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SEA LEVEL AND SALINITY VARIATIONS IN THE BALTIC SEA - AN OCEANOGRAPHIC STUDY USING HISTORICAL DATA

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GÖTEBORG 1997

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Akademisk Avhandling

För vinnande av filosofie doktorsexamen i Oceanografi (examinator professor Anders Stigebrandt) som enligt beslut av Tjänsteförslagsnämnden, Institutionen för Geovetenskaper vid Göteborgs Universitet kommer att offentligt försvaras fredagen den 4 april kl. 10.15 i Hörsalen, Geovetarcentrum, Guldhedsgatan 5A, 413 81 Göteborg.

Abstract

The Baltic is a large semi-enclosed sea with positive freshwater balance and restricted water exchange both with the Kattegat and between the interior sub-basins. Sea level variations cause barotropic transports and are therefore important for the salinity of the Baltic. Thus, with long time series of sea level recordings from the Baltic Sea large scale transport processes can be studied.

The spatial variation of the daily sea level variability has been investigated for periods from a few days up to several years. For periods longer than one month, the Baltic Sea behaves like an open fjord with increasing amplitudes from the mouth and inwards. For shorter periods, the Baltic Sea acts like a closed lake, and the variability has a minimum in the Stockholm area and a maximum in the extreme north and south. With a five-box model, it is shown that most of the sea level variance on time scales longer than two months is due to external forcings provided by the sea level in the Kattegat and the freshwater supply to the Baltic Sea. These external forcings explain between 50 and 80% of the total sea level variance in the Baltic Sea with a maximum in the central parts.

A coupled three-basin model explains 85% of the sea level variance. The relative importance of different forcings is investigated, and it is concluded that for periods longer than 2 months, external forcings plus internal forcings due to air pressure and density gradients explain around 80% or more of the sea level variance. For shorter periods 30-80% of the variance is explained. Including the wind stress, which is especially important during winter, increases the explained variance with a few percentage points for periods longer than 2 months and with 10-30 percentage points for shorter periods.

The mean sea level in the Baltic Sea is also investigated with the three-basin model. It is concluded that the approximate contributions to the mean sea level slope are: density gradients 55%, air pressure gradients 30% and wind stress 15%. The estimated mean sea levels compare quite well with mean sea levels in the geodetic height system NH60 which is found to be well suited for oceanographic purposes.

The three-basin model is also used to study the barotropic transports between the sub-basins and between the Baltic proper and the Kattegat. Among other things it is found that major Baltic outflows are more common than major Baltic inflows.

The annual mean salinity in three different depth intervals decreased with around 1 psu during the period 1977-1990. It is found that this was due to an increased freshwater supply. The increased freshwater supply also impeded the import of saltwater from the Kattegat, thereby decreasing the salinity in the deeper parts of the Baltic Sea. It is argued that the changed vertical distribution of salt within the Baltic Sea in the same period was partly due to increased vertical mixing.

Keywords: Baltic Sea, sea level variability, mean sea level, salinity, long-term, three-basin model, barotropic transports, major Baltic outflow

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List of papers

This thesis comprises four papers which are referred to by their Roman numerals. Paper I and II were written before my marriage, and were therefore published in my maiden name Samuelsson.

I: Samuelsson, M., 1996, Interannual salinity variations in the Baltic Sea during the period 1954-1990, *Cont. Shelf Res.*, **16**, 1463-1477.

II: Samuelsson, M., and A. Stigebrandt, 1996, Main characteristics of sea level variability in the Baltic Sea, *Tellus*, **48A**, 672-683.

III: Carlsson, M., 1997, A coupled three-basin sea level model for the Baltic Sea. Submitted to Continental Shelf Research.

IV: Carlsson, M., 1997, The mean sea-level topography in the Baltic Sea determined by oceanographic methods. Submitted to Marine Geodesy.

