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Trends in sea level variability in the Baltic Sea

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This study aims to investigate sea level variability on the coasts of Finland and its changes over the past 100 years. The sea level probability distributions have apparently changed in shape. The annual maximum sea levels show a significant increasing trend, the increase being concentrated in the latter half of the 20th century. Annual variability shows an apparent increasing trend with the most pronounced increase occurring in the 1960s and 1970s. This was confirmed by examining the standard deviations as well as the spectra of the sea level. Short-period variability of the order of only a few days shows long-term changes that well exceed random variations, and it is therefore permissible to interpret these variations as reflecting the variations of short-term meteorological phenomena. The variations are not the same in different basins, but a minimum in the 1960s and a subsequent increase in the wintertime variability up to the 1980s can be seen in all of them. In the Gulf of Finland a 30 year cycle was found in the short term variability. On the other hand, the overall trend during the 20th century shows only a marginal increase that is not statistically significant. For all Finnish tide gauges, the annual mean sea level was found to be linked significantly with the NAO (North Atlantic Oscillation) air pressure index. The annual standard deviation of the sea level also correlates with the NAO, but the correlation is not statistically significant in every basin.

Introduction

The sea level and its variations are controlled by the tide, and meteorological and climatological processes, including the hydrological balance. In the Baltic Sea, sea level variations are principally controlled by the last two. The sea level can be measured with high precision, and thus we may correspondingly expect investigation of sea level variability to yield further insight into these controlling phenomena. The mean sea level and its variation are, therefore, currently the subject of various studies and interests. This seems to be of particularly great importance from the point of view of the monitoring and prediction of effects related to global climate change. The problems of sea level rise and changes in sea level variability are of scientific and also in many ways of practical importance, especially in coastal lowlands.

Investigation of sea level variations in the Baltic Sea has long traditions. Exhaustive investigations have been made by various authors (Stenij and Hela 1947, Hela 1948, 1950, Lisitzin 1958, 1959, 1966a, 1966b, 1974, Krauss 1974). They studied sea level variations and driving forces, mean sea level and secular land uplift, etc., using the tide gauge data gathered up to that time. Diagnostic, statistical, and harmonic analysis approaches have been used.

More recently, Ekman and Stigebrandt (1990) studied the seasonal variation and the pole tide of the Baltic Sea level using Stockholm (Sweden) monthly data, and found a statistically significant increase in the amplitude of the annual variation for the period 1825–1984. Their results also suggested an increase in the amplitude of the pole tide. Samuelsson and Stigebrandt (1996) chose six Swedish sea level records of daily means for studying the spatial behaviour of the variability in the Baltic Sea. They used an externally-forced sea level model to separate externally and internally-driven variations.

Lisitzin (1958) studied the relation between the sea level and the severity of the winter. She found a relatively high correlation, 0.67, between the sea level at Utö and the air temperature in Mariehamn.

Ekman (1996a) used annual and monthly mean sea levels from 56 stations to study the interannual and seasonal sea level variations and the pole tide in the Baltic Sea and the adjacent part of the North Sea, and found a common geographical pattern for them. Ekman (1996b, 1997) also studied extreme annual means in the Baltic Sea and anomalous winter climate coupled to them. He found that the normal seasonal variation with a minimum in the spring and a maximum in the autumn was replaced by a variation with a pronounced maximum for high water years and minimum for low water years, both occurring during winter. He also found that this phenomenon was closely related to anomalous winter climate.

Ekman (1998a) studied the interannual variability of the annual mean sea level in Stockholm and winter winds and temperatures, and found some covariation in their mutual behaviour. Ekman (1998b) considered the seasonal sea level variation in wintertime using Stockholm monthly sea level data, and found some statistically significant secular changes. He concluded that the main origin of these appears to be in changes of wind conditions over the transition area between the North Sea and the Baltic Sea.

Makkonen *et al.* (1984) briefly considered the long-term trend of short-period sea level variability in their study of long-term variations of the physical parameters of the Baltic Sea.

Vermeer *et al.* (1988) used fully-measured monthly means from 13 Finnish sea level stations to study land uplift and sea level variability and the various processes affecting it in the Baltic Sea.

Alexandersson *et al.* (1998) studied the long-term variations and trends of storm characteristics over northwestern Europe using geostrophic winds during 1881–1995. They found that storminess was at a high level during about 1881–1910 for the main part of the area studied, thereafter declining slowly and irregularly to around 1965. After that the frequency of storms was found to increase almost to the levels of the first decades. This recent increase was found to show some similarity to the NAO index.

Studies performed for the IPCC Assessments (Intergovernmental Panel on Climate Change; IPCC 1990, 1996, 2001) include an exhaustive set of studies about sea level changes to be expected in future, especially that of the global mean sea level. Current scenarios for the next one hundred years predict an increase in global mean sea level of 0.1 to 0.9 m (IPCC 2001). The range of variation arises, amongst other things, from the various scenarios for greenhouse gases and from uncertainties in modelling the physical processes connected with sea level prediction. The main reasons for an increase in the global sea level are the thermal sea water expansion and the potential gradual melting of the overland cryosphere. The climate change is likely to affect factors controlling the difference in water level between the Baltic Sea and the North Atlantic. One of the latter mechanisms will be discussed below.

In this study, we use the long-period time series of high-accuracy tide gauge data from Finnish tide gauges. The main focus is on achiev-

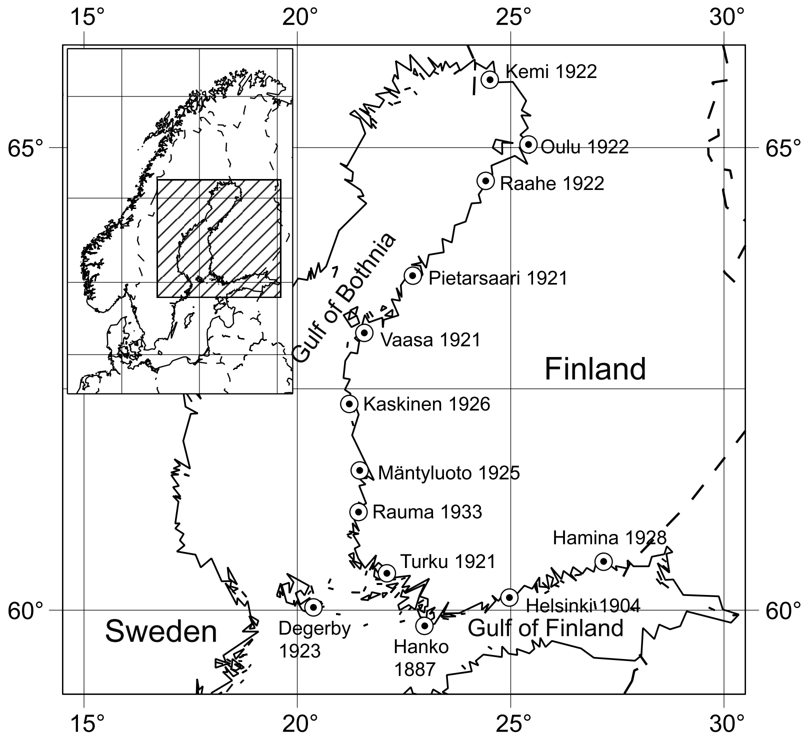

Fig. 1. Locations and years of establishment of the Finnish tide gauge stations.

ing further insight into the sea level variation statistics and to determine whether trends can be detected in intra- or interannual variability and in the occurrence of high or low sea levels. A detailed physical reasoning about the deviations and changes, e.g. a determination of the process involving Baltic Sea level dependence on the NAO (North Atlantic Oscillation) forcing and possible links to climatic changes are not within the scope of this report. Neither do we report quantitatively on the effects of the hydrological balance on the sea level and its variations nor the effects of a seasonal ice cover on them.

Data and methods

The calculations were based on sea level data from the northern Baltic Sea up to the year 1999. Data were collected from 13 tide gauge stations operated by the Finnish Institute of Marine Research (FIMR). The locations and years of establishment of the stations are given in Fig. 1. The longest time series exists for Hanko, starting in 1887, and the shortest for Rauma, starting in 1933, while the rest cover periods of at least 70 years. We used the data from all the stations, but in several specific investigations representative stations were used. In those cases, the choice of stations was based on an exhaustive analysis of data quality and physical representativeness. In addition, the requirement for a continuous time series limited the number of stations available for spectral analysis.

