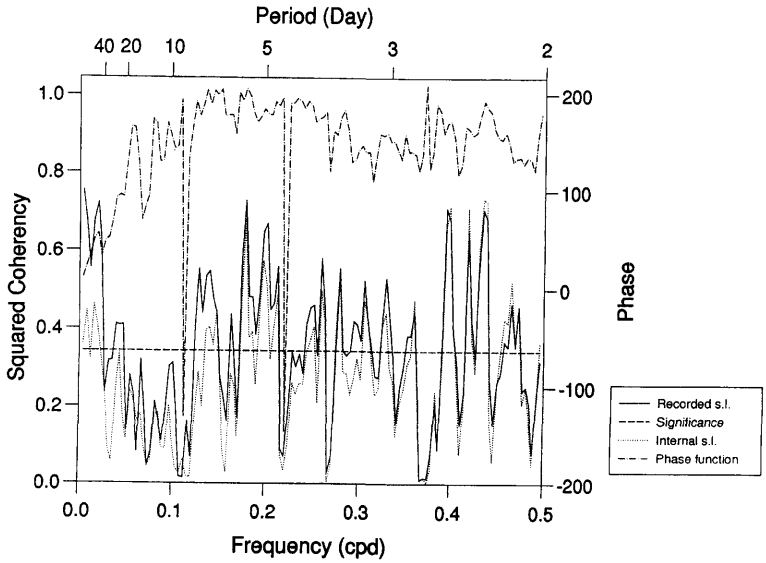

Fig. 8. Cross spectrum analysis between Klagshamn and Ratan, the squared coherency and the phase function for the recorded sea levels are shown together with the squared coherency for the internal (recorded minus external) sea levels. The significance level is 99% and a Hanning window of length 256 is used.

recorded sea levels. The phase function for the internal sea levels looks much the same. It can be seen that the coherency for the long periods ($\geqslant 20$ days) drops when the externally forced sea levels are removed. In a wide period band (3–20 days) the coherency for the recorded sea levels are a little higher than the coherency for the internal sea level variations, and the phase shift is about 180°. For even shorter periods the phase shift is still about 180°, but the two coherencies are almost identical. There are three maxima with a high significant coherency, namely 60, 57 and 55 h. The conclusion that can be drawn from this study is that the long periods are mainly forced externally while the short periods are forced internally with the Baltic Sea acting as a closed basin. Compared with the conclusions drawn from the "filtering" via eq. (5), the spectra have also provided information regarding the phase difference between sea level stations, but the clarity is lost due to the high resolution.

The extended model, see the previous section, is run for nine years, 1979–1987. The start values are the recorded sea levels the 31 December 1978 transformed to a common height system, NH60 (Ekman and Mäkinen, 1991, 1996). For Helsinki (the Gulf of Finland) the value at Forsmark is chosen. The best agreement between recorded and modelled sea levels is found for Stockholm, and in Fig. 9 the recorded and modelled sea levels are shown for the year 1987 with results from both the extended and the external model. It can be seen that the extended model predicts the sea level variations better than the external model, but the high frequency variations are not resolved so they are presumably due to the wind. The model is particularly off in predicting sea level maxima where probably the wind is playing a vital role. Sea level minima are much better computed by the model. It should be mentioned that the sea level in Stockholm may be influenced by the runoff from lake Mälaren, an effect that is not included in the model.

The effect of the internal model can be found by subtracting the result from the external model from the results of the full model. The new series has been subject to variance calculations, and the results are displayed in Table 3. Comparing these results with those in Table 2 it can be seen that ~20% of the internally forced variance in the period band 2 days–2 weeks is explained by the air pressure variations. The density data are monthly means and do not contribute to the variance in this band. For periods longer than 2 weeks the

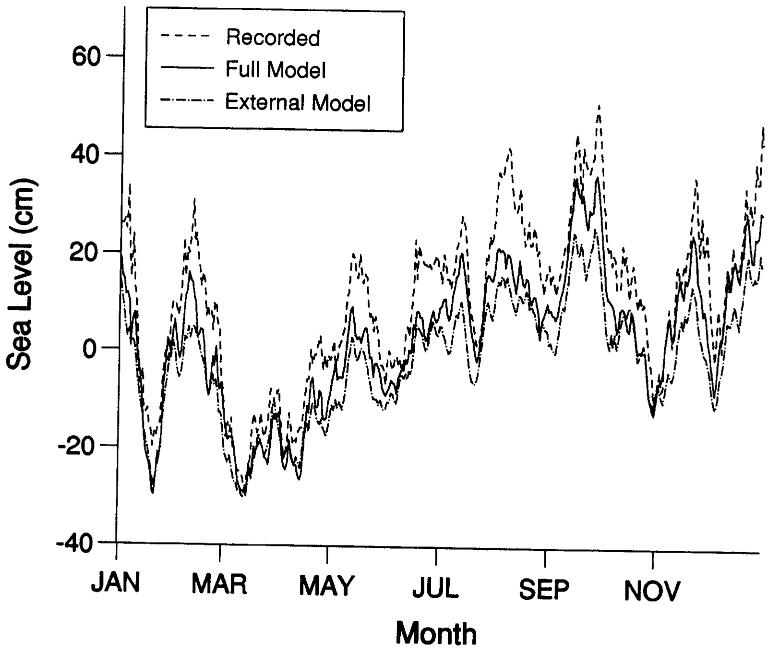

Fig. 9. The recorded and modelled, external and full = external + internal sea levels at Stockholm for the year 1987.