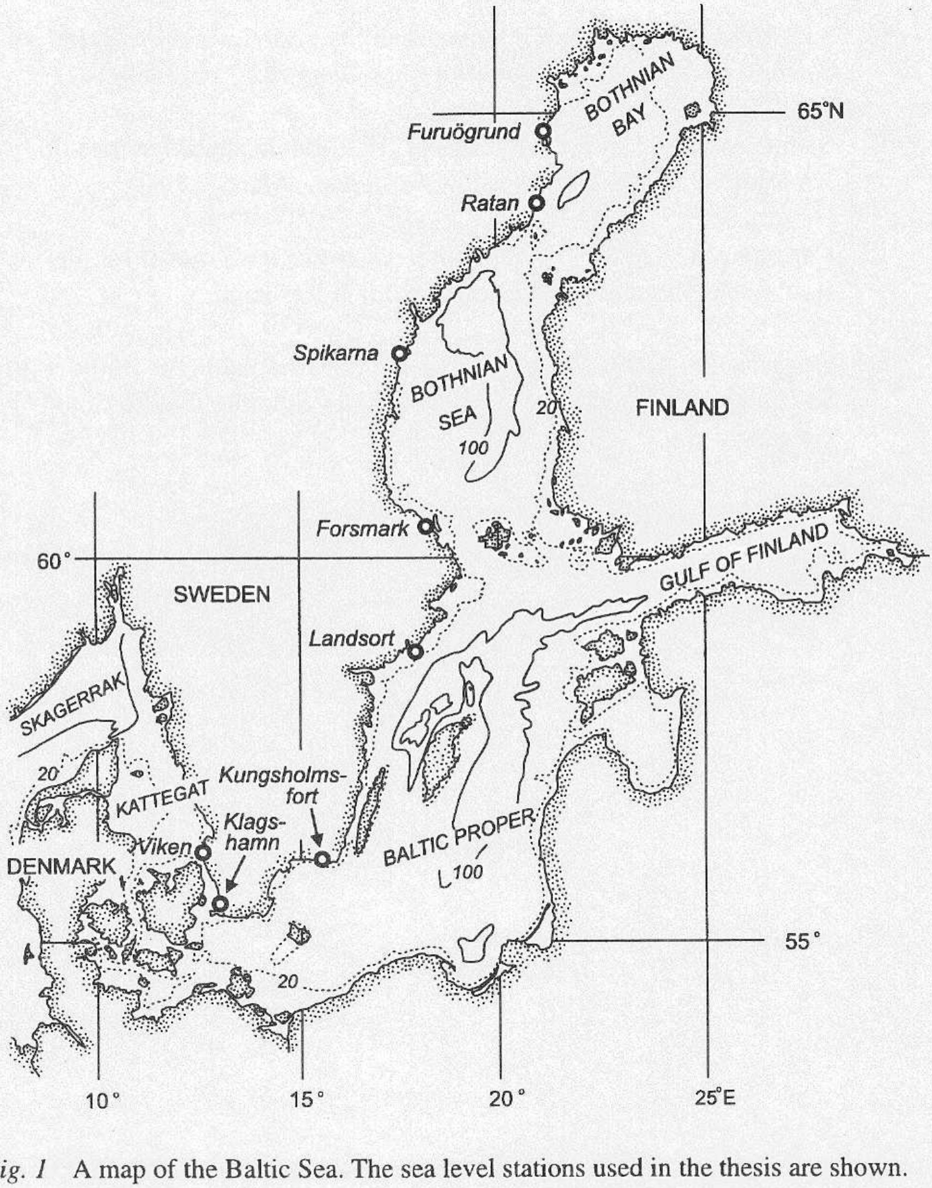

Fig. 1 A map of the Baltic Sea. The sea level stations used in the thesis are shown.

1 Introduction

In this thesis some large scale processes in the Baltic Sea are studied. Historical data are used to study the fluctuations of the system, determine important time scales and develop and verify sea level models. The main focus is on sea level variations through which barotropic transports can be estimated. Interannual variations of the annual mean salinity are also studied and related to variations of wind mixing and supplies of freshwater and sea-water.

1.1 The Baltic Sea

The Baltic Sea is a semi-enclosed sea consisting of three well defined sub-basins, the Baltic proper (with the Gulf of Finland), the Bothnian Sea and the Bothnian Bay, see Fig 1. The freshwater balance is positive, mostly determined by the river discharge. The annual mean runoff is about 14 200 m^3s^{-1} (Bergström and Carlsson, 1994). There are large variations over the year with a maximum of almost 25 000 m^3s^{-1} in May due to the melting of snow and ice. There is also a net supply of freshwater due to precipitation on minus evaporation from the sea surface of the Baltic Sea. The long-term annual mean value is 2 000 m^3s^{-1} (Omstedt et al., 1997) but there are large variations both in space and time. The annual mean value varies between 900 to 4 000 m^3s^{-1}.

The entrance area to the Baltic Sea (the Belt Sea and the Öresund) is rather narrow and shallow (see Fig. 1). In the Belt Sea the sill depth is 18 m, while in the Öresund it is only 8 m. The minimum vertical cross-sectional areas are about 300 000 m^2 and 100 000 m^2 respectively. These connections act as low pass filters for the sea level variations, high frequency variations of the sea level in the Kattegat are effectively damped while low frequencies can pass almost undisturbed into the Baltic Sea. The water in the Kattegat is more saline than the water in the Baltic Sea, and the incoming water forms a system of dense bottom pools and currents through which new deepwater is transported into the Baltic proper. On its way, the inflowing saltier water is diluted by entrained fresher Baltic water. Eventually, the current has obtained the same density as the surrounding water and is interleaved. The depth where this happens depends on the density and the flow rate of the inflow. Most inflows are interleaved at about 50-100 m, i.e. in or around the halocline, see Stigebrandt (1987).

The water exchange between the sub-basins is also affected by narrow and shallow passages. Between the Baltic proper and the Bothnian Sea the main passage is through the Åland Sea where the effective sill depth is about 40 m, but there is a narrow trench with a depth of about 70 m. The minimum vertical cross-sectional area is roughly 800 000 m^2. The connection between the Bothnian Sea and Bay, the Northern Kvark, consists of two parallel passages with sill depths of about 25 and 15 m and with minimum cross-sectional areas of 30 000 m^2 and 60 000 m^2, respectively. The surface water of the Baltic proper (Bothnian Sea) forms the deep water of the Bothnian Sea (Bothnian Bay), but on its way it is mixed with and diluted by the surrounding fresher water, see Marmefelt and Omstedt (1993).

The choked water exchange with the Kattegat impedes salt exchange, and due to this and the positive freshwater supply the salinity is low in the Baltic Sea. In the Kattegat the surface salinity is 15-25 psu while it is around 9 psu in the Arkona basin (southwestern Baltic proper). Within the Baltic Sea there is a horizontal gradient due to the positive freshwater balance and the choked water exchange between the sub-basins. In the northern Baltic proper the surface salinity is 7 psu, and in the Bothnian Sea and Bay the surface salinity is around 5 and 3 psu, respectively. All three sub-basin have strong vertical stratification. During summer there are well developed thermoclines at about 20 m, but during autumn strong winds and cooling gradually deepen the surface layers until they reach the permanent haloclines. The halocline is at about 60-70 m in the Baltic proper and at about 40 m in the Bothnian Sea and Bay. In the deep waters below the haloclines the stratification is moderate to weak.

1.2 The papers in this thesis

The following topics are discussed in the papers comprising this thesis.

In paper I interannual variations of freshwater and seawater supply to and salinity in the Baltic Sea are investigated. Trend analysis was applied to see whether the observed change of the salinity in the Baltic Sea is statistically significant and the causes of the changes were discussed. Papers II to IV deal with sea level variations. In paper II sea level records from the Kattegat and the Baltic Sea are analysed and the variance is partitioned among different period bands. External and internal forcings are separated using a five-box model of the Baltic Sea. Paper III describes a three-basin sea level model driven by the recorded sea level in the Kattegat, freshwater supply, wind stress and horizontal gradients of air pressure and density. With this model, sea level variations with periods between 2 days and 9 years are studied. In paper IV, the sea level model is used to compute the north-south gradient of the mean sea level in the Baltic Sea, and the results are compared with results from a geodetic model.

2 Historical data and data analysis

To describe the state of a system measurements of relevant state variables must be obtained. Data sets collected over several years are useful in many ways. One field of application is to study the variability of the system including long-term changes. Knowledge of how a certain variable varies can be used to interpret new data sets, for instance one may investigate whether a new set of data describes a normal phenomenon or an event that occurs very seldom.