Up to the early 1980s, tide gauges mostly produced continuous chart recordings, using the reliable equipment constructed by H. Renqvist and R. Witting (Hela 1948). Nowadays, Finnish sea level stations have been instrumented with fully-automated data recording units (Milos 500, Vaisala Co.) for real-time operation and telecommunication. The chart recordings were manually digitized to provide 24 recordings a day with a recording resolution of 1 mm, but up to 1970 the data were published and later stored into the computer database only every four hours, i.e. six recordings a day, with an accuracy of 1 cm. Since 1970, hourly data, i.e. 24 recordings a day, have been stored in the database with a 1 mm resolution.

To prevent possible errors arising from the time interval difference, this study was based on the records at 4 hour intervals and a resolution of 1 cm for the whole time series. Thus, the data set used for each station contains 140 000–240 000 observations.

The yearly and monthly extreme values were also extracted from the time series described above. In fact, since 1970 extreme values have been registered more frequently than once an hour, but our aim was to have as uniform and continuous a data set as possible, and thus 4-hourly data were used.

For various reasons, interruptions and gaps exist in the measurements, especially during the earlier decades. Some of the missing values were interpolated linearly using recordings of adjacent stations. This has been found to be a reliable method in most cases. Accordingly, those interpolated values, being few in number, were processed as if they were real observations. There are still some gaps in the data set. Gaps could not be interpolated if the data from one of the adjacent stations were missing. The effect of these incomplete data periods as well as that of interpolated values on the results was carefully analyzed and found to be negligible in the context in which they were considered.

Kemi and Hamina, additionally, are situated at the ends of the Finnish coastline (Fig. 1). In those cases, the missing values were extrapolated using the data of two adjoining stations. Especially at Kemi, where some practical problems are known to have existed in the registering of extremely low sea levels during earlier decades, the extrapolated values may be somewhat erroneous. The tide gauge at Kemi is also one of those that have been moved. The distance between the new and the old location — 6.8 km — is greater than in any other case. No conclusions have been drawn solely on the basis of the Kemi data. In the tables the findings from Kemi are in parentheses because of their questionable quality. We have not found similar problems at Hamina.

Finally, there is one more factor that could potentially affect the accuracy: the maintenance of the stations. Tide gauges are connected to the sea through a narrow underwater pipe that can become blocked by sand or other material, and the frequency of cleaning them may have varied over time. Such blocking causes exponential damping of short-period fluctuations. We have, therefore, always compared several adjacent stations, and only those features have been considered significant that are consistent at more than one station. Comparisons have not revealed problems of this nature.

By the end of 2000, a new type of intermittent error became apparent in the measurements at Hanko. It was also caused by the partial blocking of the pipe, but results in a bias in addition to the exponential damping of the short-term fluctuations. We suggest the bias to result from the water table being higher around the well of the tide gauge than the sea level; this happens during periods of very high precipitation. The tide gauge network along the Finnish coast has been built dense enough that the water level at one tide gauge can be interpolated from the neighbouring tide gauges with a standard deviation of 2 cm and a negligible bias. By interpolating all data from 1923 on we found that the ground water bias appeared first in 1986. No similar error was found in the other tide gauges. The effect of this bias on the results was carefully analyzed. The bias in annual averages is 2 cm on average and 4 cm at maximum. Even when uncorrected, it has no qualitative effect on the results, because the time series is over 100 years long. When the data was corrected by replacing the biassed measurements by the interpolated values, the residual error was found to be negligible. Still, the results from Hanko (based on the corrected data) are in parentheses in the tables.

The sea level data were used to calculate probability distributions for different time periods. These distributions were compared with each other using the Kolmogorov-Smirnov test as a significance test. Time series of different quantities, such as extreme values and standard deviations were calculated. We used linear regression to study trends, and correlation analysis to study relations between different time series. Student's t-test was used as a significance test. Since the long-term changes considered may not be linear, the regression method can give

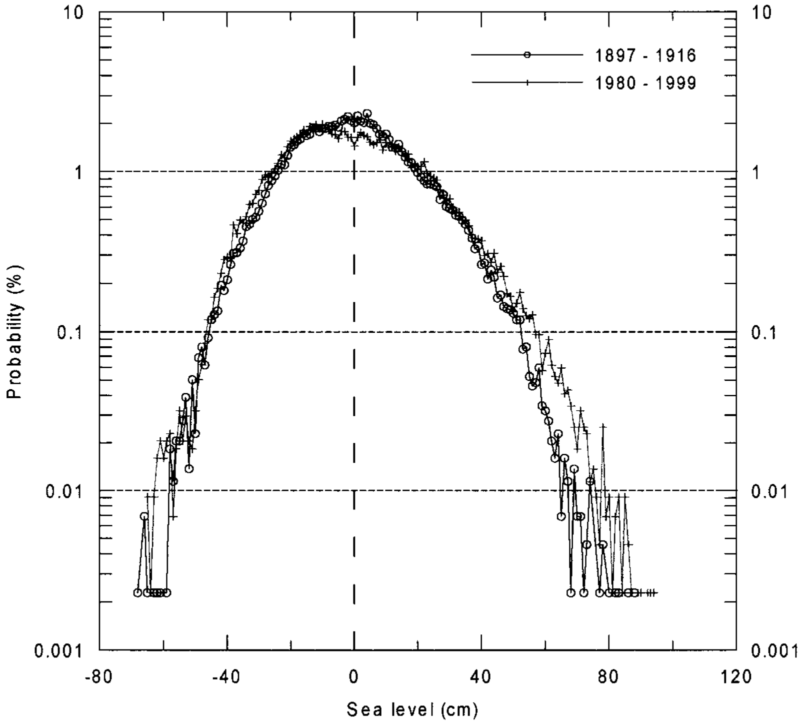

Fig. 2. Sea level probability distributions at Hanko for the 20-year periods of 1897–1916 and 1980–1999, respectively. The values have been referenced to the annual mean sea level in question. The method excludes long-term interannual variations and makes the distribution representative of intra-annual sea level variability.

information of the changes, but a quantitative evaluation for different time periods has to be interpreted case-by-case with care.

In some cases, a statistical test for comparison of the means of two samples was also used. This test was conducted by dividing the time series into two parts, in order to find out the significances of changes that appear from the curves to have happened in just a few recent decades.

Additionally, spectral analysis was conducted by calculating variances and amplitudes and studying the time development of these. The methods used will be discussed below in more detail.

The choice of a reference or zero level for the sea level is not always self-evident. This is especially the case when the long-term mean sea level has changed over time. However, quantities like standard deviations or spectra are independent of the choice of reference level. In all such cases, there is no need to change the reference level from the bedrock-bound reference level where the measurements originally have been recorded (Lisitzin 1966a).

In the case of probability distributions and extreme values, the choice of the reference level is more important. These were mainly referred to annual mean sea levels, as calculated from the observations. This should remove any interannual variations and make the distributions and extreme values representative of intra-annual sea level variability for the year. To verify that the choice of the reference level does not change the results qualitatively, a different reference level is briefly discussed below.

Probability distributions

Probability distributions of the sea levels over a long time period resemble modified Gaussian distributions. These are not exactly symmetric, with high sea levels tending to be rather more, and low sea levels rather less probable than in a Gaussian distribution.

Figure 2 gives an example of the sea level probability distributions at Hanko. The two mean 20-year period distributions shown were taken from the beginning and the end of the last cen-

Table 1. Trends in the annual maximum and minimum sea levels. The annual maximum and minimum were referred to the annual mean sea level. "Trend" is the slope of the linear regression line, "*t*" gives the *t*-test values of the trend. "Sign." indicates the significance of the trend. Relative trends were calculated by dividing the trend by the absolute value of the starting point of the regression line. (The values are calculated from observations at 4-hour intervals.)

