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An Improved Estimate for the Long-Term Mean Sea Level on the Finnish Coast

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Abstract

The main factors affecting the long-term mean sea level on the Finnish coast are the land uplift, the rise of the global mean sea level and the water balance of the Baltic Sea. The sea level variability on a timescale of a year and longer correlates significantly with the North Atlantic Oscillation (NAO) index. Thus, it is possible to express the water balance variability with the aid of the observed or predicted values of the NAO index. This correlation is used to calculate a hindcast for the long-term mean sea level at the Finnish sea level stations. This hindcast follows the observed mean sea levels more closely than the theoretical mean sea level, an estimate used for practical purposes by the Finnish Institute of Marine Research. The possibility to calculate estimates for the future mean sea levels on the Finnish coast is discussed. The differences in the correlation between the NAO index and the mean sea level in different parts of the Baltic Sea are also briefly studied. The mean slope of the Baltic Sea surface is found to correlate with the NAO index.

Key words: sea level, Baltic Sea, water balance, NAO index, theoretical mean sea level

1. Introduction

The long-term mean sea level on the Finnish coast continuously changes with time. It is important to understand this change and the factors affecting it. Knowledge of the past and present mean sea level is needed for studies of short-term sea level variability, in order to exclude the effects of long-term changes from the short-term variability mainly caused by meteorological processes. This kind of mean sea level is especially needed in the studies of extreme values and probability distributions (*Johansson et al.,* 2001). Understanding the mechanisms affecting the mean sea level also makes it possible to predict its behaviour in the future – an issue that is of practical importance for construction activities and planning.

The mean sea level has been studied at the Finnish Institute of Marine Research (FIMR) for several decades. Earlier studies include those of *Hela* (1953) and *Lisitzin* (1964, 1966a). The purpose of *Lisitzin* (1964) was particularly to determine the land

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uplift values for the Finnish tide gauges. The effects of various factors, e.g. meteorological and hydrological factors and the nodal tide, were considered and their influence eliminated before calculating the linear trend of sea level observations. Thus, the secular change in the sea level was obtained, but since the rise in the global sea level was not taken into account, the absolute rates of land uplift were not determined. The expectation values thus obtained for the annual mean sea levels – together with some values calculated by *Hela* (1953) – have been used at FIMR for the definition of the theoretical mean sea level up to 1990.

More recently, *Vermeer et al*. (1988) recomputed the relative land uplift rates by using a plane fit method. In their study, as in the earlier studies of *Lisitzin* (1964, 1966a), it was assumed that the behaviour of the mean sea level is linear. *Vermeer et al.* (1988) discussed the effect of the Baltic Sea water balance and its relation to the intensity of westerly winds. Attempts to correct for the water balance were not successful, but for the first time the effect was taken into account in the error limits given for the relative land uplift values.

The correlation between the air pressure patterns over the North Atlantic Ocean and the Baltic Sea level was reported by *Heyen et al.* (1996). The high correlation between sea level variations longer than a year and the North Atlantic Oscillation index NAO was presented by *Kahma* (1999), and *Johansson et al.* (2001). *Gustafsson and Andersson* (2001), on the other hand, used the south–north air pressure gradient over the North Sea, and were able to explain most of the sea level variations for periods shorter than a year.

Andersson (2002) investigated the correlation between the Baltic Sea level and the NAO index, as well as a regional air pressure index. She found a correlation between the NAO index and the sea level in winter. By using the regional air pressure index instead of the NAO index, an even better correlation was found.

In this study, the previous studies of *Lisitzin* (1964) and *Vermeer et al.* (1988), and the mean sea level estimates based on their results are first reviewed. Second, a new estimate for the mean sea level is calculated. To calculate this estimate, the effect of the Baltic Sea water balance is taken into account, using the NAO index to describe it. The possibility to predict the future mean sea level is also discussed. Finally, we extend the calculations to other coasts of the Baltic Sea, and briefly consider the spatial variations in the correlation between the NAO index and the sea level.

2. *Finnish sea level data*

The FIMR operates 13 tide gauges on the Finnish coast (Fig. 1a). The oldest of the tide gauges – Hanko – has been operating since 1887, and most of the others for at least 80 years. In this study, some Swedish, German, Polish and Russian sea level stations are also briefly studied. They are thus included in Fig. 1a as well. The sea level data for these stations were obtained from the Permanent Service for Mean Sea Level (PSMSL, *Spencer and Woodworth,* 1993), and will be explained in more detail in

Section 6. Fig. 1b shows the two air pressure observation sites used for determining the NAO index used in this study.

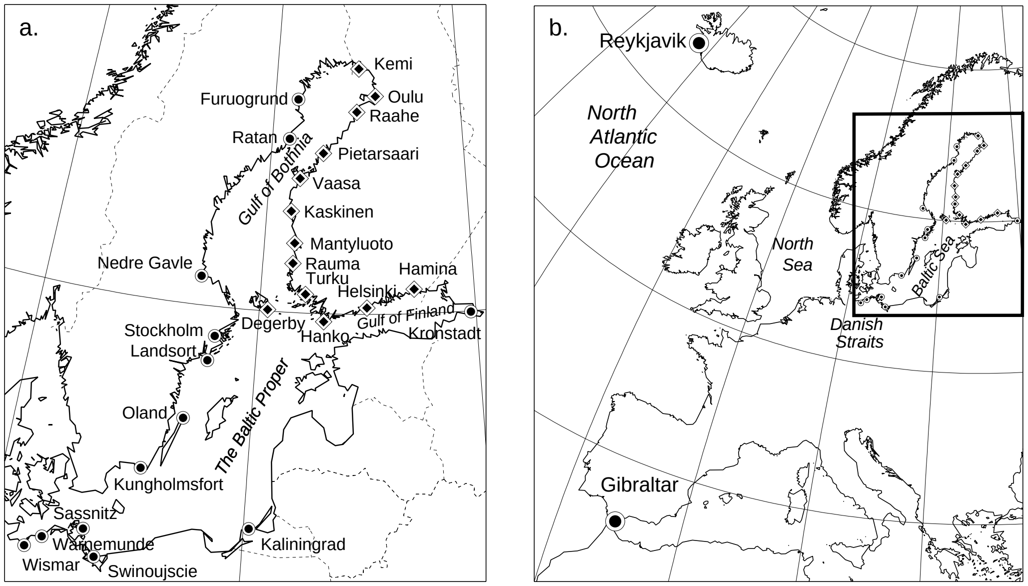

Fig. 1. a) Locations of the Finnish tide gauge stations (diamonds), as well as some Swedish, German, Polish and Russian stations (circles). b) The atmospheric pressure observation sites used for the determination of the NAO index, as a difference between normalized atmospheric pressure anomalies at Gibraltar and south-west Iceland (*Jones et al.,* 1997).

The sea level observations from the Finnish tide gauges have been stored in a database at 4-hour intervals up to 1970, and hourly after that. Since only annual mean sea level values are used in this study, this difference in the time interval should not have any effect on the results.

For various reasons, the Finnish sea level data series contain gaps with no observations, extending from some hours up to 33 months. These gaps can be patched by interpolation using the observations of adjacent stations. The interpolation has been found to be a reliable method, especially in the case of long-term means. Long-period variations of sea level (from months up to several years), often related to changes in the total water volume of the Baltic Sea, are highly correlated between adjacent stations on the Finnish coast. The interpolated values, being few in number, are thus included in this study as if they were real observations. After patching by interpolation, no gaps were left on the time series of annual mean sea levels at any of the Finnish tide gauges.

Other possible sources of erroneous values have also been taken into account and corrected. A more detailed description was presented by *Johansson et al.* (2001).

The Finnish sea level values are measured in relation to a bedrock-bound reference level (*Lisitzin,* 1966b). This reference level was defined to be 200 cm below the estimated mean sea level of 1920. The reference level obtained this way was levelled to the benchmarks of the NN elevation system, which was the first of the geodetically levelled height systems in Finland (*Lisitzin,* 1966b). Nowadays, the benchmarks are bound to the elevation system N60.