One important application of historical data is to study environmental human impact. To assess possible anthropogenic changes of the environment the state of a region before the supposed change must be known. An example is the bridge over the Öresund which is now being built. There have been many discussions about the possible effects of the bridge on the environment. One large issue has been the bridge piers and their effect on the flow resistance in Öresund. Three main questions have been discussed: Will the piers increase the flow resistance and by that decrease the transport through the Öresund? What effect will a decreased transport have on the salinity in the Baltic Sea? Can the presumed increase of flow resistance be compensated for by dredging which is the intended solution? The answers to the latter question might emerge in the years to come when the new state (with a bridge) can be compared with the pre-bridge state determined from historical data. However, it will probably be difficult to determine if there has been any change at all, the daily variations of the transports are large (see Fig. 12, paper III) and the change is assumed to be small.

In this thesis, oceanographical, meteorological and hydrological data are used. The most frequently used data set is the daily mean sea levels obtained from the Swedish Meteorological and Hydrological Institute (SMHI). These data are from continuous recordings by mareographs, and the daily mean values are the arithmetic mean of 24 recordings with one hour intervals. Salinity and density data are taken from cruise databases and the data are irregular both in space (horizontal and vertical) and in time. The measurements have been done by different persons with different devices which increases the uncertainty in the databases. Freshwater supply (land runoff) is obtained from Mikulsky (1982) for the period 1921-1975, and from Bergström and Carlsson (1994) for the period 1950-1990. The two series have a high correlation for the overlapping years, and there is no problem to connect the two series. Air pressure data are obtained from a database with grid size 1×1° and time step 3 hours, while the wind data are direct observations from meteorological stations. In both cases, SMHI has provided the meteorological data. The data used in this thesis are collected from different regions and from different periods, and the reader is kindly referred to the papers for more information.

Statistical methods can be used to study time series, and in this thesis, trend analysis and variance calculations are used. Trend analysis is discussed in section 2.1 and the variance calculations are discussed in section 2.2. Two different aspects of variance calculations are discussed. Firstly, variance versus Fourier analysis is discussed and secondly it is argued why the unexplained variance is a good measure of the precision of a model.

2.1 Trend analysis

A trend is defined as a long-term change of the mean value, and there are often trends in time series. Trends can be caused by e.g. altered forcings, but there are other possibilities. Sometimes trends are just part of a low frequency variation not resolved by the period of investigation, and sometimes the trend is non-significant due to a random process and no physical explanation need to be sought for. There are several tests to check if a trend is due to random processes or not. Linear regression is often used to determine if a series contains a significant trend, but this is not the correct method. If there is a trend in the series the rate of change can be determined by linear regression, but the correlation coefficient of the regression line says nothing about the significance of the trend. The correlation coefficient only gives a measure of how well the straight line matches the data. Even if the line has a visible slope and the correlation coefficient is high, the slope may be caused by random processes. Instead, to determine whether there is a trend in the data the statistical significance of the trend must be tested. If the test shows that there is a statistically significant trend in the time series there is reason to seek for physical explanations.

In paper I, Kendall's test for trends (Kendall and Ord, 1990) is used. Briefly, the test works as follows:
Consider a time series X of N elements, thus X= $x_1, x_2, x_3, \ldots, x_N$. Let $q_{ij}=1$ if $x_j>x_i$ for j>i (otherwise $q_{ij}=0$) and

$$Q = \sum_i \sum_j q_{ij}. \tag{1}$$

The total number of q_{ij} is 0.5*N(N-1). In a random series the probability of $q_{ij}=1$ is 0.5, and the expectation of Q is 0.25*N(N-1). If Q is larger the series has a rising trend and if Q is lower there is a falling trend. A new normally distributed variable τ with the variance σ^2 can be formed. Thus, if τ is outside the interval $\pm 1.96* \sigma$ there is a trend with 95% significance. τ and σ^2 are defined by

$$\tau = \frac{4Q}{N(N-1)} - 1 \tag{2}$$

and

$$\sigma^2 = \frac{2(2N+5)}{9N(N-1)}. \tag{3}$$

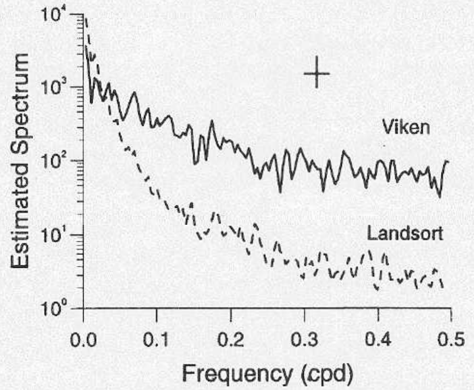

Figure 2. The spectrum of the sea level variance at Viken and Landsort, Tukey window of length 256 days. Confidence interval and bandwidth are also plotted, see e.g. Chatfield (1989).

2.2 *Variance - a useful measure*

In paper II and III the variance of the sea level is used both to determine the important time scales and as a measure of the precision of models.

Fourier analysis is often used to study time series, but the procedure is not always simple. The series must be assumed to be infinite, and the series needs to be filtered, type of window and window length must be chosen and so on. In the end, the variance of the series is partitioned among frequencies determined by the window length. In a study of known frequencies e.g. in an analysis of tides, it is interesting to know the energy (amplitude squared) associated with all specified frequencies. However, in most studies there are no fixed frequencies of special interest and Fourier analysis provides more information than can be used. In Fig. 2 the spectra are plotted for the daily sea level at Viken and Landsort. The conclusions that can be drawn from the graph are that there is

Table 1: Contributions to the sea level variance (cm^2) from different period bands. Var is the variance around the mean sea level for the period 1979-1987.