Station	Years	Maxima				Minima			
		Trend (cm/50 yr.)	*t*	Sign. (%)	Relative trend (1/50 yr.)	Trend (cm/50 yr.)	*t*	Sign. (%)	Relative trend (1/50 yr.)
Kemi	1923–1999	(9.68)	(1.51)	(86)	(0.087)	(7.96)	(1.66)	(90)	(0.082)
Oulu	1923–1999	12.9	2.48	98	0.127	2.40	0.54	41	0.028
Raahe	1923–1999	9.34	1.80	92	0.102	6.70	1.45	85	0.076
Pietars.	1922–1999	8.37	1.93	94	0.109	3.55	0.93	64	0.048
Vaasa	1922–1999	6.40	1.70	91	0.091	3.79	1.16	75	0.056
Kask.	1927–1999	10.8	2.28	97	0.162	0.74	0.24	19	0.013
Mäntyl.	1925–1999	10.4	2.57	99	0.165	0.80	0.29	23	0.015
Rauma	1933–1999	14.1	3.06	99.7	0.232	0.35	0.11	9	0.007
Turku	1922–1999	12.2	3.37	99.9	0.189	1.05	0.41	32	0.021
Degerby	1924–1999	9.87	3.09	99.7	0.187	–1.23	0.50	38	–0.028
Hanko	1888–1999	(6.19)	(3.19)	(99.8)	(0.100)	(1.25)	(0.89)	(62)	(0.024)
Helsinki	1904–1999	8.40	2.99	99.6	0.111	6.24	3.09	99.7	0.089
Hamina	1929–1999	14.7	2.41	98	0.150	4.33	0.97	67	0.052

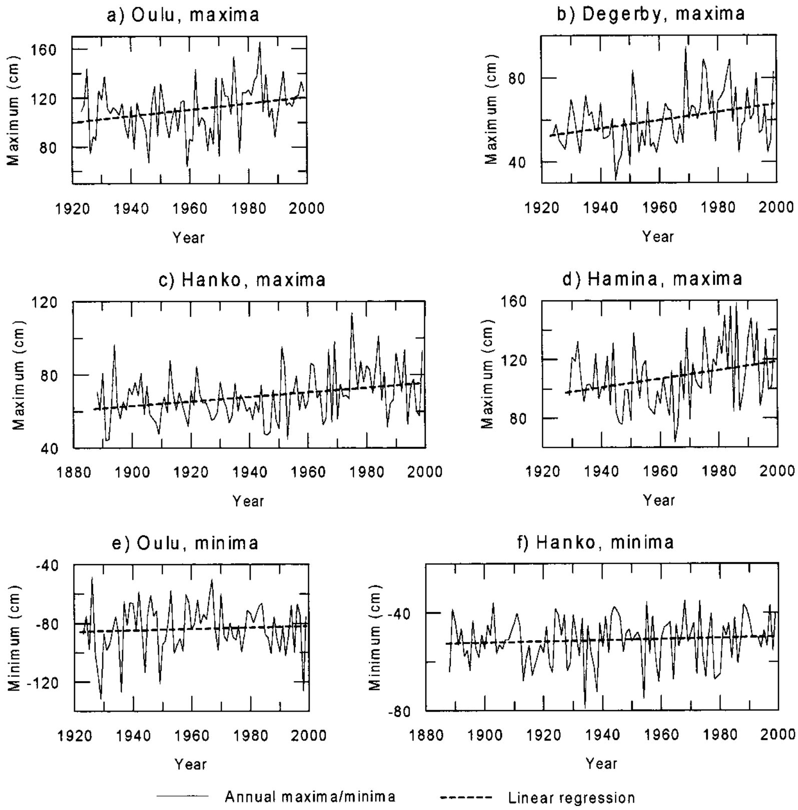

Fig. 3. — **a–d**: Time development of the annual maximum sea level at Oulu, Degerby, Hanko and Hamina. — **e–f**: Time development of the annual minimum sea level at Oulu and Hanko. (Referred to the annual mean sea level.)

tury. By comparing these it can be seen that the distribution has become somewhat broader, and that especially the probabilities for extremely high sea level values have increased.

The probability distributions for all 13 tide gauges were studied. In general, they closely resemble those given in Fig. 2. The most recent distribution was calculated for the years 1980–1999, and the earliest one for the 20 first complete years of operation of each tide gauge. Since there is a substantial amount of missing observations at Hanko prior to 1897, the earliest distribution for Hanko was calculated for the years 1897–1916.

The changes in the shape of the distribution are most clearly seen in the Baltic Sea nodal region of Degerby and its surrounding stations. However, applying the Kolmogorov-Smirnov test to the distributions of different time periods caused the rejection of the null hypothesis (that the distributions are of the same form) at the 99.9% level for all stations.

In addition to the annual distributions studied above, distributions for the winter period from November to January and for the summer period from May to July were also studied. Based on studies of monthly variances, the most pronounced variability appears to occur during the winter period thus chosen, while the summer period is the one with the smallest variability. The distributions for all the stations were calculated for 20 years, as above. Both periods show a difference in the distributions, the null hypothesis being rejected at the 99.9% level.

Extreme values

The linear regressions fitted to the data of the annual maximum values (Table 1 and Fig. 3) show an increase in the maxima on the Finnish coasts during the last 70 years. The trend in maximum values seems to be especially significant in the Baltic Sea nodal area, i.e. at Helsinki, Hanko, Degerby, Turku and Rauma. For Hanko, with the longest time history of data, the results suggest that the increase in the maxima has mostly occurred during the latter half of the century. This was further studied by a statistical test for the means of the maxima prior to 1970 and for those after 1970. The significance of the mutual difference exceeds 99% at every station.

As an overall conclusion from the results regarding the increase in the maxima, it can be said that the last 70 years' data suggest that the maxima have increased by about ten centimeters in the Baltic Sea nodal area in a half century. Annual minimum values, on the contrary, do not show an apparent trend. In the individual trends, there is no significance exceeding 90%, except at Helsinki.

The effect of a choice of zero level can be eliminated by studying the difference between highest and lowest observed sea levels, instead of studying the values referred to the annual mean sea levels. The height interval between the annual maximum and minimum behaves as we might expect from the results above. This annual maximum variation indicates an increase with time, and is in agreement with the above finding according to which the maxima show an increase but the minima have remained unchanged. For the various stations the trends of the annual maximum variation seem not, however, to be as significant as those for the maxima alone.

The results obtained are in accordance with the changes seen in the shape of the probability distributions, the probabilities for extremely high sea levels increasing and those for extremely low sea levels remaining more or less unchanged.

Standard deviations of sea level variations

As a simple measure of the variability of sea levels on different time scales, the standard deviations of the time series were calculated, and a study was made of the behaviour of the standard deviations with respect to time.

Annual variability

The behaviour of the sea level on a yearly time scale was studied using the annual standard deviations of the 4-hour interval observed data. Linear regressions with respect to time were fitted to the standard deviations obtained. Floating averages for 15 years were also calculated (Table 2 and Fig. 4).

The spatial behaviour of the annual standard deviations along the coasts is clearly apparent. The most pronounced variations occur in the innermost parts of the Gulf of Bothnia and Gulf of Finland, while a minimum is located in the central area, e.g. at Degerby. This is a

Table 2. Annual standard deviation of the 4-hour interval observed sea level at the Finnish tide gauge stations. Column "Average" is the average of the standard deviation for all the years. "Trend" is the slope of the linear regression. "*t*" is the value of the *t*-test coefficient. "Sign." gives the statistical significance.