3. *Theoretical mean sea level*

The original reference level, as well as the geodetic elevation systems, is bound to the bedrock. Because the sea level on the Finnish coast, as measured relative to the bedrock, changes with time, these reference levels or a constant value related to them are not suitable for representing the long-term mean sea level.

A simple way of determining the long-term mean sea level is to calculate a moving average of suitable length from the observations. This is not very practical, however, because it is possible to calculate a moving average only with a delay of several years, and there is no reliable way to extrapolate it ahead.

From the observations, it is reasonable to estimate that the long-term change of sea level is roughly linear. A simple linear trend – calculated from the observations – is also more practical than a moving average, since it is easily extrapolated ahead.

The FIMR has traditionally defined a certain kind of linear estimate of the mean sea level for practical purposes – construction activities, administrative and juridical issues. This time-dependent expectation value of the mean sea level is called the theoretical mean sea level, usually abbreviated MW (mean water). Up to 1990, the MW was assumed to behave linearly through the whole time series of observations. The annual change of the MW for each tide gauge was defined separately from the observations, based on the work of *Lisitzin* (1964) and *Hela* (1953). The theoretical mean sea level of 1960 (*Lisitzin,* 1966b) was used as a basis for the calculations.

At the end of the 1980s, *Vermeer et al.* (1988) determined the linear annual change of the mean sea level, using a considerably longer time series of observations than the ones used by *Lisitzin* (1964). They fitted a plane to the observed monthly mean sea levels, and thus determined the land uplift values for all the stations together, resulting in high-quality relative values between them. The values obtained were somewhat different from those of *Lisitzin* (1964). From 1990, these new values for the annual change of the MW were adopted. However, the values of the MW up to 1990 were not adjusted according to the updated values since, for practical reasons, keeping the old values unchanged was considered to be more important than their theoretical accuracy (*Vermeer et al.,* 1988).

At the beginning of the 1990s it became evident that the MW was no longer following the observed long-term mean sea level. On average, the observed mean sea level was higher than the MW. To compensate for the deviation, a decision was made to adjust the annual changes of the MW for each tide gauge from 1992 on by subtracting 3 mm/yr from them.

The theoretical mean sea level for Hanko, together with the observed annual mean sea levels, is presented in Fig. 2. The time periods of different annual change values are visible in the MW. The values for the annual change of the MW are summarized in Table 1 for each tide gauge. The MW has been decreasing at all the tide gauges up to

1992. At the latest adjustment, however, the MW turned to rise in the Gulf of Finland, i.e. at Hanko, Helsinki, and Hamina.

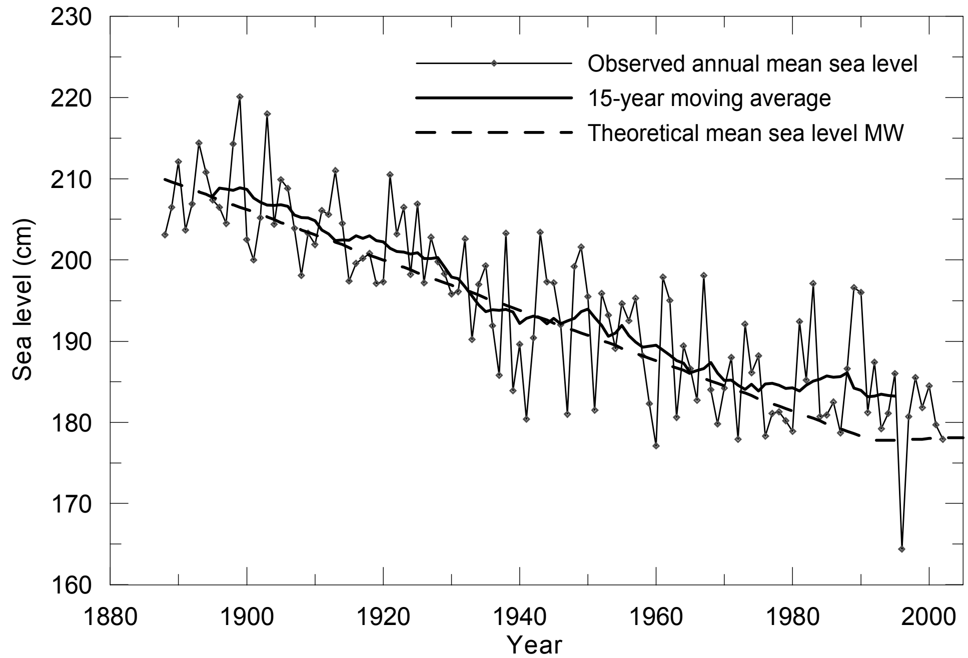

Fig. 2. Observed annual mean sea levels at Hanko, together with their 15-year moving average, and the theoretical mean sea level.

Table 1. Annual change of the theoretical mean sea level at the Finnish tide gauges. A positive value means that the bedrock is rising in relation to the mean sea level, a negative one that it is sinking. The values of the theoretical mean sea level in 1990, relative to the original bedrock-bound reference levels of the tide gauges, are also given.

Tide gauge	Annual change (mm/yr)			MW(1990) (mm) (*Vermeer et al.,* 1988)
	d_1 prior to 1990 (*Lisitzin,* 1964)	d_2 1990–1992 (*Vermeer et al.,* 1988)	d_3 1992–2005	
Kemi	7.30	7.35	4.35	1522
Oulu	7.10	6.90	3.90	1533
Raahe	7.80	7.42	4.42	1470
Pietarsaari	8.20	8.01	5.01	1420
Vaasa	8.00	7.74	4.74	1455
Kaskinen	7.40	7.25	4.25	1500
Mäntyluoto	6.40	6.37	3.37	1555
Rauma	5.90	5.45	2.45	1583
Turku	4.40	4.14	1.14	1697
Degerby	4.60	4.27	1.27	1679
Hanko	3.10	2.73	–0.27	1783
Helsinki	2.50	2.14	–0.86	1825
Hamina	2.20	1.69	–1.31	1849

As can be seen from the moving average in Fig. 2, the MW still cannot reproduce the change in the behaviour of the observed mean sea level beginning in the 1970s. The MW seemingly approaches the observed long-term mean sea level, but the adjustment could not be done in time. The change of the behaviour of the mean sea level in the 1970s was visible in the observation data set in the late 1980s at the earliest, and thus the correction of the annual change of the MW could not be made before the beginning of the 1990s.

To summarize, the theoretical mean sea level – at present established up to 2005 – is calculated using the equations:

$$\begin{aligned} &MW(y) = (1990 - y) * d_1 + MW(1990)\,; \quad y < 1990 \\ &MW(y) = (1990 - y) * d_2 + MW(1990)\,; \quad 1990 \le y \le 1992 \\ &MW(y) = (1992 - y) * d_3 + (1990 - 1992) * d_2 + MW(1990)\,; \quad 1992 < y \le 2005 \end{aligned} \tag{1}$$

where y is the year in question, and d_i are the coefficients of annual change (Table 1). The theoretical mean sea level for 1990, denoted by MW(1990) in Eqs. (1) and Table 1, was calculated by *Vermeer et al.* (1988) from the theoretical mean sea level of 1960 (*Lisitzin,* 1966b), using the annual change d_1 (*Lisitzin*, 1964).

4. Factors affecting the mean sea level

The theoretical mean sea level – even with its small inaccuracies – is sufficient for practical use. For scientific research, however, a mean sea level following the observed long-term mean sea level is needed, preferably for the whole time series of sea level observations. It is also useful to define a mean sea level that can be predicted for the future.

In order to study the behaviour of the mean sea level, the main factors affecting it must be identified. The two most important factors affecting the long-term mean sea level on the Finnish coast are the land uplift and the rise in the global mean sea level. These two factors act in opposite directions, thus partly cancelling each other. The balance between them determines whether the sea level on the Finnish coast is generally rising or falling with time. In addition, variations in the water balance play an important role in determining the mean sea level of the Baltic Sea, by changing the total volume of water. Below, all these three factors will be discussed briefly.