Station	Var	2 years-9 years	8 months-2 years	2 months-8 months	2 weeks-2 months	2 days-2 weeks
Viken	365	13	79	66	79	128
Klagshamn	303	15	57	78	75	77
Kungsholmsfort	382	23	86	122	84	68
Landsort	428	30	134	163	80	21
Forsmark	482	29	153	172	88	40
Spikarna	500	28	159	166	96	51
Ratan	631	36	187	183	121	105
Furuögrund	675	36	186	188	131	133

more energy per frequency interval at low frequencies than at high and that there is less energy at high frequencies in the central Baltic Sea than in the Kattegat. This information can also be obtained if the variance of the time series is partitioned into broad period bands which can be done by simple means. Results from such a partition applied to daily mean sea levels in the Baltic Sea and in the Kattegat are shown in Table 1.

To validate models some kind of measure must be used. The most common measure is presumably the root-mean-square error (rms-error) which is often a good measure. However, the rms-error can give an undeserved large error if there is a permanent offset between model results and observations. For example, the absolute height of the sea level is difficult to determine, and the sea level can be expressed in several different height systems. Thus, even if a model describes the sea level variations well the rms-error can be large due to a badly chosen height system. In this case, the fraction of the variance not explained by the model should be a better measure because the variance is independent of the absolute value and only the variations matter. If the variance is used as a measure, the mean value still needs to be considered to study how different forcings affect the mean value and to make sure that the model does not drift.

3 Sea level variations

3.1 Variables affecting the sea level

The sea level is affected by many kinds of motions in the sea due to astronomical, meteorological and hydrological forcings with varying time scales.

Short wind waves cause perhaps the most obvious motion of the sea surface, at least for the human eye, but they are usually neither recorded nor included in sea level discussions due to the short periods (seconds). For time scales around one day the sea level variations in the Baltic Sea are mainly driven by long waves, currents, tides and forced and free seiches. The sea level amplitudes caused by coastal waves and currents in the Baltic Sea seem to be only of the order 1 cm.

The tides in the Baltic are often neglected with the comment that the amplitude is small, and there are not many investigations of tides in the Baltic Sea. Witting (1911) concluded that the tides in the Baltic are mostly diurnal and due to the partial tides (K_1 and O_1) with amplitudes in the range 0.5 - 2cm. The semi-diurnal tides (M_2 and S_2) have amplitudes of 0.5-1.5cm. Similar amplitudes were also found by Magaard and Krauss (1966). According to Witting the diurnal tides are generated within the Baltic Sea while a small part of the semi-diurnal tides might be externally forced. Since waves, currents and tides have small amplitudes in the Baltic Sea it may be difficult to separate the signals from noise in sea level records.

The most common free seiche in the Baltic Sea occurs in the system "western Baltic proper - Gulf of Finland" with a period of around 26hours and with a typical amplitude of 10-20cm in the Gulf of Finland (Neumann, 1941 and Lisitzin, 1974). This seiche can survive up to 4-5 periods, but the amplitude decreases rather quickly. Occasionally, the amplitude can be several metres, and St. Petersburg, in the innermost part of the Gulf, can been flooded. The worst occasion was in November 1824 when the sea level rose to 4.21m above mean sea level, see Fonselius (1996). In the system western Baltic proper - Gulf of Bothnia there are seldom seiches, but the period should be around 39hours and with an amplitude of up to 40cm (Neumann, 1941).

Wind stress and air pressure variations force sea level variations on the time scale days to weeks. The wind stress causes Ekman transports that shuffle water around but may also cause sea level slopes in the wind direction. A rising air pressure forces water towards regions where the pressure is lower which gives rise to sea level gradients. Variations of density are causing sea level variations but the process sustaining density variations seem to be rather slow why the sea level is affected on the time scale months. In the Baltic Sea there is a permanent horizontal salinity gradient which causes a higher mean sea level in the northern parts than in the southern (see section 3.3).

In a semi-enclosed sea the volume budget is intimately coupled to sea level variations. Volume changes in the Baltic Sea are due to water exchange with the Kattegat, freshwater supply and thermal expansion/contraction. During major in- and outflows the mean sea level in the Baltic Sea can change with almost a metre in a few weeks. The amplitude of the sea level change due to the seasonal thermal expansion should be about 2cm (Stigebrandt, 1995). Water exchange with the Kattegat is the most important forcing of the sea level on time scales longer than two months, as shown in paper II and III.

On even longer time scales, centuries, the post-glacial uplift is important as sea bottom becomes dry land. Eustatic change of sea level due to melting/growing of glaciers and long-term heating/cooling (thermal expansion) of sea water has the same time scale. The apparent land uplift, the difference between land uplift and eustatic sea level change, can be seen as a trend in sea level records. In the southern part of the Baltic Sea, the apparent rate of land uplift rate is -1mm year^{-1} while in the north the rate is 9mm year^{-1}, see Fig. 3. The apparent uplift of land has been under investigation for a long time, and the first

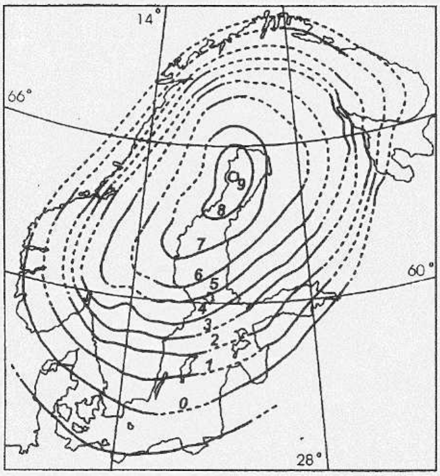

Figure 3. The apparent post-glacial uplift in Fennoscandia (redrawn from Ekman, 1996)

sea level stations were set up in the middle of the 19th century. At Stockholm the sea level has been recorded since 1754, and this record is the world's longest continued sea level recording (Ekman, 1988).

The post glacial uplift is a problem when studying sea level variations, but the problem can be dealt with by detrending the series. More cumbersome when sea level records are compared with oceanographic calculations are the locations of the mareographs. Sea level stations are often placed where it is important for human activity to know the sea level variations, e.g. in harbours. Consequently, the stations are usually located in the coastal zone, often in shallow areas with islands and narrow straits between the sea level stations and the open sea. A typical example of this is the Stockholm sea level station which also may be affected by the large freshwater supply from Lake Mälaren. There are also several stations situated nearby the outlets of large rivers, e.g. Spikarna and Kemi, where the freshwater influence from river discharges should be significant. Thus, a large scale model should not be able to explain 100% of the recorded sea level.