Station	Years	Average (cm)	Trend (cm/50 yr.)	*t*	Sign. (%)
Kemi	1923–1999	(27.8)	(1.03)	(1.21)	(77)
Oulu	1923–1999	26.2	1.89	2.22	97
Raahe	1923–1999	25.4	1.67	2.03	95
Pietars.	1922–1999	23.2	1.86	2.39	98
Vaasa	1922–1999	21.8	1.86	2.43	98
Kaskinen	1927–1999	21.2	2.44	3.06	99.7
Mäntyl.	1925–1999	20.5	2.41	3.15	99.8
Rauma	1933–1999	20.3	2.86	3.08	99.7
Turku	1922–1999	20.4	1.95	2.44	98
Degerby	1924–1999	19.0	2.47	3.18	99.8
Hanko	1888–1999	(20.0)	(1.29)	(3.05)	(99.7)
Helsinki	1904–1999	22.0	1.26	2.30	98
Hamina	1929–1999	24.9	2.59	2.96	99.6

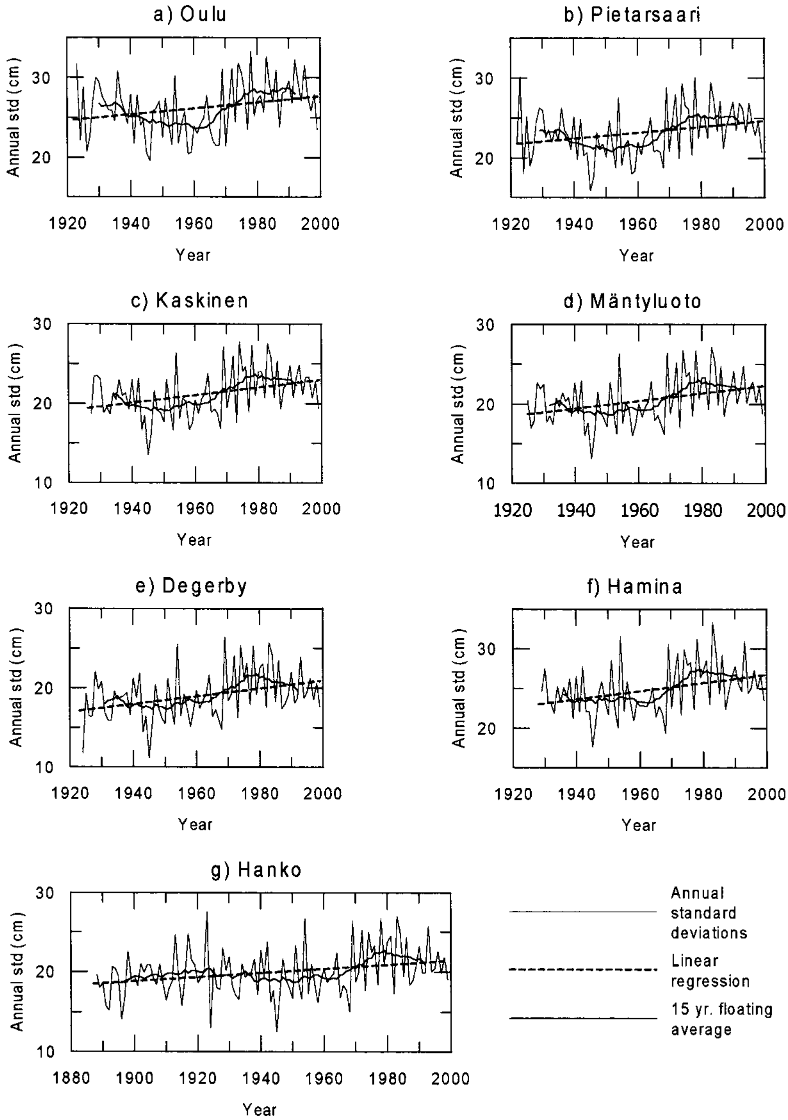

Fig. 4. Annual standard deviations of the sea level for the tide gauge stations of Oulu, Pietarsaari, Kaskinen, Mäntyluoto, Degerby, Hanko and Hamina. Annual values, 15-year floating averages and linear regressions given.

well-known feature of the physically relevant characteristics of sea level variations in the Baltic Sea (e.g. Stenij and Hela 1947, Hela 1950, Lisitzin 1959). The Åland archipelago and Degerby are located near the nodal region of the uninodal oscillation of the Baltic Sea.

The results show that the annual standard deviations have increased. The trend is statistically significant (99%) at six tide gauges and almost significant (95%) at the rest, except Kemi (Table 2).

A closer look at the time series and their floating averages (Fig. 4) reveals that the increase of the standard deviations is concentrated in the 1960s and 1970s. Before this, the deviations may even have slightly decreased, at least in the northern part of the Gulf of Bothnia. Since 1980, the standard deviations seem to slightly decrease again.

A statistical test for the means of the standard deviations prior to 1970 and for those after 1970 gives a significance of mutual difference exceeding 99% at every station, which is in accordance with the results obtained for the annual maxima above. The significance appears to have a maximum near this choice of the year for the division.

Short-term variability in winter and summer

It is known that on time scales of up to 5–10 days the variations in the sea level of the Baltic Sea are controlled by meteorological forcing. This is revealed e.g. by comparing the power spectra of the sea level variations with those of air pressure.

To study possible changes in sea level variability on the above time scales, variability within 8-day periods was calculated. The study concentrated especially on the winter (November–January) and summer (May–July) periods, as chosen above for the probability distributions.

Accordingly, each individual winter and summer period was 92 days long, containing 552 individual observations. Every such period was divided into subperiods of eight days (48 observations) giving 11 subperiods. The remaining four days were excluded. Then, the standard deviations were calculated for these subperiods and averaged over a whole winter or summer, giving a quantity that we call hereafter the "average standard deviation".

A linear regression was fitted to the annual values thus obtained, and floating averages over 15 years were also calculated (Table 3 and Fig. 5).

The regression was calculated for the 67-year period of 1933–1999. This was the longest period for which proper data were available for all the Finnish tide gauges. The t-values reveal that in the individual tide gauge data sets there are no statistically significant trends (significance exceeding 99%) in the short-term average standard deviations.

The 15-year floating averages for the winter period are given in Fig. 5, together with the annual values for two representative stations. We call attention to the faithful reproduction of both the general features and the small variations when nearby stations are compared. This clearly excludes local or instrumental explanations of the variability.

To see whether this variability is statistically significant we used the confidence limits for the power spectrum which will be calculated below.

Table 3. Average standard deviation of the sea level at the Finnish tide gauge stations in winter (November–January) and summer (May–July), calculated from 4-hour interval observations as a mean of 8-day consecutive subperiods. Column "Average" gives the average of average standard deviation over 8 days for the years 1933–1999. "Trend" is the slope of the linear regression line, "t" gives the t-test values of the trend. "Sign." indicates the significance of the trend.

Station	Winter period, November–January				Summer period, May–July			
	Average (cm)	Trend (cm/50 yr.)	t	Sign. (%)	Average (cm)	Trend (cm/50 yr.)	t	Sign. (%)
Kemi	(21.0)	(0.08)	(0.08)	(7)	(10.3)	(0.09)	(0.20)	(16)
Oulu	19.2	0.96	1.08	71	9.39	0.61	1.29	80
Raahe	17.9	0.66	0.90	63	8.55	0.23	0.68	50
Pietars.	14.4	1.15	1.98	95	7.22	0.40	1.55	87
Vaasa	11.8	0.62	1.28	79	6.53	0.05	0.23	18
Kaskinen	10.8	0.94	2.07	96	5.75	0.42	1.76	92
Mäntyl.	9.70	0.57	1.39	83	5.21	0.10	0.46	36
Rauma	9.13	0.66	1.70	91	5.08	0.16	0.84	59
Turku	8.95	0.57	1.56	88	5.41	0.24	1.31	81
Degerby	6.86	0.09	0.31	24	4.38	0.11	0.71	52
Hanko	(8.55)	(0.49)	(1.33)	(81)	(5.44)	(0.05)	(0.25)	(20)
Helsinki	12.0	0.62	1.33	81	6.95	–0.07	0.29	23
Hamina	15.9	1.24	1.82	93	8.65	0.15	0.44	34