In addition to these factors, there are also others that apparently affect the mean sea level in the Baltic Sea. The mean temperature and salinity of seawater affect its volume and thus the surface level. The effect of these factors can, however, be considered to be small in comparison to the abovementioned three factors, and they are thus ignored in this context. River run-off adds fresh water to the sea, thus affecting the total water volume as well as the salinity. The river run-off is discussed in more detail below, in connection with the water balance. Long-period astronomical oscillations – e.g. the nodal tide of 18.6 years (*Lisitzin*, 1974) – also might have a small effect. However, spectral analyses of the sea level time series on the Finnish coasts have not revealed any significant oscillations with periods longer than one year (*Vermeer et al.,* 1988), and a possible effect of tidal oscillations can thus be ignored.

4.1 The rise in the global mean sea level

A regional composite of ten sea level time series from west-central Europe, as obtained from *Gornitz* (1995), is presented in Fig. 3. This time series can be taken to represent approximately the large-scale mean sea level affecting the Baltic Sea – called "the global mean sea level" in this context. In the 19th century the global mean sea level remained constant. In the 20th century, however, a rise in the global mean sea level has been observed. This rise so far has been linear: no apparent acceleration is visible in the observations.

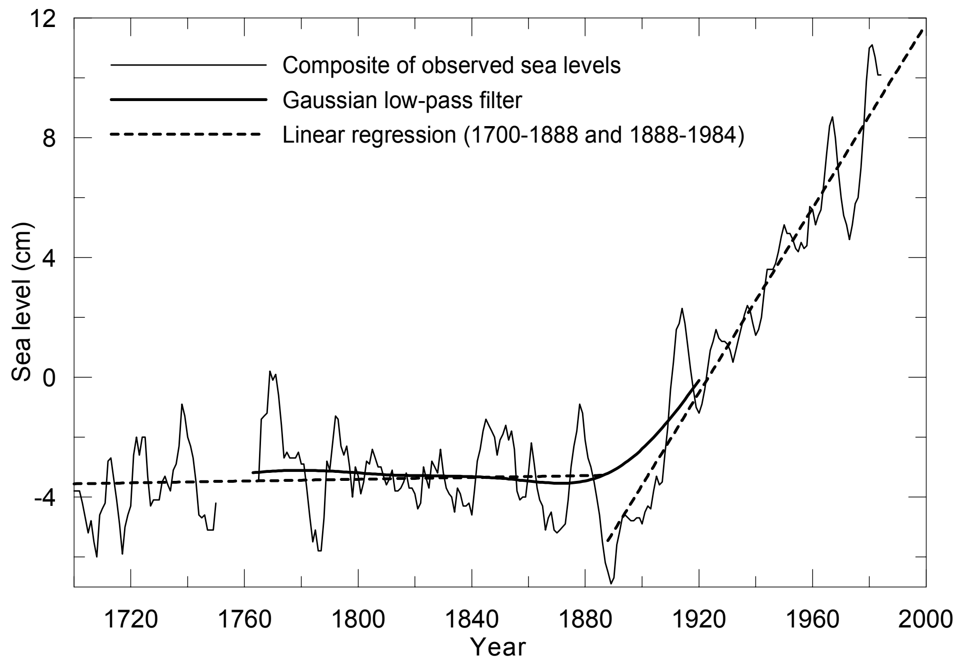

Fig. 3. The sea level from west-central Europe 1700–1984, a regional composite of 5-year moving averages from ten stations (*Gornitz,* 1995). The linear trends before and after 1888, as well as a Gaussian low-pass filtered average, are also presented.

The linear rise during the 20th century amounts to 1–2 mm/yr, according to the Intergovernmental Panel on Climate Change (*Church et al.,* 2001). The IPCC also summarizes estimates presented elsewhere, ranging from 1.2 to 2.4 mm/yr. This global sea level rise of the 20th century, as well as possible explanations for it, are studied in detail in *Church et al.* (2001).

Applying a Gaussian low-pass filter with an averaging interval of 129 years and a standard deviation of 45 years to the time series of Fig. 3, it is possible to determine that the turning point of the trend is around the year 1890. For practical reasons, we chose to use the year 1888 in this study, because it is the first complete year of observations from the tide gauge of Hanko. A linear regression fit applied to the years 1888–1984 results in a value of (1.54 ± 0.11) mm/yr for the trend, whereas during 1700–1888 the trend is (0.01 ± 0.04) mm/yr, the uncertainty limits corresponding to one standard deviation.

4.2 The water balance of the Baltic Sea

The water balance plays an important role in determining the mean sea level in the Baltic Sea. The amount of water in the Baltic Sea, which is a semi-enclosed sea, is principally determined by the inflow and outflow of water through the Danish Straits. The freshwater run-off, precipitation and evaporation have a smaller effect.

The mean sea level in the Baltic Sea can deviate from the mean sea level in the North Sea outside the entrance to the Baltic Sea, because of air pressure and wind conditions around the entrance. The Baltic Sea mean level variability, represented by the sea level observations at Degerby, as reasoned below in Section 6, amounts to ± 50 cm, corresponding to a water volume variability of 365 km^3, the area of the Baltic Sea being 365 000 km^2 (*Lisitzin*, 1974). Due to the water balance variability, the observed annual mean sea level on the Finnish coast may deviate as much as 10 cm from the long-term moving average. This water balance variability is visible even in the 15-year moving averages of the sea level (Fig. 2).

The exchange of water through the Danish Straits is determined by meteorological conditions, such as wind and air pressure over the Strait area. The sea level in the Baltic Sea correlates with the NAO index (*Kahma,* 1999, *Johansson et al.,* 2001, *Andersson*, 2002). This correlation can be roughly explained by a high NAO index being caused by a high air pressure in the south and a low air pressure in the north, on average. This kind of a gradient causes a prevailing geostrophic wind from the west, which in turn pushes more water through the Straits into the Baltic Sea, thus causing a high sea level. The NAO index also correlates with other atmospheric factors like the mean air pressure in the Baltic Sea area, as well as the amount of precipitation. These atmospheric phenomena also affect the mean sea level in the Baltic Sea, thus contributing to the correlation.

The correlation between the river run-off and the sea level was discussed by *Vermeer et al.* (1988). According to their results, the correlation is apparent. The river run-off cannot, however, affect the sea level directly. If that were the case, a high river run-off should occur earlier or at the same time as a high sea level. Instead, an opposite time lag of 0.5 years was found. Since the water level variations hardly can affect the fresh-water run-off, this points to a common external cause, causing both a high sea level, and a high river run-off a half year later. *Vermeer et al.* (1988) proposed this common factor to be the number of cyclonic weather disturbances passing over Fennoscandia and releasing rain and snow, and at the same time causing a wind direction that would cause an inflow into the Baltic Sea. These kind of atmospheric phenomena might also be correlated with the NAO index.

There are several different ways to define the NAO index. In this study, we use a normalized index defined by *Jones et al.* (1997), calculated as a difference between normalized atmospheric pressure anomalies at Gibraltar and south-west Iceland (Fig.

1b). Our calculations have shown that an index defined this way and averaged over the winter period December–March correlates with the sea level on the Finnish coast better than other indices, such as a simple pressure difference between southern (Azores) and northern (Iceland) areas.

In Fig. 4, the annual values and 15-year moving averages of the NAO index as well as the sea level at Hanko are presented. The similarity in the behaviour of these two quantities is apparent, even at the annual level. The coefficients of determination (R^2) for the correlation between the NAO index and the mean sea levels at the Finnish tide gauges are given in Table 2, calculated from both the annual values and the 15-year moving averages. The statistical significance for the correlation between the annual values exceeds 99.9 % at every tide gauge. In the case of the 15-year moving averages, the statistical significance is 77–98 %.

Table 2. The correlation between the winter NAO index and the annual mean sea level at the Finnish tide gauges. The coefficient k is the regression coefficient obtained from a linear regression between the annual mean sea level and the winter NAO index. The coefficients were calculated using the method of maximum likelihood, as explained in Section 5 in the text. R^2 is the coefficient of determination. The uncertainty limits of k and k_{15} represent one standard deviation.