3.2 Modelling sea level variations

One way to understand Nature better is to construct models with which ideas about the forcing and functioning can be tested and different forcings can be estimated. Most models are too complicated for analytical solutions why one has to rely on numerical solutions. Many oceanographic models use 2D or 3D schemes to solve the Navier-Stokes equation. These models often have a rather fine grid and a time step of less than one hour. High resolution and accompanying small time step make it difficult to run the model for long periods. With a simpler model, e.g. a box-model, the broad dynamical features can often be found. It is also easier to study effects of different kinds of forcings and, as the understanding grows, additional physical processes can be included in the model. Since this kind of model is computationally economical even longer time scales, years and decades, can be studied. The limits of realistic simulations are often set by the length of the forcing data.

Stigebrandt (1980) modelled the water exchange between the Kattegat and the Baltic Sea with a simple model, treating the Kattegat and the Baltic Sea as two boxes connected with a channel. The transport through the channel was computed under the assumption that the longitudinal barotropic pressure gradient is balanced by quadratic flow resistance in the channel. The estimated sea level in the Baltic Sea agreed rather well with the sea level at

Landsort. The same model was later used by e.g. Omstedt (1987). Mattsson (1995) added linear flow resistance in the parametrization of the flow in the Öresund and was able to increase the explained variance of the sea level in the Baltic Sea from 83% to 85%, a small but significant increase (tested by the generalized likelihood ratio test). Mattsson found that the component of linear resistance is most probably caused by the rotation of the earth.

In paper II external and internal forcings of the daily sea level variations in the Baltic Sea are separated using a five-box model. External forcings are due to the water exchange with the Kattegat and the freshwater supply to the Baltic Sea while the internal forcings considered in that paper are due to the horizontal variations of density and air pressure. Partitioning of the unexplained sea level variance among different period bands showed that the external forcings left 10-35% of the variance unexplained for time scales longer than two months. For shorter periods the unexplained variance was greater and in the period band 2days - 2weeks the external forcings did not explain any variance in the northern and southern parts of the Baltic Sea. Adding the internal forcings decreased the unexplained variance with 20-50 percentage points. It was concluded that in order to increase the precision of the model the wind stress must be included which led to the development of the model described in paper III.

In paper III the Baltic Sea is approximated by three channels connected in series by two short and narrow straits. The mean sea levels in the channels are determined by the freshwater supply and water exchange with the other channels and with

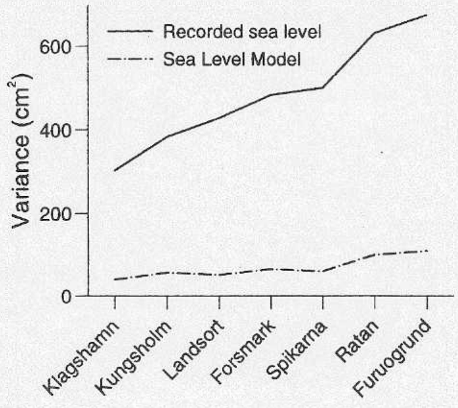

Figure 4. The variance of the daily mean sea level at seven stations in the Baltic Sea during the period 1979-1987 and the unexplained variance given by the three-basin model (from paper III).

the Kattegat. In each channel two perpendicular quasi-steady slopes are maintained by the wind stress and by horizontal gradients of air pressure and density. With this model, 90% or less of the variance could be explained for periods longer than two months, and for shorter periods 40-80% is explained. For the investigated period, 85% of the sea level variance could be explained, see Fig. 4. were the unexplained variance given by the sea level model is plotted together with the variance of the recorded sea levels. The seven stations are rather evenly distributed along the Swedish coast from the southern Baltic Sea to the northern (see Fig. 1).

The model in paper III shows that the wind stress is the most important forcing for periods shorter than 2weeks. In the Bothnian Bay the wind effect can be seen in all period bands. The seasonal variations of the unexplained variance was also studied, and the results show that the importance of the wind effect is largest during winter. It can also be seen that the precision of the model is higher during summer than during winter. Thus, to improve the model further, processes that are strongest during winter must be added and/or better described. In the parametrization of the drag coefficient (Large and Pond, 1981) used in the model, the influence of unstably stratified conditions in the air are not included. When the air is unstably stratified, which occurs mainly during autumn and winter, the drag coefficient is increased. The drag coefficient is also influenced by the presence of sea-ice, and depending on ice type and meteorological conditions the drag coefficient may vary by a factor of four (Overland, 1985). When the model is run with the drag coefficient doubled during winter, the amplitude of the sea level variations increases indicating that an improved parametrization of the drag coefficient will increase the precision of the model.

3.3 Mean sea level

Calculating the variance of the recorded sea level is easily done, but the mean sea level is more difficult to determine. A height must be measured relative to a reference level and there is no natural references in the sea. As a consequence, all mareographs have their own reference level which usually consist of a mark in the rock. In order to compare sea level recordings from different stations the sea levels need to be transformed to a common height system. To do this the sea levels must first be related to a specific year due to the horizontal gradient of the post-glacial uplift in the Baltic Sea. The importance of using a specific reference year can

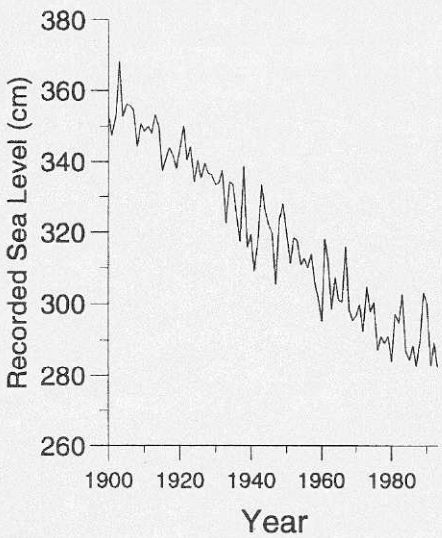

Figure 5. The annual mean sea level at Ratan during 1900-1990 given in the local height system.

be understood from looking at Fig. 5 where the annual mean of the sea level at Ratan is plotted for the period 1900-1993. The local height system is used and the apparent uplift causes a negative trend. Thus, the sea level difference between Ratan and e.g. Kungsholmsfort, where the uplift is almost zero, will depend on the year of the investigation.