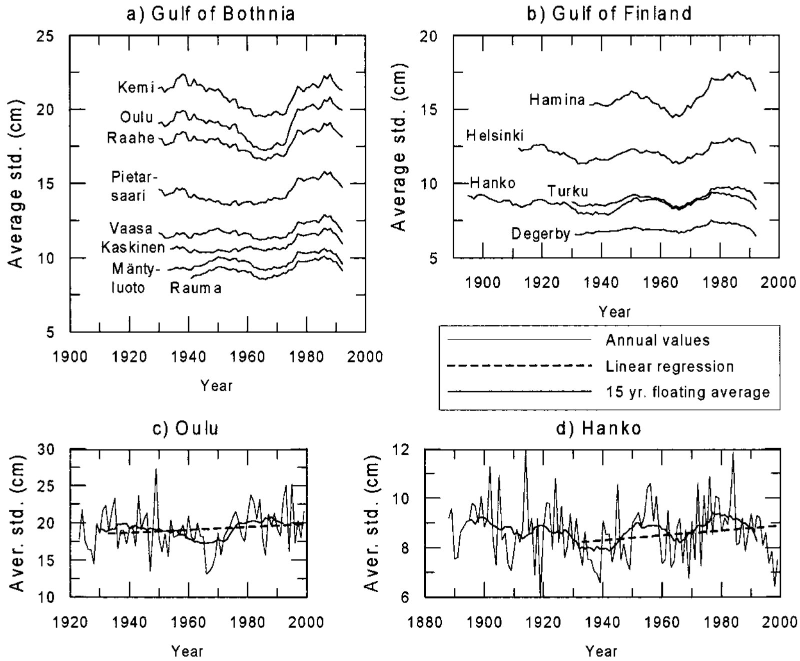

Fig. 5. Average standard deviations for 8 days in the winter period for the various Finnish tide gauge stations. — **a**: Gulf of Bothnia, 15-year floating averages. — **b**: Gulf of Finland, 15-year floating averages. — **c** and **d**: Annual values, 15-year floating averages and linear regressions (1933–1999) for Oulu and Hanko.

The average standard deviation defined as above and its 15-year floating average are in effect another way to calculate the square root of the spectral variance of periods of less than ten days. The 95% confidence limits for these spectral variances in the case of uncorrelated random data are an order of magnitude smaller than the variations between different 20 year periods (cf. Table 4). The same applies also to the variations in Fig. 5, which thus can be considered to well exceed the 95% confidence limits. This means that the variability reflects real changes, which are presumably caused by changes in the short-term meteorological phenomena.

The changes do not seem to be uniform but vary in different basins. In the northern part of the Gulf of Bothnia the average standard deviation decreases from 1930 to 1970. In other basins there is only small variation or fluctua-

Table 4. Spectral variances (cm^2) at Helsinki over different frequency intervals, as calculated for 20-year periods. The 95% confidence limits are also given. (The upper and lower confidence limits for each individual variance are obtained by multiplying the variance by the coefficient given in the table.)

Years	< 10 days	10–30 days	30–90 days	90–350 days	90–400 days	400 days–5 years
1910–1929	78.1	41.2	145	179	223	46.4
1920–1939	78.7	40.8	84.6	146	234	46.8
1930–1949	69.0	36.5	127	167	193	81.8
1940–1959	70.8	44.5	102	135	169	81.9
1950–1969	66.0	43.8	90.7	150	183	88.7
1960–1979	69.7	36.3	107	157	233	83.8
1970–1989	76.6	44.6	123	183	309	76.8
1980–1999	83.3	34.2	94.4	161	237	106
95% limits	1.0096	1.13	1.23	1.39	1.38	1.9
	0.9904	0.88	0.79	0.67	0.67	0.38

tions up and down. There is, however, one common feature, a local minimum in the 1960s followed by an increase until the 1980s. This coincides with the increase of storminess reported by Alexandersson *et al.* (1998). The behaviour of these average 8-day standard deviations is somewhat similar to that of the variations in the annual standard deviations.

The behaviour of the floating averages prior to the 1930s could be studied only at Hanko and Helsinki. In Fig. 5b and d, a slightly decreasing trend in the 1890s–1930s is visible. The results obtained suggest a fluctuation in short-term variability (here in the average 8-day standard deviations) in wintertime with a period of 30 years. There is an almost significant (95%) peak at 28–32 years in the power spectrum of these short-term average standard deviations for Hanko and Helsinki.

The most recent data from the middle of the 1980s show again a decreasing trend in short period variability. This is in accordance with the behaviour of the annual standard deviations, which suggests a slight decrease in the latest data.

In addition to the 8-day data based variability, all the calculations were repeated by dividing the data into subperiods of five and ten days. The results and conclusions remained essentially the same.

Finally, in addition to the average standard deviations of consecutive short-term subperiods studied above, the standard deviations of the whole 3-month (92 day) periods in winter and summer were also investigated. The standard deviations defined in this way show an increasing trend at every station in both winter and summer, the only exception being Kemi in summertime. However, the statistical significance for these individual trends does not exceed 85%.

To conclude, there are decadal variations in the magnitude of the short-term water level changes in the wintertime, for which the statistical significance exceeds 95%. We interpret these as reflecting corresponding changes in the wind climate. These changes are somewhat different in different basins but they all show a common feature: an increase from the 1960s to the 1980s, in agreement with the observed changes in the wind climate (Alexandersson *et al.* 1998). On the other hand, similar changes in summertime and a general statistically significant increasing trend of average standard deviation were not found.

Spectral analysis

The studies of the standard deviations suggest that a change in the sea level behaviour ought to have occurred at greater time scales than three months. This was further investigated by examining sea level spectra.

Variances in different frequency intervals at Helsinki

Sea level data have been collected at Helsinki for 96 years, and the data form a continuous high quality data set. The last 90 years of data were divided into calculation periods of 20 years (i.e. N = 43 830 observations). Power spectra were calculated for those periods using a discrete Fourier transform:

$$X(f_k) = \frac{2}{N}\sum_{n=0}^{N-1} w(n)x(t_n)e^{-i(2\pi/N)kn} \tag{1}$$

$$E(f_k) = \frac{N\Delta t}{\frac{2}{N}\sum_{n=0}^{N-1} w(n)^2} X^*(f_k)X(f_k) \tag{2}$$

where $X(f_k)$ is the complex amplitude spectrum and $E(f_k)$ is the power spectral density. $x(t_n)$ is the sea level time series and $w(n)$ the window function. A Blackman-Harris window was used:

$$\begin{aligned} w(n) = 0.35875 - 0.48829\cos\left(2\pi\frac{n}{N}\right) \\ + 0.14128\cos\left(4\pi\frac{n}{N}\right) \\ - 0.01168\cos\left(6\pi\frac{n}{N}\right) \end{aligned} \tag{3}$$

In order to somewhat smooth the results, adjacent periods were set to overlap each other by ten years. The observation interval was Δt = 4 hours as above, and the trend was removed from the data prior to spectral calculations. A sample of a power spectrum obtained this way is shown in Fig. 6.

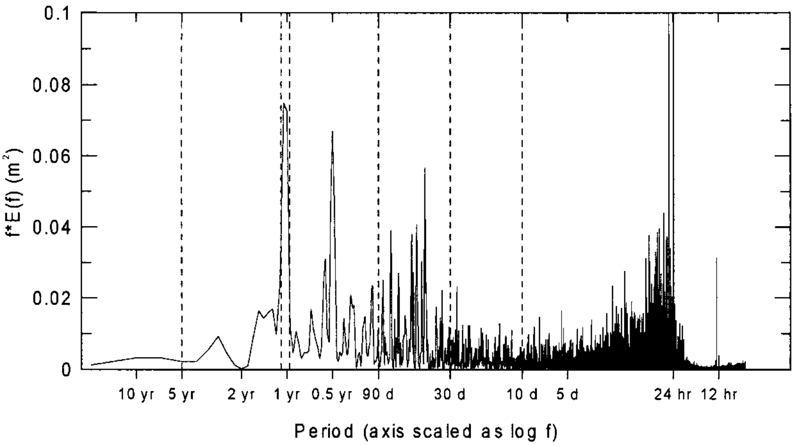

Fig. 6. Sea level power spectrum, calculated with a Blackman-Harris window, from the detrended time series of the 4-hour interval values at Helsinki, years 1980–1999. The annual and semiannual cycles are visible, as well as the diurnal and semidiurnal tidal components. The two diurnal tides visible extend beyond the axis limits. (The 25.8 h component extends to 0.71 m^2 and the 23.9 h component to 0.74 m^2.)

The spectra were divided into frequency intervals, indicated by the dashed vertical lines in Fig. 6, and variances for these intervals were calculated as the sum of the power spectral densities:

$$\mathrm{Var}(k_1,k_2) = \Delta f \sum_{k=k_1}^{k_2} E(f_k), \quad \Delta f = \frac{1}{N\Delta t} \qquad (4)$$

where Δf is the width of a frequency band.