Tide gauge	Years of data	Annual means		15-year moving averages	
		k (cm)	R^2	k_{15} (cm)	R^2
Kemi (A)	1923–2002	6.7 ± 1.1	0.40	4.2 ± 4.9	0.64
Oulu (O)	1923–2002	6.6 ± 1.1	0.38	3.5 ± 4.5	0.49
Raahe (B)	1923–2002	6.6 ± 1.0	0.42	4.6 ± 4.8	0.72
Pietarsaari (P)	1922–2002	6.4 ± 1.0	0.44	4.9 ± 5.1	0.77
Vaasa (V)	1922–2002	6.1 ± 1.0	0.44	4.4 ± 4.6	0.74
Kaskinen (S)	1927–2002	6.2 ± 1.0	0.44	4.5 ± 4.7	0.73
Mäntyluoto (M)	1925–2002	6.1 ± 1.0	0.44	4.8 ± 5.0	0.68
Rauma (R)	1933–2002	6.1 ± 1.0	0.46	3.9 ± 5.2	0.68
Turku (T)	1922–2002	6.1 ± 1.0	0.44	4.7 ± 4.9	0.70
Degerby (D)	1924–2002	5.8 ± 0.9	0.44	4.4 ± 4.5	0.61
Hanko (H)	1888–2002	5.7 ± 0.8	0.37	4.6 ± 2.9	0.67
Helsinki (E)	1904–2002	6.1 ± 0.9	0.38	5.2 ± 4.0	0.80
Hamina (F)	1929–2002	7.0 ± 1.2	0.37	5.2 ± 5.5	0.60

The coefficients of determination are high enough to permit the estimation of the Baltic Sea water balance with the aid of the NAO index, using a linear dependence. Even the correlation in the annual values is quite high; especially the extreme values tend to coincide. For instance, the lowest value of winter NAO index since 1824 was measured during the winter 1995–1996, the value of the normalized index being –2.32. This coincides with an unusually low annual mean sea level in 1996. At Hanko, this annual mean sea level is the lowest ever measured in relation to the long-term linear trend (Fig. 4).

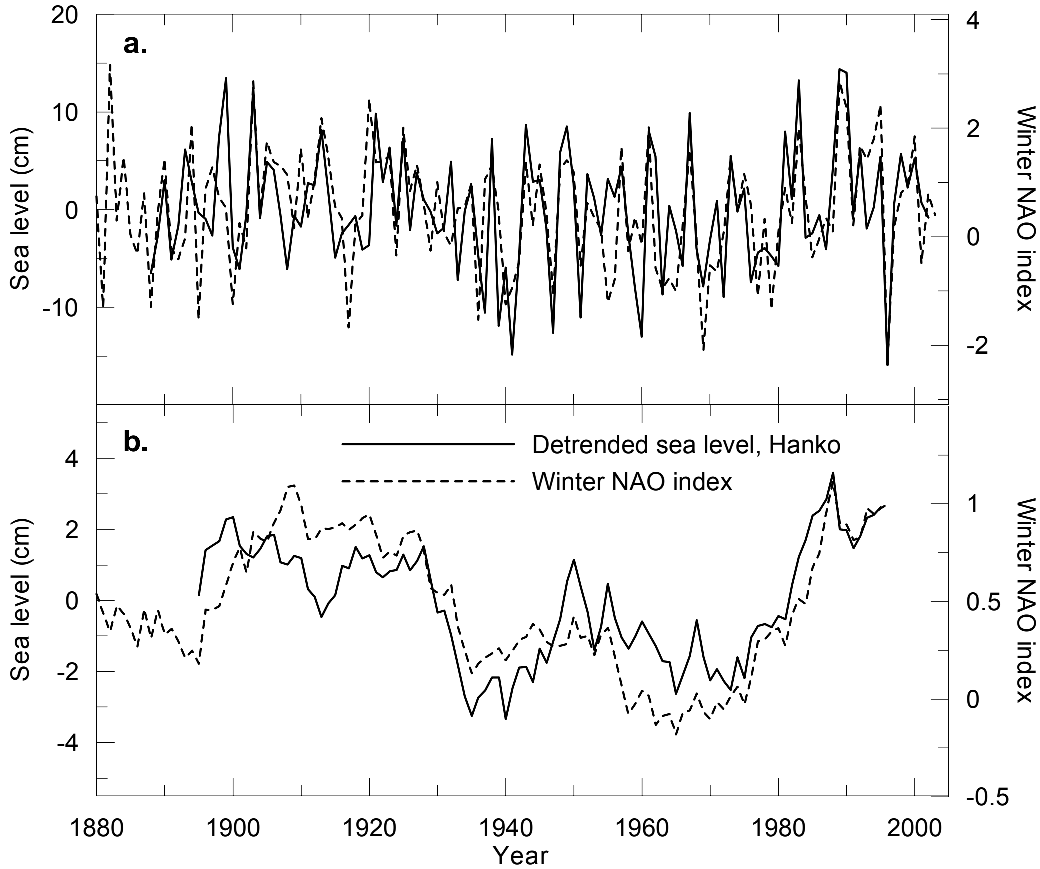

Fig. 4. a) Detrended annual mean sea levels at Hanko and the winter (December–March) NAO index. b) 15-year moving averages.

From the coefficients *k* (Table 2), it can be seen that a variability of one unit in the normalized NAO index corresponds to a variability of 5.7–7.0 cm in the mean sea level. Thus, the total observed variability of the NAO index – between –2.3 and 3.2 – corresponds to approximately 30–40 cm of sea level variability, which is of the same order as the maximal variations of the annual mean sea level values. An apparent regularity in the *k* values with respect to location is also evident – this subject will be discussed in more detail in Section 6.

4.3 Land uplift

The relative rate of land uplift on the Finnish coasts is of the order of 2–8 mm/yr, depending on the location (*Vermeer et al.,* 1988). To obtain the absolute land uplift values, the estimated rate of global mean sea level rise during the 20th century should be added. The land uplift is strongest on the coast of the Gulf of Bothnia, around the tide gauge of Vaasa, and weakest on the coast of the Gulf of Finland.

The land uplift is the effect of postglacial rebound after the melting of the ice sheets over the area. The phenomenon can be modelled and the uplift rate determined. The modelling is complicated, however, and for the purpose of this study it is sufficient to assume that the land uplift is a linear phenomenon during the time interval considered.

From the observed sea level time series, it is possible to determine the relative land uplift or the relative fall in the sea level – that is, the linear movement of the sea level in relation to the bedrock. This can be done by a linear trend fitting, after correction of known factors affecting the results. This was – in principle – the approach used by *Lisitzin* (1964) and *Vermeer et al.* (1988). In their studies, the effect of the water balance remained uncorrected, and was thus included in the uncertainty of the land uplift rates.

5. Improved theoretical mean sea level on the Finnish coast

Taking into account the effects of the global mean sea level, the water balance and the land uplift, the mean sea level at a station *i* on the coast of the Baltic Sea, in relation to the bedrock, can be approximated as:

$$h_i(t) = R_i + h_g(t) - u_{ai}t + k_i N(t) + l_i t + \varepsilon_{hi}(t) \tag{2}$$

where $h_g(t)$ is the global mean sea level as a function of time t. The coefficient u_{ai} is the local absolute land uplift rate, assumed to be constant over time. The portion of the water balance that can be explained by the correlation with the NAO is represented by $k_iN(t)$, $N(t)$ being a measure of the NAO phenomenon and k_i a constant. All the sea level variations independent of the three factors mentioned are included in $l_it + \varepsilon_{hi}(t)$. The long-term mean of $\varepsilon_{hi}(t)$ is assumed to be 0, and it does not have any linear trend with respect to time: the trend is expressed by the term l_it. The trend l_it contains the effect of the possible changes in salinity, for instance. R_i is a levelling constant, dependent on the choice of the bedrock-bound reference level at the station in question.

The NAO phenomenon is represented by the NAO index, a normalized air pressure difference between two locations. The observed NAO index $N_{ind}(t)$ can be formulated as:

$$N_{ind}(t) = N(t) + nt + \varepsilon_N(t) \tag{3}$$

where $N(t)$ represents the phenomenon itself, and $\varepsilon_N(t)$ contains the random variations with a long-term mean of 0 and no trend in time. The possible trend in the difference between the observed and the "real" NAO is represented by the term nt. Assuming that the index $N_{ind}(t)$ truly represents the phenomenon $N(t)$, n can be estimated to be small.