The next problem is to decide which height system to use. Is the height to be given above the non-tidal, the mean or the zero geoid? The difference between the geoids is due to the treatment of the tide. The tide can be divided into a permanent and a periodical part. At the equator the permanent tide is around 30cm higher than at the poles. If the permanent tide is neglected the non-tidal geoid is obtained, while the mean geoid is obtained if it is included. Both geoids are difficult to calculate, several mathematical problems can not be solved without making assumptions that violates the physics. To avoid these problems the zero geoid can be used. The zero geoid is obtained if the direct effect of the attraction of the Sun and the Moon is eliminated but effects of the deformation of the earth are retained. For a thorough description of different geoids and height systems, see Ekman (1989).

For sea levels the most appropriate geoid is the mean geoid since this is the form a mean sea surface not disturbed by any meteorological, hydrological or oceanographical forcings would have. Ekman and Mäkinen (1991, 1996) constructed a height system, NH60, which gives the height above the mean geoid, the zero point is NAP (Normaal Amsterdam Peil) and the sea level is related to 1960. To test their height system, the mean sea levels at several stations around the Baltic Sea were calculated and compared with mean sea levels given by an oceanographic model constructed by Lisitzin (1957, 1958 and 1962). The two models diverged throughout the Baltic Sea, the oceanographic model giving a higher north/south sea level difference than the geodetic model. There are several questionable parts in Lisitzin's model, e.g. the level of no motion is assumed to be very shallow, and she used monthly mean values of the wind speed. To account for varying wind directions an empirical factor depending on the relative distribution of northerly (NE, N, NW) and southerly (SW, S, SE) winds was added to the parametrization of the drag coefficient. She then assumed that wind speeds are uniformly distributed with respect to the direction which is not true. The wind speed was converted from Beaufort number to metres per second using a factor of 2.1 which overestimates the low speeds and underestimates the high. The model by Lisitzin thus has several questionable parametrizations.

For a fair comparison between the geodetically determined mean sea levels and oceanographic estimates, a new and better oceanographic model was needed. The sea level model described in paper III was therefore used to calculate the mean sea level for a 15-year-period. The seasonal variations of the mean sea level agree well with the geodetic model, except during winter. As discussed above, the precision of the sea level model is worse during winter than summer. Thus, the precision of the computed mean sea levels during winter can probably be improved. The long-term mean sea level given by the two models agree throughout the Baltic Sea, with the largest discrepancy, 2 cm, at Landsort, see Fig. 6. In paper IV it is concluded that NH60 is suitable for oceanographic purposes involving absolute height e.g. for calculations of barotropic transports and to check the mean sea levels estimated by models. In the geodetic model a few stations did not fit into the general pattern, presumably due to errors in the local levelling. At these stations, the geodetic model can be corrected with the oceanographic sea level model.

4 Barotropic transports

There are several different devices for current measurements. Hence, it is not so difficult to determine the speed and direction of a current, but it can be difficult to calculate the corresponding transport

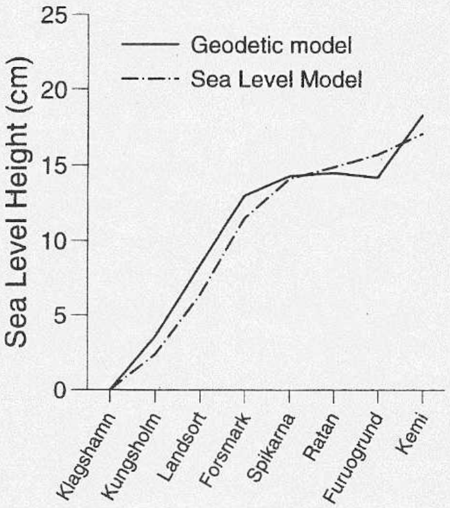

Figure 6. The mean sea level given by the three-basin model and the geodetic model (from paper IV).

through a vertical section. The speed and direction of a current vary both in time and space, and especially in wide straits and straits with irregular topography it may be difficult to assign the correct vertical cross-sectional area in which the recording current meter is representative. Ambjörn and Gidhagen (1979) used current measurements from the period 15 June to 15 August 1977 to calculate transports in the Åland Sea and the Archipelago Sea (between the Baltic proper and the Bothnian Sea). The estimated transport out of and into the Bothnian Sea were 143 and 88 $km^3 month^{-1}$, respectively. As much as 38 $km^3 month^{-1}$ could not be accounted for when the freshwater supply (19 $km^3 month^{-1}$) and the volume change (-2 $km^3 month^{-1}$) were considered. Ambjörn and Gidhagen concluded that the inconsistency of the volume transports was due to the low spatial resolution of the current measurements. This problem should diminish as the Acoustic Doppler Current Profiler (ADCP) becomes more common in use.

Another problem with current measurements is the, usually, short duration of the measuring period, e.g. Ambjörn and Gidhagen (1979) used a two-month-period. The short period makes it difficult to determine whether a common or uncommon event is measured. One way to at least partly overcome this problem is to use a (realistic) computer model. For example, with the coupled three-basin sea level model described in paper III, barotropic transports can be estimated for long periods. If the model is run for the same period as currents have been measured the barotropic transport can be subtracted from the measurements, and the baroclinic component can be revealed. The model can also be useful to estimate transports where there are few or no measurements at all as in, for instance, the Northern Kvark.

In paper III the transports between the sub-basins are estimated. The mean outflow from the Bothnian Bay is around 30 while the inflow is around 22 $km^3 month^{-1}$. Wulff and Stigebrandt (1989) estimated the transports to 23 and 15 $km^3 month^{-1}$ respectively using Knudsen's relations, i.e. the actual transports are higher than the mean values given by Knudsen's relation. This is commented upon below. The estimated transport between the Bothnian Sea and the Baltic proper has a weak seasonal variation. During winter the mean outflow is around 60 and the inflow is around 40 $km^3 month^{-1}$, during summer the out- and inflows are about 15 $km^3 month^{-1}$ less. The mean transports estimated by Wulff and Stigebrandt are twice as large, $117 km^3 month^{-1}$ (outflow) and $99 km^3 month^{-1}$(inflow) indicating that there must be strong baroclinic transports.