The first frequency interval included periods less than ten days. This corresponds to the same time scale that was used as the subperiod for the average standard deviations study above. The next ceiling was chosen to include periods up to one month. This time scale should correspond to a transition in the behaviour of the Baltic Sea changing from a closed basin to totally respond to the ocean as an open bay (Samuelsson and Stigebrandt 1996).

The time period for the studies of the standard deviations of winter and summer was three months. The annual boundary (400 days) was chosen so that the strong annual peak (365 days, somewhat broadened by the spectral window used) would stay within the intra-annual frequency interval. The uppermost boundary of five years omits the lowest frequencies of rather more uncertain amplitudes. This is because the length of each time series was 20 years. The confidence limits for the spectrum estimates were calculated taking into account the bandwidth of the Blackman-Harris window and the bandwidth of the frequency interval.

The results (Table 4) show that the variances for the shortest periods had decreased until the 1950s–1960s and increased after that. These variations exceed the 95% confidence limits of the spectrum band. There are no apparent trends at fluctuation periods between ten days and three months. The variances for intra-annual periods longer than three months show a decrease up to 1940s–1950s, and then an increase after that. The significance for the increase in variance between 90 and 400 days is only 27%–56%, not being statistically significant. The variance on time scales longer than 400 days has increased at the 94% confidence level.

The high peak of 309 cm^2 for periods of 90–400 days corresponds to the period of strong variability on a yearly time scale in the 1970s and 1980s, seen in Fig. 4.

It turned out that the annual peak has a strong influence on the variance between 90 and 400 days. The variance between 90 and 350 days (thus excluding the annual peak) also shows a maximum in the period 1970–1989, but not as pronounced as the variance between 90 and 400 days.

Qualitatively, the spectral analysis gives results comparable to the study of the standard

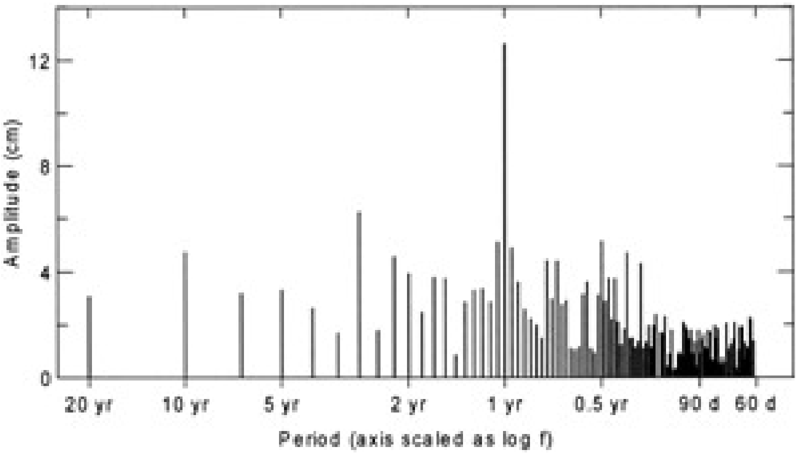

Fig. 7. Sea level amplitude spectrum, calculated from the detrended time series of the monthly means at Helsinki, years 1980–1999. The annual cycle is distinctly visible.

deviations. Short-term fluctuations have changed less, but the results suggest an increasing trend on time scales longer than three months in the 1940s–1980s. (Table 4)

Annual spectral peak

Ekman and Stigebrandt (1990) studied the annual spectral peak based on the monthly sea level data from Stockholm, Sweden. They used consecutive 20-year periods in their calculations. According to their results, the amplitude of the annual sea level cycle has increased significantly, at the 99% level, over the years 1825–1984. Especially the last 20-year period of 1965–1984 showed a distinct increase in the amplitude of the annual peak.

A similar analysis was carried out for the data from Pietarsaari, Helsinki and Hamina. The amplitude spectra were calculated as in Eq. 1, for $N = 240$ and $\Delta t = 365.24/12$ days. However, since we were specially studying the annual period, and since the length of the time series used (20 years) is an integral multiple of the period studied, no special window was used. Thus $w(n) \equiv 1$ in Eq. 1.

An example of an amplitude spectrum thus obtained is presented in Fig. 7. The amplitudes obtained for the annual peak are given in Table 5, and the time development is illustrated in Fig. 8. Our results are in accordance with those obtained by Ekman and Stigebrandt (1990), i.e. the amplitude of the annual peak has been increasing. It was especially high for the years 1970–1989. Between 1930–1949 and 1970–1989,

Table 5. Amplitude and phase angle of the annual sea level peak at Pietarsaari (Pietars.), Helsinki and Hamina, as calculated from the time series of the monthly mean sea level. 20-year periods overlapping by 10 years, for 1910–1999.

Years	Amplitude A (cm)			Phase φ (months)		
	Pietars.	Helsinki	Hamina	Pietars.	Helsinki	Hamina
1910–1929	–	10.1	–	–	6.10	–
1920–1939	–	10.5	–	–	6.20	–
1930–1949	10.5	8.4	9.2	5.49	6.04	6.00
1940–1959	11.0	10.2	11.1	5.69	5.99	6.02
1950–1969	11.9	11.8	12.7	5.82	5.99	6.06
1960–1979	13.4	13.0	14.1	5.64	5.88	5.91
1970–1989	17.0	16.6	17.9	5.29	5.48	5.49
1980–1999	13.3	12.6	13.5	4.71	4.88	4.93

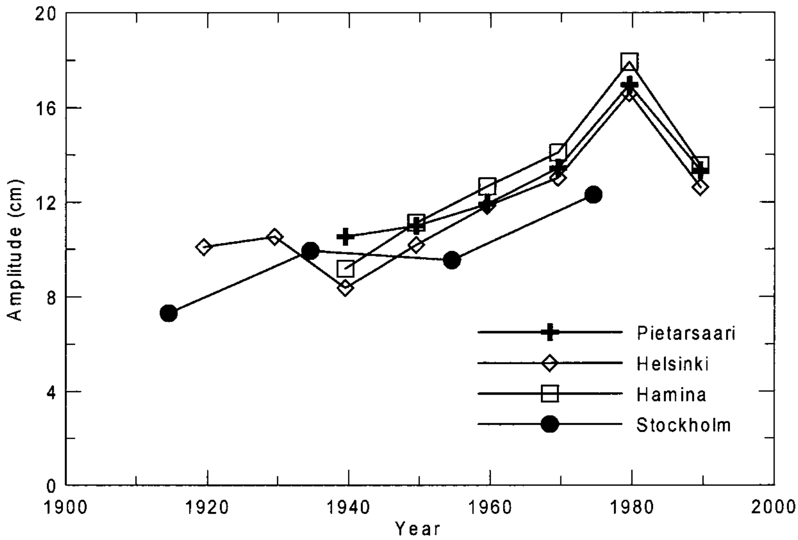

Fig. 8. The amplitude of the annual peak in the Fourier spectra, calculated for overlapping 20-year periods using monthly mean sea levels at Pietarsaari, Helsinki and Hamina. The data for Stockholm are from Ekman and Stigebrandt (1990).

the amplitude almost doubled. As for the present time, however, our data extend to 1999 and the most recent years show a lower amplitude again.

We may note that, when using periods of 20 years, the results depend somewhat on the (arbitrary) choice of a period. The general increasing trend in the amplitudes is to be found, however, even if the periods are chosen another way.

In addition to the amplitudes, Table 5 lists the phase angles of the annual peaks in the different 20 year periods. Using the amplitudes and phases given, the annual cycle of the sea level h is represented as

$$h(\tau) = A\sin\left[(\tau + \varphi)\frac{2\pi}{T_y}\right] \quad (5)$$

where A is the amplitude and φ the phase angle. Time τ is given in months, starting from the beginning of a year. T_y is the period, being 12 months for the annual cycle. A phase of 6.0 months thus corresponds to the annual maximum occurring at the end of September and the annual minimum occurring at the end of March.

It can be seen from Table 5 that this angle has diminished at all the stations considered. In practice, this means that the annual mean cycle of the sea level has shifted forward. Accordingly, the sea level currently tends to be at its highest one month later than 50–70 years ago. According to a *t*-test, however, this shift is not statistically significant for any of the stations separately.