The behaviour of the NAO itself with respect to time can be expressed as:

$$N(t) = N_0 + mt + \mu(t) \tag{4}$$

where N_0 is a constant and the factor m describes the linear trend of the NAO. The residual variations without any linear trend with respect to time are included in $\mu(t)$. Assuming the time series of $N_{ind}(t)$ is long enough to be representative of the long-term behaviour of the NAO, it is possible to determine N_0 and $n + m$ by linear regression, so that the residual $\mu(t) + \varepsilon_N(t)$ has no linear trend and the mean of it vanishes over the period considered. A linear regression of the observed NAO index $N_{ind}(t)$ in 1888–2002 results in a value $n + m = (–0.001 \pm 0.003)$ 1/yr. Thus, no significant trend is actually found. During the years 1933–2002, on the other hand, a slight trend of (0.009 ± 0.006) 1/yr is found.

If only the years 1888–2002 are considered, $h_g(t)$ can be approximated to be a linear function of time, $h_g(t) = Gt$. Thus, by taking this into account and combining Eqs. (2) and (4), we get:

$$h_i(t) = (R_i + k_i N_0) + (k_i m + G - u_{ai} + l_i)t + k_i \mu(t) + \varepsilon_{hi}(t) \tag{5}$$

where G is a constant, describing the rate of the global mean sea level rise.

The linear trend can be eliminated from Eq. (5) by linear regression. The two last terms of Eq. (5) do not contain any linear trend, and thus the residual is:

$$h_{2i}(t) = k_i \mu(t) + \varepsilon_{hi}(t) \tag{6}$$

The residuals $h_{2i}(t)$ and $\mu(t) + \varepsilon_N(t)$ do not contain any linear trend, and thus it makes sense to calculate a linear correlation between them. If the three terms $\varepsilon_N(t)$, $\varepsilon_{hi}(t)$ and $\mu(t)$ are independent of each other, the regression factor k_i is obtained directly from the linear fit. These coefficients k_i for the Finnish tide gauges were presented in Table 2.

Neither of the two residuals is a direct cause of the other one – both can be considered to be affected by a common background process, $N(t)$. Thus, neither of them can be considered to be error-free when calculating a regression. In this case, the regression coefficient is obtained by calculating the linear regression using the maximum likelihood effective variance method. In this method, the uncertainty in both variables is taken into account. Because the true uncertainties of $h_{2i}(t)$ or $\mu(t) + \varepsilon_N(t)$ are unknown, they have been approximated by the standard deviations of their time series in this study. This implies that the relative uncertainties in both variables are of the same order.

After determining the coefficient k_i, the effect of water balance can be corrected from the sea level time series, yielding a NAO-corrected mean sea level $h_i'(t)$:

$$h_i'(t) = h_i(t) - k_i N_{ind}(t) = R_i + (G - u_{ai} - k_i n + l_i)t - k_i \varepsilon_N(t) + \varepsilon_{hi}(t) \tag{7}$$

Assuming that the residuals $\varepsilon_N(t)$ and $\varepsilon_{hi}(t)$ are independent and normally distributed, the difference $\varepsilon_{hi}(t) - k_i\varepsilon_N(t)$ is also normally distributed with a mean of 0 and no linear trend. Thus, a linear regression fitted to Eq. (7) yields the coefficients R_i and $\hat{u}_{ri} = u_{ai} + k_i n - l_i - G$, where we denote an estimate of the relative land uplift coefficient by $\hat{u}_{ri}$, and $k_i n - l_i$ is left as an error term. When the coefficients R_i, $\hat{u}_{ri}$ and k_i have thus been determined, it is possible to calculate an estimate for the mean sea level:

$$w_i(t) = R_i - \hat{u}_{ri} t + k_i N_{ind}(t) \tag{8}$$

The estimate $w_i(t)$ corresponds to the mean sea level $h_i(t)$ in Eq. (5), except for the residuals $\varepsilon_{hi}(t)$ and $k_i\varepsilon_N(t)$. With the aid of the coefficients R_i, $\hat{u}_{ri}$ and k_i, it is possible to calculate the mean sea level even for those years when the sea level observations are missing, provided that there are observations or a prediction for the NAO index. Of course, it is also assumed that the land uplift and global sea level rise are behaving linearly. Thus, in practice, Eq. (8) is only applicable to the 20th century – or to the years 1888–2002, as stated above.

It should still be noted, that the trends $k_i nt$ and $l_i t$ may depend on the time period considered. Thus, they appear as error terms when the method is extended beyond the range of observations used to determine the coefficients. They can, however, be estimated to be small.

To reduce the effect of short-term variability and to estimate the long-term behaviour of the mean sea level, a 15-year moving average may be calculated for $w_i(t)$. We call the estimate thus obtained the "improved theoretical mean sea level (iMW)", to indicate that it is a new, more accurate way to calculate an estimate for the time-dependent expectation value of the mean sea level. In Fig. 5, the improved theoretical mean sea level calculated in this way is presented for some of the Finnish tide gauges, along with the theoretical mean sea level presented earlier, as well as the observed annual mean sea levels.

The annual value of the iMW can be determined from the observations only with a delay of 7 years, because it is based on a 15-year moving average. At first, it might thus not seem to be a better alternative for the mean sea level than a simple moving average of sea level observations. However, since the NAO index time series generally date back to the 19th century, it is possible to extend the iMW backwards to the beginning of the 20th century.

For practical purposes, an extension of the iMW up to the present year would be useful. We calculated a rough estimate by assuming that the NAO index $N_{ind}(t)$ during the years 2004–2010 obtains the value observed in 2003: $N_{ind}(2003) = +0.40$. This extrapolation is included in the iMW estimates in Fig. 5, which thus extend up to year 2003. Naturally, the estimate is also based on the assumption that the global mean sea level will rise linearly in 2003–2010, the rate being the same as in 1888–2002.

The actual value of the coefficient G – the global mean sea level rise – has no effect on the results. As long as it is constant – that is, the global mean sea level behaves linearly in time – it can be combined with u_{ai} to yield a coefficient of relative land uplift, which is assumed to be the predominant linear trend in the long-term time series of the mean sea level.