The largest estimated barotropic transports between the Kattegat and the Baltic Sea have the same magnitude as the transport reported by Liljebladh and Stigebrandt (1996) for the major inflow in January 1993. The annual mean flow calculated from Knudsen's relation gives $950 km^3 year^{-1}$ out of and $475 km^3 year^{-1}$ into the Baltic Sea. The transports computed by the sea level model were much higher, 1500 and $1050 km^3 year^{-1}$, respectively. A plausible explanation is that a substantial part of the volumes forced into the Baltic proper gives a barotropic signal but does not contribute to the deepwater flow before flowing back again towards the Kattegat.

The daily mean transports through the different straits calculated for several years with the sea level model give enough material for a statistic study. In paper III the seasonal variation of the in- and outflow was calculated. For the Belt Sea/Öresund it was found that the outflow has low values during summer and higher during winter. The inflow has the same variation except for February which has the lowest monthly mean value. When all February values (in the period 1979-1987) were examined, it was discovered that the strength of the inflows were the same as for the inflows during the other months but the number of days with inflow was low. In February 1983, there were 25 consecutive days with outflow during which $260 km^3$ of water left the Baltic Sea and the recorded sea level at Landsort dropped with around 80 cm. This is comparable with the sea level rise during the large major inflow in January 1993 (e.g. Liljebladh and Stigebrandt, 1996).

The sea level model has been run for 15 years (1979-1993) and during this period there were two inflow events that lasted between 15-19 days, whereas there were fourteen outflows episodes with the same length. Five outflows lasted for 20-24 days and two outflows lasted for 25-29 days, see Table 2. For the two other straits within the Baltic Sea the situation was similar, but the events had shorter duration. The longest outflow through the Åland Sea was between 20-24 days and in the Northern Kvark the longest outflow was in the interval 15-19 days.

Table 2: The number of in- and outflow events in different classes of duration in the period 1979-1993

Duration	**the Belt Sea, the Öresund**		**the Åland Sea**		**the Northern Kvark**	
days	**in**	**out**	**in**	**out**	**in**	**out**
5 - 9	131	191	47	154	23	114
10 - 14	11	43	1	13	0	5
15 - 19	2	14	0	2	0	2
20 - 24	0	5	0	1	0	0
25 - 29	0	2	0	0	0	0

Only continuous periods have been counted, one day with a transport of opposite sign ended an event. This is why the major inflow in January 1993 is not seen in the table, the inflow was not continuous but interrupted by small outflows. Also major outflows are interrupted by one or two days with inflow, so the table does not show the whole truth. Another part of the truth can be seen if the cumulative estimated transport for certain periods, e.g. 15 and 25 days, is calculated. The distribution of cumulative transports of 15 and 25 days (with time lag of one day) are plotted in Fig. 7 and it can also here be seen that large outflows are more common than large inflows giving rise to asymmetric curves. The large inflow in January 1993 can be seen as a small peak in the interval 145-150 $km^3 period^{-1}$ for the 15 days cumulative transports. The model does not manage to calculate the inflow properly, the transports are too low and the episode is too short, since the estimated sea level at Klagshamn is a few centimetres too high during this period. This may be due to the bad parametrization of the wind stress during winter time, which does not give a steep enough sea level slope.

Before a major Baltic inflow occurs there must be a period with high air pressure over southern Scandinavia which gives rise to a low sea level in the Kattegat. Accompanying easterly winds maintain a sea level slope in the Baltic Sea giving relative high sea levels in the south, and water is forced out of the Baltic Sea. This leads to a lowering of the mean sea level in the Baltic Sea. When the air pressure falls and the winds becomes westerly the sea level in the Kattegat rises, at the same time the sea surface slope in the Baltic changes

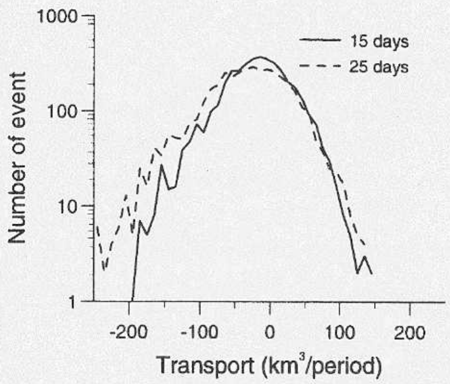

Figure 7. The distribution of estimated cumulative barotropic transports between the Kattegat and the Baltic proper. The interval is 5 $km^3 period^{-1}$.

direction and the sea level in the south drops. Thus, saline water can enter the Baltic Sea, and a major inflow may occur if the situation with low air pressure and strong westerly winds becomes sufficiently long.

Outflows are not so important for the Baltic Sea, the only direct effect is a lowering of the sea surface, but a low sea level in the Baltic Sea is one of the prerequisites for major Baltic inflows (see below). Thus, a major inflow can follow after a major outflow, but it is not a necessity. The Kattegat, on the other hand, is much influenced by the relatively fresh Baltic outflows and major outflows would certainly give strong density signals strengthening the stratification. A strong pulse of relatively fresh water from the Baltic Sea would probably also soon be noticeable in the Skagerrak where the freshwater contained in the coastal currents mainly comes from Baltic.

5 Salinity variations

It is well known that the salinity of the Baltic Sea varies on a wide spectrum of time scales, e.g. Fonselius (1969). There may be many reasons for the variations but the ultimate reasons should be changes in the freshwater supply to the Baltic Sea and in the salt exchange with the Kattegat, see Stigebrandt (1983). Mixing alone can not change the total salt content in the Baltic Sea but it can redistribute the salt.

In paper I, long-term salinity variations in the Baltic Sea were studied using historical data sets of several different variables for the period 1954-1990. In Fig. 8 the annual mean salinity of three different layers in the Baltic proper is plotted. The three layers are: the surface layer (20-60m), the halocline (60-100m) and the deepwater (100m-bottom). Available data are not evenly spread in time and to avoid effects of seasonal variations the top 20m of the surface layer was excluded. In Fig. 8 it can be seen that during 1977-1990, the salinity decreased in both the halocline layer and the deepwater. The decrease is significant according to Kendall's test for trends, see section 2.1. In the halocline layer and the deepwater the salinity decreases with about 1.5psu. There is also a significant trend in the surface layer, but this is much weaker, the decrease is only 0.6psu.