Monthly mean sea levels

The changes that have occurred in the annual cycle can be further examined from the behaviour of monthly mean sea levels. This is in fact how Ekman (1998b) continued his studies into the secular increase found by Ekman and Stigebrandt (1990). Ekman (1998b) used Stockholm monthly sea level data 1825–1984, in 20-year periods detrended by the corresponding average of annual means. He considered sea level variations in wintertime, and found secular changes of sea level that were statistically significant at the 99% level: an increase in December–January and a decrease in February–March. We found that the corresponding changes are not statistically significant for the Hanko sea level time series 1887–1984 (significances 77% and 97%) or 1887–1999 (significances 88% and 44%). Apparently the significances found by Ekman come from the oldest data of the 1825–1984 Stockholm time series.

In addition, we studied the trends of monthly means one by one. The observed monthly mean sea levels were first referred to the annual mean sea level by subtracting that from the monthly means. We found, with just a few exceptions, that the monthly means during April–October have decreased and those in November–March have increased. Generally, these trends for individual stations cannot be considered statistically significant, because only a minority of them exceeds a 90% significance. Their sign is also dependent on the exact choice of the years considered. As an overall result, we did not find reliable trends in the monthly means of Finnish sea level data.

To further study the phase shift found, the interannual occurrences of minimum and maximum monthly means were studied. It appears that these extreme monthly means tend to occur fairly uniformly along the coast of Finland, and therefore only Helsinki was studied further, being the station with the longest uninterrupted series of monthly means. The observation period of 1904–1999 was divided into four periods of 24 years. For each period, the number of annual minimum or maximum monthly means occurring in each month were calculated (Table 6).

As can be seen from Table 6, the maximum monthly means seem to occur in November–January more frequently nowadays than before. On the other hand, the occurrence of maximum monthly means in February, August and October was more common in the earliest decades. Generally, the maximum monthly means seem nowadays to be concentrated in the autumn and winter months, whereas in earlier decades there were some occurrences in spring and summer as well. For the minimum monthly means, occurrences in March and May seem to have become rather more frequent than before during the most recent periods, whereas occurrences in December seem to have been more common in the earlier decades.

It is interesting to compare these results with the phase angles of the annual cycle obtained above. A phase angle of 6.1 months, typical for the decades before 1950 at Helsinki, corresponds to a maximum occurring in late September and a minimum occurring in late March. A phase angle of 5.4 months, typical for the decades after 1960, corresponds on the other hand to a maximum in October and a minimum in April. A real actual occurrence of an extreme month cannot, of course, be defined by a sinusoidal mean cycle only.

According to Ekman (1998b), the maximum monthly mean in Stockholm has shifted from July–August to December. Our results are in accordance with this, suggesting an increase in the frequency of maxima in November–January and a decrease in August.

Reference levelling and mean sea level

The studies of probability distributions and

Table 6. The number of annual maximum and minimum monthly means occurring in specific months at Helsinki.

	Maximum monthly means				Minimum monthly means			
	1904–1927	1928–1951	1952–1975	1976–1999	1904–1927	1928–1951	1952–1975	1976–1999
Jan.	5	3	6	7	1	1	2	0
Feb.	3	2	0	2	2	7	4	2
Mar.	1	0	1	1	7	3	8	6
Apr.	0	3	0	0	0	4	2	3
May	0	0	0	0	6	3	6	7
Jun.	0	0	0	0	2	1	0	1
Jul.	1	1	1	0	1	0	0	0
Aug.	4	1	2	0	0	0	0	1
Sep.	2	3	1	3	0	1	1	0
Oct.	1	8	4	1	1	1	0	2
Nov.	2	1	4	5	1	1	0	1
Dec.	5	2	5	5	3	2	1	1

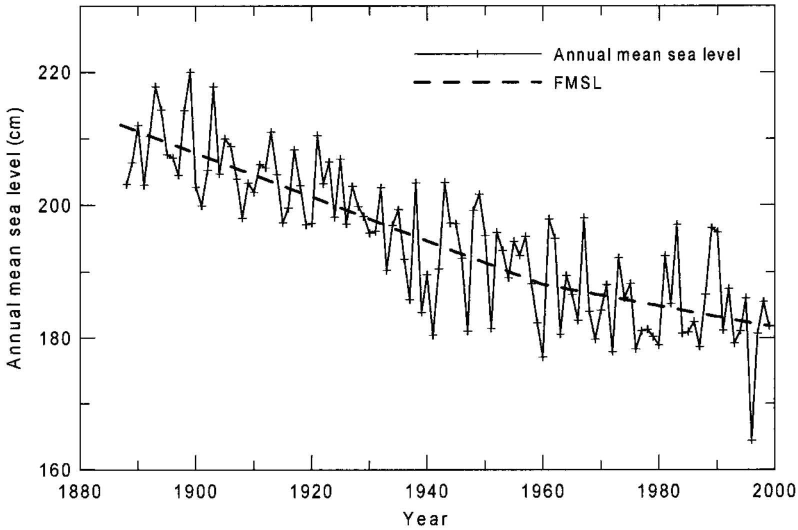

Fig. 9. Annual mean and fitted mean sea level (FMSL) at Hanko, referred to the FIMR standard bedrock-bound reference level.

extreme values above were conducted by referring the sea level observations to the annual mean sea levels calculated from the observations. It is interesting to compare them, however, with results obtained using another kind of reference levelling. This reference level should correspond to the long-term mean sea level. However, it is not a trivial task to define the concept of "average sea level" physically.

In the field, the tide gauge network is referred to the Finnish high-precision levelling system (N60) by regular levelling surveys carried out by FIMR and the Finnish Geodetic Institute. As is generally known, the mean sea level in the northern Baltic Sea has had a general decreasing trend with time. This is mainly due to the land uplift (Lisitzin 1966b, Vermeer *et al.* 1988). The sea level has lowered significantly over the period considered, up to the 1970s (Fig. 9). Therefore, a fixed bedrock-bound reference level cannot be used as a zero level.

A mean sea level following the concept of "a fitted mean sea level (FMSL)" was, therefore, constructed. It was determined independently for each tide gauge station as a linear regression in two parts with respect to time. The first regression line was fitted to the annual mean sea levels up to 1960, and the latter one onwards from that. The latter part was fitted to coincide with the first one, making the FMSL continuous. In Fig. 9, we see the fitted mean sea level for Hanko. The FMSL method was selected after testing several different ways of doing the mean sea level fit.

It is not possible to find out an absolutely right way of doing the fit. The results calculated using such a reference level might thus be somewhat questionable. However, to estimate the effects of the choice of a reference level, we repeated the calculations of probability distributions and extreme values by referring the observations to FMSL.

The results obtained are in agreement with those obtained above. The probability distributions have changed and the maxima have been increasing, while the minima have not changed. The individual trends and their significances apparently differ somewhat, but their overall behaviour remains unchanged.

The sea level and NAO index

In order to roughly explore the connection between climate and the behaviour of the sea level, correlations between the sea level and air pressure gradients were studied. As an air pressure index we used the common concept of the North Atlantic Oscillation index (NAO). The NAO used is the longitudinal surface air pressure difference between Ponta Delgada, Portugal, and Stykkisholmur, Iceland (Icelandic Meteorolog-

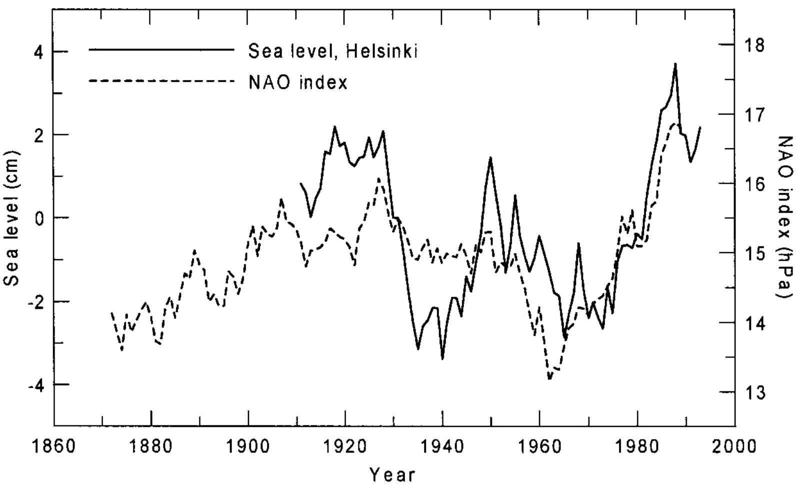

Fig. 10. Detrended annual mean sea level at Helsinki and the annual mean NAO index, 15-year floating averages.

ical Office, Jónsson T., NAO data, monthly means 1865–1996).