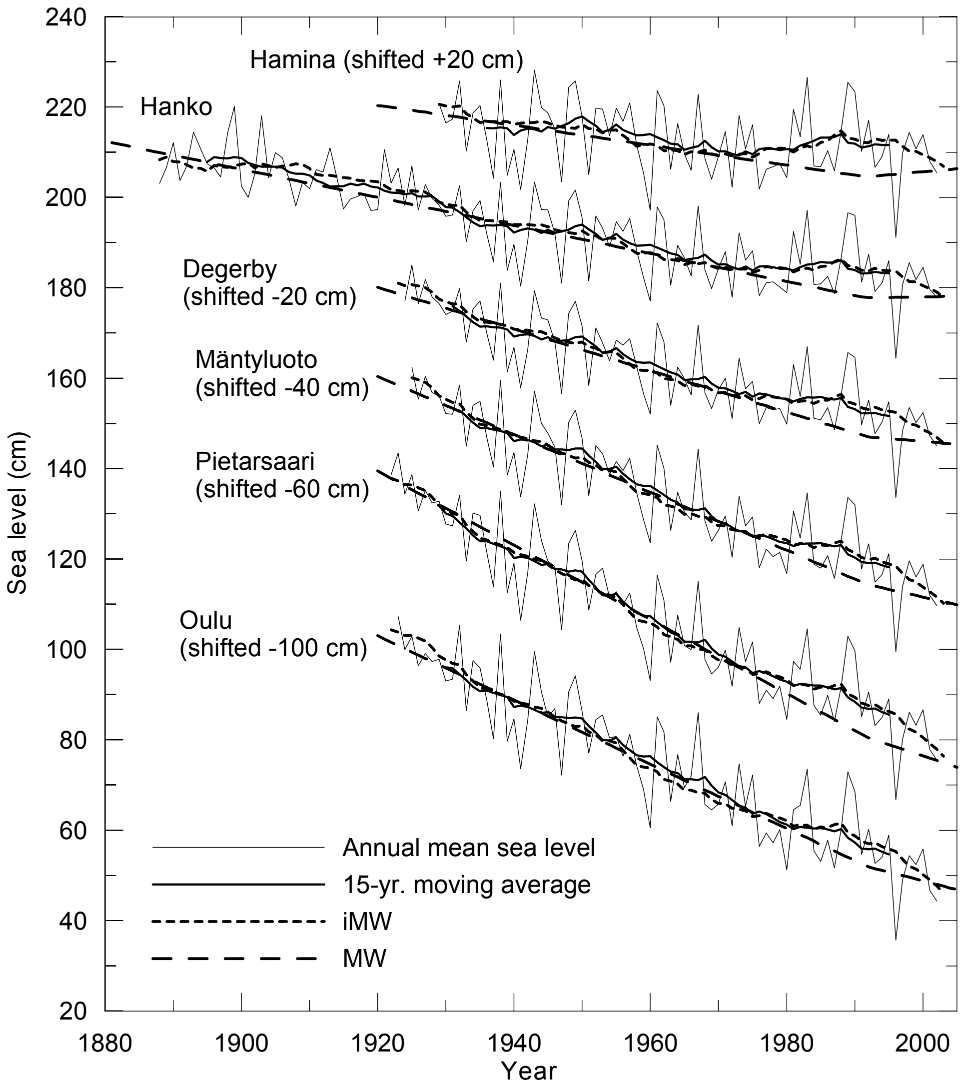

Fig. 5. The improved theoretical mean sea level iMW and the theoretical mean sea level MW at selected Finnish tide gauges, as well as the observed mean sea levels and their 15-year moving averages. The sea levels are given relative to the bedrock-bound reference level. The vertical scale is for Hanko, the other stations have been shifted for clarity.

5.1 *Scenarios for the mean sea level in the future*

Once the coefficients k_i, R_i and $\hat{u}_{ri}$ have been calculated from the observed sea level and the NAO index, it is possible to predict the mean sea level even in the future using Eq. (8) – provided that a prediction for the NAO index is available, from a climate model for example.

The usefulness of the iMW in predicting future sea levels can be tested with the sea level observations of Hanko, forming the longest time series among the Finnish observations. The coefficients R_i, $\hat{u}_{ri}$ and k_i for Hanko were calculated using only the sea level and the NAO index observed in 1888–1970. These coefficients, together with the observed values of the NAO index in 1971–2002, were then used to predict the mean sea level in 1971–2002. It turned out that the mean sea level predicted this way corresponds to the observations almost as accurately as an iMW calculated using coefficients obtained from the whole time series of observations. Thus it seems likely that, if the correlation between the Baltic sea levels and the NAO index does not change its nature in the future, the iMW would be usable for the prediction of the future sea levels.

However, when Eq. (8) was derived, it was assumed that the global mean sea level $h_g(t)$ is rising linearly. In the future, this might not be the case, and some modifications to the equations given above are needed.

In order to take into account the possible non-linear change in the future global mean sea level, Eq. (5) has to be adjusted to give:

$$h_i(t) = R_i + k_i N_0 + h_g(t) + (k_i m - u_{ai} + l_i)t + k_i \mu(t) + \varepsilon_{hi}(t) \tag{9}$$

where $h_g(t)$ is not necessarily a linear function of time. In case we have an estimate for $h_g(t)$, it can be subtracted from Eq. (9), resulting in an equation similar to Eq. (5) except that the coefficient G has disappeared. Thereafter, the methods described above are applicable, resulting in the coefficients k_i, R_i and $\hat{u}_{ai} = u_{ai} + k_i n - l_i$, the only difference being that the method now yields an estimate $\hat{u}_{ai}$ for the absolute land uplift rate instead of the relative one.

Now we get an estimate $w_{i2}(t)$ for the mean sea level:

$$w_{i2}(t) = R_i - \hat{u}_{ai} t + k_i N_{ind}(t) + h_g(t) \tag{10}$$

We noted above that the calculation of $w_i(t)$ is independent of the fairly uncertain value of the global mean sea level rise in the 20th century. Only the assumption of a constant coefficient G was needed. In the case of $w_{i2}(t)$, however, it is necessary to explicitly define the rate of the global mean sea level rise during the 20th century.

6. *Other coasts of the Baltic Sea*

So far, only the Finnish tide gauge data have been considered. It is interesting to consider the possibility of extending the calculations to other parts of the Baltic Sea as well. The factors affecting the mean sea level and the equations derived from them should, in principle, be applicable to the whole Baltic Sea, as the water balance and the global mean sea level rise should affect the entire basin equally. The land uplift values, on the other hand, differ greatly in different parts of the Baltic coastline.

The data for some Swedish, German, Polish and Russian sea level stations were obtained from the Permanent Service for Mean Sea Level (PSMSL, *Spencer and Woodworth*, 1993), and the data for the Russian station Kronstadt from *Bogdanov et al.* (2000). The choice of stations was based on the availability of annual mean sea level data at least from the early 20th century up to the recent years, with gaps no longer than nine consecutive years. The locations of the stations chosen are presented in Fig. 1a.

The correlations between the annual mean sea levels and the winter NAO index for these stations are presented in Table 3. The annual mean sea level series were first corrected for the linear trend caused by the effects of the global mean sea level rise and the local land uplift. The linearity of the global mean sea level rise made it appropriate to limit all the time series to the years 1888–2002, even though there are earlier observations from several of the stations available.

Table 3. The correlation between the winter NAO index and the annual mean sea levels at different stations on the Swedish, German, Polish and Russian coasts. The correlations were calculated for the annual values and 15-year moving averages, to be compared to Table 2.

Station	Years of data	Missing (yrs)	Annual values k (cm)	Annual values R^2	15-year moving averages k_{15} (cm)	15-year moving averages R^2
Furuogrund (U)	1916–2001	2	6.5 ± 1.0	0.42	5.5 ± 5.2	0.87
Ratan (N)	1892–2001	1	6.0 ± 0.8	0.37	2.9 ± 2.0	0.52
Nedre Gävle (G)	1896–1986	–	5.8 ± 0.9	0.29	8.5 ± 8.2	0.46
Stockholm (C)	1889–2001	–	5.2 ± 0.7	0.37	3.5 ± 2.2	0.66
Landsort (L)	1888–2001	–	5.0 ± 0.7	0.37	4.0 ± 2.5	0.86
Ölands norra udde (Ö)	1888–2001	–	4.8 ± 0.6	0.28	3.6 ± 2.3	0.48
Kungholmsfort (K)	1888–2001	–	4.5 ± 0.6	0.33	3.8 ± 2.4	0.69
Sassnitz (Z)	1936–2000	11	4.0 ± 0.8	0.27	0.8 ± 4.2	0.68
Wismar 2 (I)	1888–2000	1	3.0 ± 0.4	0.19	3.0 ± 1.7	0.25
Warnemünde 2 (W)	1888–2000	1	3.1 ± 0.4	0.19	0.4 ± 1.3	0.20
Swinoujscie (J)	1888–1999	6	3.9 ± 0.5	0.19	3.2 ± 2.0	0.32
Kaliningrad (X)	1926–1986	9	6.2 ± 1.2	0.21	2.9 ± 37	0.56
Kronstadt (Y)	1888–1993	–	7.3 ± 1.0	0.26	8.6 ± 5.7	0.50

On average, the Swedish sea level stations behave similarly to the Finnish ones – the coefficient of determination R^2 for the annual values varies from 0.3 to 0.4 at most stations. The stations in the southern Baltic Sea, however, show a markedly weaker correlation with the NAO index. At first, this seems contradictory since we assumed the NAO index to be related to the total water volume of the Baltic Sea, thus affecting all the sea level stations similarly.

It is also evident that the value of the coefficient k_i differs at different sea level stations – which should not be the case if the coefficient represented only the effect of the total water volume of the Baltic Sea. The value of k_i also seems to behave regularly with respect to the location, being largest in the inner parts of the Gulf of Bothnia and the Gulf of Finland.