Time series of the salt exchange with the Kattegat, freshwater supply and mixing were studied in paper I (with the wind mixing represented by the variance relative to the annual mean sea level). The largest change occurred for the freshwater supply. During the eighties, the freshwater supply by runoff from land was much higher than during the seventies, see Fig. 9. The mean annual supply by runoff during the seventies was 13 300 m^3s^{-1} which increased to 15 400 m^3s^{-1} during the eighties. A high freshwater supply is known to decrease the salinity of the inflowing Kattegat water (see Stigebrandt, 1983) and in paper I it was shown that during the eighties the amount of incoming water was decreased. The depth of interleaving in the Baltic proper (of the incoming water) varies but most of the water enters in the halocline region. Consequently, the largest effect of a decreasing salinity in inflowing water can be seen in the halocline (see Fig. 8). In the surface layer, the change is comparatively small due to 1) the large volume involved and 2) the increased wind mixing during the eighties which increased the rate of entrainment of saltier water from below.

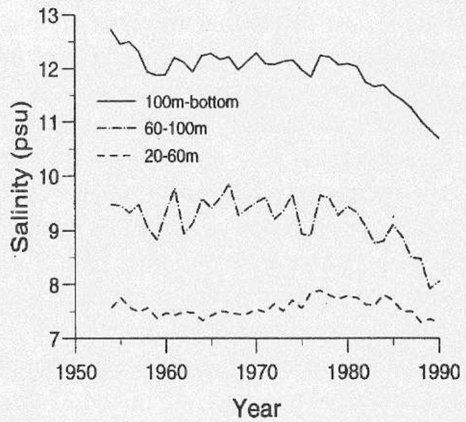

Figure 8. The annual mean salinity in three different layers in the Baltic proper during the period 1954-1990 (from paper I).

Only intense and long lasting inflows, so called major Baltic inflows, are dense enough to penetrate to the deepest layers, see e.g. Fonselius (1969), Stigebrandt

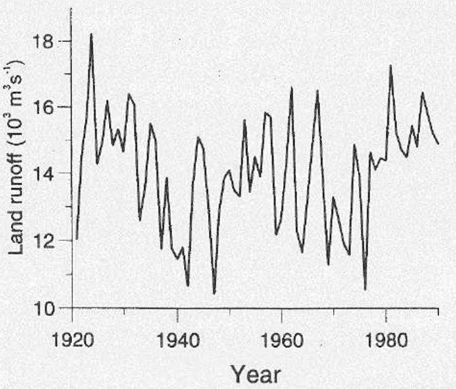

Figure 9. The annual mean land runoff to the Baltic Sea during the period 1921-1990. Data are from Mikulsky (1982) for the period 1921-1949 and from Bergström and Carlsson (1994) for the period 1950-1990 (from paper I).

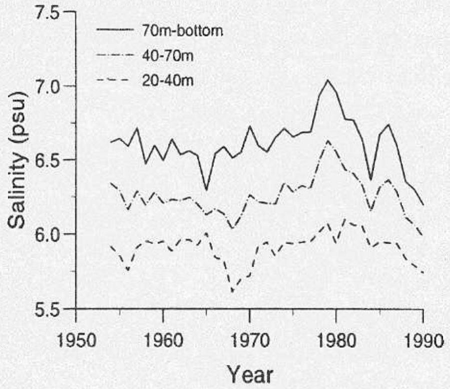

Figure 10. The annual mean salinity in three different layers in the Bothnian Sea during the period 1954-1990 (from paper I).

(1987) and Kõuts and Omstedt (1993). These major Baltic inflows occur very irregularly, and there may be several years between two major inflows with anoxia in large volumes of the deep basins as a result. In the deepwater there is a steady decrease in the salinity in the period 1977-1990, see Fig. 8. This decrease confirms earlier studies which have shown that there were no major inflow during 1977-1990, e.g. Matthäus and Frank (1992). In fact, the stagnation period lasted until January 1993, see e.g. Fonselius (1996).

New deepwater is, as already mentioned, diluted on its way northwards in the Baltic Sea which weakens the salt signal in the northern sub-basins. Due to the decrease of salinity in the surface layer in the Baltic proper (about 0.6 psu) during the eighties the salinity in the Bothnian Sea decreased with 0.5 to 0.8 psu with the largest decrease in the deepwater, see Fig. 10. In the Bothnian Bay the salinity reduction was even weaker, the decrease was around 0.3 psu. In percentage the decrease of salinity was around 10% in all three basins.

6 Outlook for the future

In the future the coupled three-basin model can be used in different ways. One application is to used the model for predictions of the daily mean sea levels in the Baltic Sea. To increase the precision of the predictions, especially during winter, the effects of unstably stratified air and the presence of sea-ice should be included in the parametrization of the drag coefficient. Another, more general enhancement, would be to improve the description of the topography. Furthermore, the precision of short term predictions may be increased using data assimilation.

The wind in the Baltic Sea is much influenced by the surrounding land masses, and a drag coefficient determined for the open ocean might not be quite adequate for the Baltic Sea. With the present model, the best formulation of the drag coefficient can be found by running the sea level model with different parametrizations and comparing the estimated sea levels with recorded data. The most suitable parametrization can then be used in more complex models, e.g. 3D-models. In 3D-models the grid size and the time step are much smaller than in the present model, and therefore free seiches and coastal effects can be included. The present model can be run in parallel with more complex models to make sure that the precision of large scale processes are not lost in favour of the precision of the smaller scale processes.

The mean sea levels estimated by the model can be used to correct local levelling errors at any location along the coast around the Baltic Sea. Today, the model calculates the sea level at eight specific stations, but new stations can easily be added. The only information that needs to be provided is the distance between the station and the nodal lines (for the longitudinal and transversal slopes). Hence, with the model, the daily mean sea level at any location in the Baltic Sea (except the Gulf of Finland) can be calculated.

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