Table 3. *Contributions to the sea level variances (cm^2) for the modelled internal sea levels from different period bands; Var is the variance around the mean sea level for the whole period; the % of the modelled internal variance with respect to the internal (recorded minus external) variance is also given*

Station	Var	2 years–9 years	8 months–2 years	2 months–8 months	2 weeks–2 months	2 days–2 weeks
Klagsham	33.8	0.4	0.7	4.2	12.4	16.0
	22%	24%	25%	28%	22%	21%
Stockholm	24.5	1.7	5.6	7.1	6.4	3.6
	25%	33%	35%	20%	25%	25%
Forsmark	49.4	2.9	11.5	13.0	13.8	8.3
	40%	55%	55%	32%	51%	28%
Spikarna	49.4	2.9	11.5	13.0	13.8	8.3
	31%	57%	48%	30%	38%	17%
Ratan	85.8	4.5	15.2	19.0	25.3	21.8
	31%	47%	39%	30%	40%	21%

model explains about 40% of the internally forced variance. If the high frequency variation of the sea level at Klagshamn is better resolved, e.g., by including the effect of winds and/or by increased horizontal resolution in the model, the in-out flows would be more accurate. This would presumably add more variance to the externally forced sea level, and the sea level in Stockholm would also be better resolved. It should also be mentioned that the inclusion of a linear resistance term due to rotation (geostrophic control) in the flow model for the entrance channels, eq. (8), increases the prediction of the externally forced sea level in the Baltic Sea by a few per cent

(Mattson, 1995). There are thus at least 2 effects not accounted for in our model that would lower the variance given by internal forcing and thereby probably increase the fraction of the internal sea level variance given by the model. However, it still seems that most of the internally forced variance is due to the wind.

The main purpose of the present paper is to describe the overall characteristics of the long-term sea level variability in the Baltic Sea. In addition, we have made efforts to model some of the variability. The externally forced variability was determined using an existing model. The internally forced variability was then determined from the difference between the observed and the externally forced sea level. It is apparent that the wind acting on the surface of the Baltic Sea accounts for most of the internal variability. There are good simple models for wind effects in simple, shallow, non-rotating and partially mixed estuaries (e.g., Garvine, 1985). However, the Baltic is strongly stratified, large (rotating) and partitioned into several basins by relatively shallow and narrow passages, and the inclusion of wind forcing in the model is not as straightforward as in Garvine (1985).

6. Conclusions

The variance of the observed sea level records shows that, at all stations, there is a pronounced annual cycle with maximum variance in late autumn — early winter. Within the Baltic Sea the variance is increasing from south to north for periods longer than 2 weeks. For shorter periods the highest variance occurs at Klagshamn and Ratan.

Using an externally forced sea level model, externally and internally forced contributions to the sea level variability were separated. It is found that 50 to 80% of the sea level variance in the Baltic Sea is due to external forcing. However, most of the variance for short periods is due to internal forcing but the internal forcing also induces some variance of longer periods. The internally forced sea level in the model, due to varying air pressure and density, explains only a minor part of the observed internally forced variance. There are two reasons for this, the computed internal variations might still include an external part, and we have omitted the effect of a varying wind which is the topic of a forthcoming paper.

An analysis of the internally forced sea level shows very clearly that for periods shorter than about one month the Baltic Sea oscillates like a closed basin with bellies at the extreme ends and a node in between (a half-wave-length oscillator). For longer periods the oscillations are like those in an open basin with amplitudes increasing from the node in the mouth to the inner part of the basin (a quarter-wave-length oscillator). This is in accordance with recent results by Ekman (1996) who found that the amplitudes of some long-period oscillations (the annual, semi-annual and "pole-tide" periods) increases from the southern Baltic Sea towards the Bothnian Bay.

The cross spectrum between Klagshamn and Ratan was calculated for both the recorded and the internally forced sea levels. It is found that the external forcings give significant coherency for lower frequencies with a phase shift of between 0° and 90°, while the internal forcings give a significant coherency for higher frequencies with a phase shift of 180°. The results support the earlier conclusion that the Baltic acts either as an open bay/fjord or as a closed basin depending on the time scale considered.

The limited transport capacity of the straits in the mouth explains the shift in the kinematics of the internally forced oscillations of the sea level in the Baltic. Externally forced high frequency motions (in the Kattegat) are strongly choked by the narrow straits. Only external sea level oscillations of periods longer than about one month may penetrate with appreciable amplitude (Stigebrandt, 1980). By symmetry, this implies that internally forced oscillations in the Baltic Sea of periods from about one month and shorter essentially behave as if the Baltic Sea were closed. For oscillations of longer periods, however, the sea level in the entrance area of the Baltic will be fixed by the sea level in the Kattegat implying that a node will be established here. Thus, the dynamical properties of the Baltic Sea as an externally forced oscillator also explain its properties with respect to internally forced oscillations.

The properties of the internally forced sea level response of the Baltic reported in this paper have some important consequences with respect to modelling. Using a closed Baltic Sea model may give a reasonably correct response only for time scales shorter than about one month. For computations of the internally forced response on longer time scales an open model is required.

7. Acknowledgements

The sea level, density and air pressure data were obtained from the Swedish Meteorological and Hydrological Institute (SMHI). This work was supported by the Swedish Environmental Protection Agency (SNV). Comments and suggestions by two anonymous reviewers led to significant improvements of the presentation of this paper.

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