The annual means of the NAO index and the detrended annual mean sea level on the coasts of Finland (i.e. in the Baltic Sea) seem to have an overall apparent positive correlation. This can be seen from Fig. 10, in which the long-term variations in both quantities well resemble each other. The significance for the correlation between the annual mean NAO and the annual mean sea level exceeds 99.9% at every tide gauge station (Table 7). (The detrending of annual mean sea levels in this context means removal of a simple linear trend, not the FMSL.)

Generally, we may consider it as plausible that the meteorological forcing, and winds having a large west-to-east component, associated with a high NAO index (anomaly), tend to keep the Baltic sea level high.

An interesting finding was that the annual standard deviation of the sea level also seems to correlate with the NAO index (Fig. 11). The correlation is not as strong as that between the mean sea level and NAO. The correlation

Table 7. Correlation between the annual mean NAO index and the mean sea level as well as the annual standard deviations of sea level. "R^2" gives the square of the correlation coefficient and "t" is the value of t-test coefficient. "Sign." gives the statistical significance.

Station	Annual mean sea level vs. annual mean NAO			Annual standard deviation of sea level vs. annual mean NAO		
	R^2	t	Sign. (%)	R^2	t	Sign. (%)
Kemi	(0.332)	(5.98)	(99.9)	(0.096)	(2.77)	(99)
Oulu	0.275	5.22	99.9	0.102	2.86	99
Raahe	0.307	5.64	99.9	0.101	2.84	99
Pietars.	0.307	5.69	99.9	0.086	2.63	99
Vaasa	0.273	5.24	99.9	0.076	2.45	98
Kaskinen	0.268	4.99	99.9	0.067	2.21	97
Mäntyl.	0.231	4.58	99.9	0.068	2.26	97
Rauma	0.244	4.47	99.9	0.053	1.86	93
Turku	0.229	4.66	99.9	0.072	2.38	98
Degerby	0.199	4.20	99.9	0.041	1.74	91
Hanko	(0.145)	(4.26)	(99.9)	(0.043)	(2.18)	(97)
Helsinki	0.211	4.93	99.9	0.061	2.44	98
Hamina	0.197	4.03	99.9	0.108	2.83	99

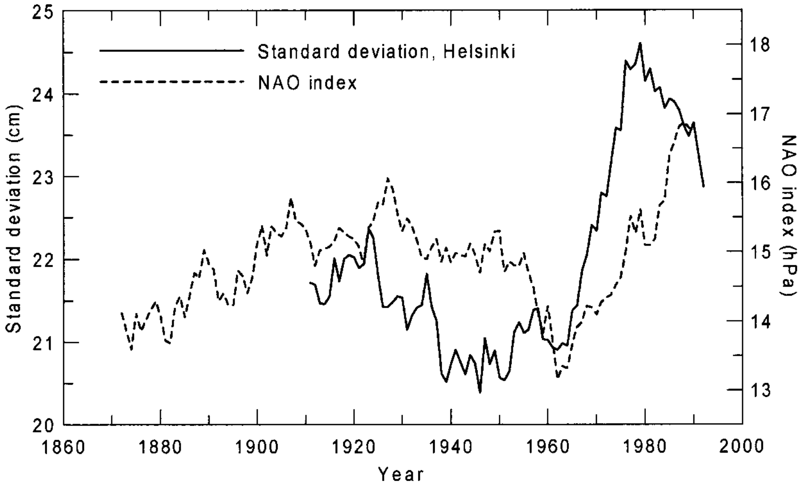

Fig. 11. Annual standard deviations of sea level at Helsinki and the annual mean NAO index, 15-year floating averages.

between the sea level standard deviation and the NAO is only significant at the 91%–99% level, depending on the tide gauge station considered (Table 7).

A detrended annual mean sea level and sea level standard deviation do not show any mutual correlation. This should mean that they both correlate with the NAO independently.

The correlation between the monthly means of the NAO index and the monthly mean sea level is especially strong in winter — from December to March. Usually, the correlation is strongest in the northern part of the Gulf of Bothnia. No apparent correlation was found between the monthly values of the NAO and the sea level standard deviations in a given month. The average standard deviations of 8-day periods, however, correlate slightly with the winter (December–March) mean NAO index. The significance for this correlation exceeds 95% at ten tide gauges, being lower for Turku, Degerby and Hanko in the Baltic Sea nodal area.

The NAO index we used was defined as a simple pressure difference. Other authors (Jones *et al.* 1997) calculated the NAO index by first normalizing the pressures in a suitable way. The areal pressure variations around Iceland are at least twice as large as those in the Azores. Thus, a simple pressure difference between these two locations tends to bias the NAO in favour of the Icelandic site, even though this kind of an index is a direct measure of the strength of the westerlies (Jones *et al.* 1997).

The 15-year floating average of the Jones *et al.* (1997) NAO index calculated from the winter months only has been shown to have an even higher correlation than the NAO index used above with the 15-year detrended floating average of the sea level in Hanko (Kahma 1999). We, therefore, repeated the above calculations using the NAO index given in Jones *et al.* (1997), defined as the difference between normalized air pressures in Gibraltar and southwest Iceland. An index defined in this way correlates with annual mean sea levels in a way that is in accordance with the results above. There is no apparent correlation between sea level annual standard deviations and a normalized NAO index, however. This suggests that the correlation between the NAO index and the sea level standard deviations is mostly caused by variations in the air pressure in the Icelandic (northern) areas.

Conclusions

This study was based on data from the set of 13 tide gauges along the coasts of Finland. The results reveal changes in the Baltic Sea water level and its variability during past decades. Changes were detected in probability distributions, extremes, standard deviations and spectral peaks.

An increasing overall trend was found in variability on a yearly scale, but the increase is not linear and seems to peak in 1980 (Fig. 4 and Table 2). The variability on shorter time scales shows significant decadal changes in the wintertime, but no statistically significant overall trend.

As for the extremes (Fig. 3 and Table 1), the maxima have increased significantly; the increase in the maxima is especially evident, and proportionally greatest, in the nodal area of the specific (uninodal) oscillation of the Baltic Sea, i.e. in the region of Rauma, Turku and Degerby. The above might suggest the changes in maxima to be related to spatially and temporally larger-scale meteorological and hydrological phenomena rather than to local storms. The latter cause pronounced extremes at the closed ends of the bays of the Gulf of Finland and Gulf of Bothnia. As for the lowest sea levels, no essential trends in minima were detected. Generally, however, the sea level height distribution has become broader i.e. illustrating an increase in the occurrence of high sea levels especially (Fig. 2).

The changes in the variability have been most pronounced in 1960–1980, during which period e.g. the standard deviations and spectral amplitudes increased most dramatically. This coincides with the period when the earlier steady long-term trend in mean sea level changed its behaviour (Fig. 9). The reason is likely to be connected with long-term climatic variations, such as an increase in the NAO, which has an overall correlation with the mean sea level (Fig. 10). Except for the transition in 1960–1980, the correlation between the NAO index and short-term variability in sea level is not that clear. As a first explanation for the NAO correlations we may note that a large meridional NAO index represents pronounced zonal geostrophic wind forcing from west to east. This favours a flow of water from the North Sea into the Baltic Sea and atmospheric forcing in the area.

The amplitude of the annual spectral peak in the sea level shows an increase (Fig. 8). This is in accordance with the finding of an increase in the amplitude of the annual cycle of the sea level by Ekman and Stigebrandt (1990), using the Stockholm data from 1825–1984. However, our data covering the most recent years show the distinct increase up to the period 1970–1989 but a pronouncedly lower amplitude again for the latest years. In addition to the amplitude increase, the annual cycle of sea level seems to have been shifted from the early 1900s by approximately one month.

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