The calculations in Section 5 would be best suited for the mean sea level of the whole Baltic Sea – representing the total water volume of the sea. It is complicated to calculate such a mean sea level, the main problems being different land uplift rates and an uneven distribution of long time series of sea level observations around the coasts of the Baltic Sea.

However, the mean sea level of the Baltic Sea is sufficiently well represented by the sea level stations located in the middle of the basin. The internal oscillations of the Baltic Sea (forming the slope of the sea surface) have a nodal point in the middle of the Northern Baltic Proper, somewhat south of the sea level stations of Degerby, Hanko and

Stockholm (*Wübber and Krauss*, 1979). Especially Degerby, which is located in a nearly open sea area in the middle of the basin, has been found to represent the variations of the total water volume of the Baltic Sea. Thus, if the effect of the land uplift is subtracted from the iMW of Degerby, the residual should represent the mean sea level of the Baltic Sea.

6.1 The slope of the Baltic Sea

The reason for the differences in the correlation at different stations might be related to the mean slope of the Baltic Sea. While a prevailing wind from the southwest pushes more water into the Baltic Sea, it might also cause a slope on the water surface, which would tend to raise the sea level in some parts of the sea and lower it in other parts. Thus, this effect would reinforce or counterbalance the effect of the water volume changes in different parts of the Baltic Sea.

The effect of the mean slope can be taken into account by modifying Eq. (2) slightly, to yield the following representation for the mean sea level h at a station i, located at point (φ_i, λ_i):

$$\begin{aligned} h(\varphi_i, \lambda_i, t) = R_0(\varphi_i, \lambda_i) + h_g(t) - u_{a0}(\varphi_i, \lambda_i)t + s_\varphi(t)(\varphi_i - \varphi_0) \\ + s_\lambda(t)(\lambda_i - \lambda_0) + k_0 N(t) + l(\varphi_i, \lambda_i)t + \varepsilon_{h0}(\varphi_i, \lambda_i, t) \end{aligned} \tag{11}$$

where the levelling constant R_0, as well as the land uplift rate u_{a0}, depend on the location, defined by latitude φ and longitude λ. The time-dependent, spatially linear slope of the Baltic Sea surface between the point (φ_i, λ_i) and the mid point of the sea, (φ_0, λ_0), is represented by the coefficients s_φ and s_λ. The coefficient k_0 represents the correlation between the NAO index and the total water volume in the Baltic Sea, represented by the sea level at the mid point (φ_0, λ_0) detrended by the land uplift.

Assuming that the slope coefficients s_φ and s_λ correlate with the NAO index, they can be represented as:

$$s_\varphi(t) = s_{\varphi 0} + z_\varphi t + k_{s\varphi} N(t) + \sigma_\varphi(t) \tag{12}$$

and correspondingly for s_λ. Coefficients $s_{\varphi 0}$ and z_φ represent the mean slope and the linear, NAO-independent trend of the slope in time t. The term $\sigma_\varphi(t)$ contains all the residual variations, having a long-term mean of 0 and no linear trend in time.

Combining Eqs. (11) and (12) yields:

$$\begin{aligned} h(\varphi_i, \lambda_i, t) = \left[R_0(\varphi_i, \lambda_i) + s_{\varphi 0}\Delta\varphi_i + s_{\lambda 0}\Delta\lambda_i\right] + h_g(t) \\ + \left[z_\varphi \Delta\varphi_i + z_\lambda \Delta\lambda_i - u_{a0}(\varphi_i, \lambda_i) + l(\varphi_i, \lambda_i)\right]t + \left[k_0 + k_{s\varphi}\Delta\varphi_i + k_{s\lambda}\Delta\lambda_i\right]N(t) \\ + \left[\varepsilon_{h0}(\varphi_i, \lambda_i, t) + \sigma_\varphi(t)\Delta\varphi_i + \sigma_\lambda(t)\Delta\lambda_i\right] \end{aligned} \tag{13}$$

where $\Delta\varphi_i = \varphi_i - \varphi_0$ and $\Delta\lambda_i = \lambda_i - \lambda_0$. Eqs. (2) and (13) are similar in structure, the only difference being that the location-dependent coefficients R_i, u_{ai}, k_i and $\varepsilon_{hi}(t)$ have been broken down to:

$$R_i = R_0(\varphi_i, \lambda_i) + s_{\varphi o}\Delta\varphi_i + s_{\lambda o}\Delta\lambda_i \tag{14a}$$

$$u_{ai} = u_{a0}(\varphi_i, \lambda_i) - z_\varphi \Delta\varphi_i - z_\lambda \Delta\lambda_i \tag{14b}$$

$$k_i = k_0 + k_{s\varphi}\Delta\varphi_i + k_{s\lambda}\Delta\lambda_i \tag{14c}$$

$$\varepsilon_{hi}(t) = \varepsilon_{h0}(\varphi_i, \lambda_i, t) + \sigma_\varphi(t)\Delta\varphi_i + \sigma_\lambda(t)\Delta\lambda_i \tag{14d}$$

Thus, if the slope actually does correlate with the NAO index, the coefficient k_i should have a linear dependence on location. When a regression analysis for k_i with respect to location for all the 26 stations considered above is calculated, a significant linear dependence of k_i on latitude and longitude is found (Table 4). According to a Student's *t*-test, the significance exceeds 99.9 % in both cases. It should be noted that the spatial distribution of the stations considered is such that latitude and longitude are mutually correlated – the southern stations being also located more on the western side than the northern stations. Thus, a two variable regression of k_i with respect to both φ and λ is not appropriate. In Fig. 6, the coefficient k_i is plotted as a function of latitude and longitude, to illustrate the linear dependence.

Table 4. Linear dependence of the regression coefficient k on the location of the station, for different parts of the Baltic Sea. The mid point was chosen to be at Degerby. For an explanation of the station letters, see Tables 2 and 3.

Region	Stations	k vs. φ		k vs. λ	
		$k_{s\varphi}$ (cm/°)	R^2	$k_{s\lambda}$ (cm/°)	R^2
Baltic Sea	All	0.25	0.64	0.23	0.88
Gulf of Finland	C, T, D, H, E, F, Y	1.08	0.37	0.17	0.89
Bay of Bothnia	A, O, B, P, V, U, N	0.25	0.69	0.12	0.65
Bothnian Sea	V, S, M, R, T, D, G	0.11	0.56	0.07	0.44
The Baltic Proper	D, C, L, Ö, K, J, X	0.13	0.16	0.33	0.96
Southwestern Baltic Sea	K, I, Z, W, J	0.51	0.56	0.37	0.95

The slope of the Baltic Sea might not be best represented by a single plane over the whole sea. Instead, the different basins might respond to the NAO forcing with different slopes. To study this, the Baltic Sea was divided into five regions and linear regressions calculated for them. The results are included in Table 4.

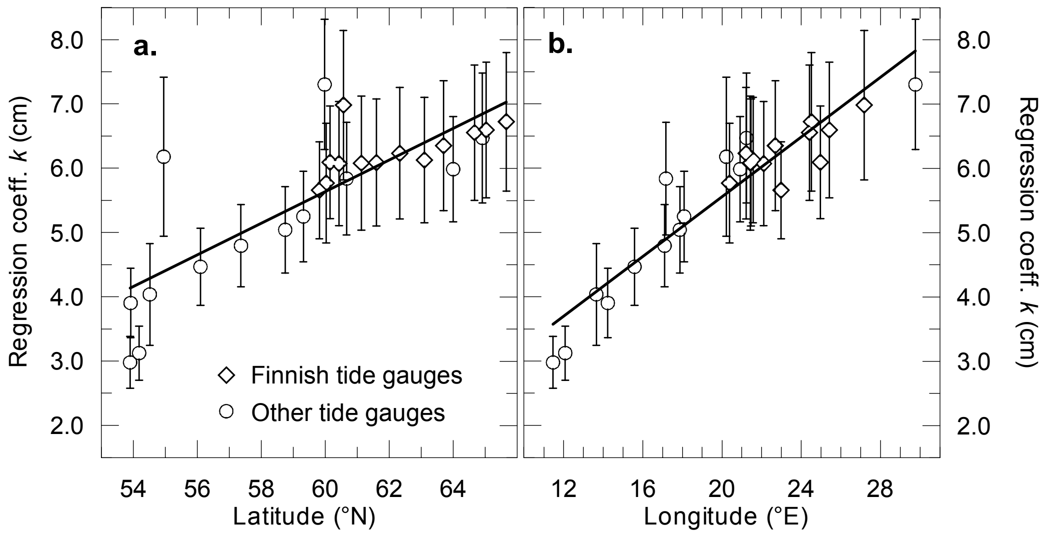

Fig. 6. The regression coefficient k for the regression between the annual mean sea levels and the winter NAO index, as a function of a) latitude and b) longitude.

6.2 Observations from the 19th century

The PSMSL data set, utilized above, contains observations from Stockholm beginning at 1889. The Stockholm sea level time series – being the longest still continued sea level series in the world – actually dates back to 1774. For the years 1825–2000, the series of annual mean sea levels is continuous (*Ekman,* 1988). As the NAO index data set used dates back to 1824, it is possible to calculate the correlation between sea level and the NAO index for a significant part of the 19th century.

It turns out that the annual mean sea levels and the winter NAO index in the 19th century do not show a correlation as significant as that in Table 3 – the value of R^2 being only 0.12 for the 15-year moving averages of 1825–1900 (assuming a linear behaviour of the global mean sea level during this period). For the correlation between the annual values, however, the value of R^2 still remains at a level of 0.20. *Andersson* (2002) also found a weaker correlation during the 19th century than the 20th century, when investigating the sea level observations at Stockholm and the NAO index. She suggested the reason for this to be in the physical process itself – related to changes in the location of the air pressure centres over the North Atlantic Ocean.

On the other hand, the reason for the weaker correlation might also be related to the quality of the observations themselves. The reconstructed series of the NAO index is uncertain on the 19th century. The sea level values of Stockholm, on the other hand, were measured using tide poles in the 19th century, the more reliable mareograph equipment being in operation starting from 1889.

The reliability of the sea level observations can be studied by comparing the annual mean sea levels at Stockholm and Hanko. Tide pole observations from Hanko region form a series of annual mean sea levels starting at 1858. The mutual correlation between these two stations is weaker during the 19th century than during the 20th century. Assuming that the sea level behaviour in this respect has not changed in time, this might indicate inaccuracies in the observations themselves.

The PSMSL data set contains sea level observations dating back to the 19th century from the three southern stations Wismar (1849–), Warnemünde (1856–) and Swinoujscie (1811–). At Kronstadt, a continuous series of annual mean values is available for the years 1835-1993 (*Bogdanov et al.,* 2000). The correlations between these data sets and the NAO index during the 19th century are all weaker than the respective correlations during the 20th century. Especially in the case of the 15-year moving averages, the method no more gives any sensible values for the coefficient k. The 15-year moving averages – with a variability of only a few centimetres – are very sensitive to small inaccuracies in the levelling of the measurements.

7. Discussion

It is evident that the improved theoretical mean sea level iMW, as calculated in this study, corresponds to the observed long-term mean sea level better than the theoretical mean sea level MW (Fig. 5). Up to the 1980s, the fairly linear behaviour of the long-term mean sea level made it possible to make reasonably good predictions for the MW in the future using a linear extrapolation. The latest changes in the Baltic Sea water balance, however, have made the prediction more uncertain. Thus, at present the MW is established for only a few years ahead.

The MW is still used for practical purposes and it is currently established up to 2005. From that time on there are not yet any values for the MW. If the iMW presented here, or an improved version of it, were extended to the future, it might be possible to use such a scenario to aid in the definition of the future MW, the officially used elevation system of the Finnish sea level observations. If, for example, the iMW meets the MW at some point in the future, as it seems likely (Fig. 5), the iMW prediction might be used from that point on as the definition of the MW. In order to be able to calculate estimates for the future iMW, scenarios for the global mean sea level, as well as for the NAO index, are needed.

The above discussion does not take into account the possibility that the correlation between the NAO index and the sea level, which is an essential part of estimating the iMW, might not hold for the future. Although it seems likely that the weak correlation between the NAO index and the sea levels in the 19th century is caused by errors in the observations, it is also possible that the correlation itself has changed its nature (cf. *Andersson,* 2002). In such case, it might not be reasonable to assume that the present correlation would hold in the future, either.

Still, it might be reasonable to use an iMW scenario to predict the mean sea level a few years ahead – such as the 5–10 years needed for MW definition. During such a short period, the error limits due to uncertainties are expected to remain at an acceptable level.

The dependence of the correlation between the sea level and the NAO index on location is represented by the linear correlation between the regression coefficient k_i and the location. The results imply that a high NAO index correlates with a slope causing the sea level to be higher in the northeastern part of the Baltic Sea than in the southwestern part. Thus, at the northern stations this reinforces the effect of the total water volume of the Baltic Sea, which in the case of a high NAO index tends to be high, causing the coefficient k_i to be higher in the northern areas.

Three stations apparently deviate from the general linear dependence of k_i on latitude (Fig. 6a) – Kaliningrad, Hamina and Kronstadt. In the case of the latter two, the exceptionally high k_i values result from the location of the stations in the innermost part of the Gulf of Finland. The k_i values, being exceptionally high for the latitude of the stations, are still in accordance with the eastern longitudes (Fig. 6b). A similar conclusion can be drawn for Kaliningrad. This suggests that the slope might be principally east-west oriented, the correlation with latitude resulting from the mutual correlation between the two coordinates. The coefficients of determination are also generally higher for the longitudinal correlation than for the latitudinal one.

The correlations of k_i with longitude vary somewhat in different areas of the Baltic Sea, the strongest correlations being found in the Baltic Proper and in the southwestern Baltic Sea. The Gulf of Bothnia seems to be least well correlated, which can be explained by the gulf being roughly north-south oriented, which does not favour the formation of a clear east-west directed slope.

In this study, we chose to use the NAO index for representing the variability of the large-scale atmospheric circulation, which in turn affects the Baltic Sea water balance. However, the studies of *Andersson* (2002) suggest that a regional air pressure index might correlate even better with the Baltic Sea levels. On the other hand, *Kauker and Meier* (2003) have found that the sea level pressure variability over the Baltic Sea region is explained by two other teleconnection patterns in addition to the NAO index – the Scandinavia pattern and the East Atlantic/West Russia pattern. Including these kinds of indices in our analysis might further improve the representation of the effect of the water balance, and thus result in even more accurate mean sea level estimates.

8. Conclusions

An estimate for the long-term mean sea level on the Finnish coast was calculated, and denoted “the improved theoretical mean sea level”, iMW. In the current mean sea level estimate, the effect of the Baltic Sea water balance was taken into account. This has not been done in the earlier estimates. The contribution of the water balance was estimated with the aid of the NAO index. The NAO index correlates significantly with the annual mean sea levels on the Finnish coast, explaining 37–46 % of the interannual variability.

It is evident that the improved theoretical mean sea level iMW follows the observed sea levels more precisely than the theoretical mean sea level MW based on the earlier estimates (Fig. 5). In particular, the behaviour of the mean sea level in the 1980s and 1990s is well reproduced. This is due to high NAO index values during these decades (Fig. 4), which cause mean sea levels to be higher than a linear estimate would suggest.

The improved theoretical mean sea level can also be extended to the future, provided that there are scenarios available for the global mean sea level and the NAO index. By constructing a scenario for the next 5–10 years, the iMW could be utilized to define the theoretical mean sea level for practical purposes, e.g. construction activities and administrative and juridical issues.

In addition to the mean sea level, the slope of the Baltic Sea surface in the east-west direction also correlates with the NAO index. This can be explained by prevailing westerly winds, connected with a high NAO index, causing the sea surface to tilt in such a way that the sea levels in the eastern part of the Baltic Sea are higher than in the western part. This reinforces the effect of the NAO index on the sea levels in the northeastern part, and weakens the effect in the southwestern part.

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