Small Publications in Historical Geophysics

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Extreme Annual Means in the Baltic Sea Level during 200 Years

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1. Introduction

The occurrence of extreme sea levels in the Baltic Sea has earlier been investigated by, among others, Bergsten (1950) and Lisitzin (1957). However, these and other studies concentrated on a short-time perspective. We will here investigate extreme sea levels in the Baltic Sea in a long-time perspective, concentrating on extreme annual means of the sea level.

In order to get a sufficient number of extreme years to study - high water years as well as low water years - it is necessary to have a very long sea level series, well over 100 years long. Such a long series is the one from Stockholm which contains about 200 years, see Ekman (1988). Nordenskiöld (1858) was the first to quantify variations in the annual means here.

Already Forssman (1876) noted that deviating annual mean sea levels of the Baltic proper tended to be correlated with those of the Kattegat. We now know that the long-term changes of the Baltic Sea level are mainly governed from outside the Baltic, from the North Sea. Carlsson & Stigebrandt (1996) have recently shown that sea level changes of more than one month duration predominantly are of this type and have a minimum (node) in the southwestern Baltic, close to the entrance, and a maximum in the northern end of the Gulf of Bothnia (see also Ekman, 1996a). Thus, such sea level variations will show up quite distinctly at Stockholm. Furthermore, Carlsson & Stigebrandt have shown that sea level variations of shorter duration than one month are mainly internal changes which have their minimum (node) in the middle of the Baltic Sea, close to Stockholm, and their maxima in the far south and far north. It should also be noted that the seiches of the Baltic Sea have their nodal line close to Stockholm (Lisitzin, 1974). Thus, Stockholm is practically free from short-term variations of any importance and, hence, an ideally situated station for studying long-term changes driven externally.

Using the Stockholm series we will now investigate the sea level behaviour during extreme years of the Baltic Sea. In order to also study possible interference between externally and internally driven extreme situations close to the Baltic entrance we will, in addition, make use of the old sea level series of Swinemünde as well as of other stations in the Baltic Sea area.

2. Extreme sea level years

Let us define an extreme sea level year as a year when the annual mean deviates from the regression line by more than twice the standard deviation,

$|\Delta l| > 2.0\,\sigma$

Statistically this should occur in 5 % of the cases, which means about 10 years out of the 200 in the Stockholm series, provided the series is reasonably normally distributed (which it is).

From Ekman (1988) we know, however, that this long series has to be described by two regression lines with somewhat different inclinations. This reflects the significant change in the apparent land uplift due to the corresponding change in the climatic rise of sea level around the 1880s. Accordingly we have applied one regression line for the time period 1774 - 1884 and another one for the period 1885 - 1991. The exact choice of the time periods can be shown to be not very critical here. Of course one could apply a second degree curve instead but that seems somewhat less relevant from a geophysical point of view.

The two regression periods turn out to have slightly different standard deviations, the difference being, however, statistically insignificant (6.4 and 5.6 cm, respectively). We adopt the 100-year-period 1892 - 1991 used in Ekman (1996a) as a standard period for the standard deviation, yielding an approximate 2σ-limit of 11.5 cm. Henceforth, this will be used as a fixed limit for defining the extreme sea level years.

In the way described above we can now detect the following 13 extreme sea level years, 8 high water years, denoted by +, and 5 low water years, denoted by -:

(1775 +)
1804 -
1807 +
(1822 +)
1831 -
1863 +
1875 -
1899 +
1903 +
1941 -
1947 -
1989 +
1990 +

Years within brackets are somewhat uncertain due to insufficient amount of data; they will be further commented in the following section.

3. Investigation of high water years

It is well known from many studies (e.g. Woodworth, 1984, or Tsimplis & Woodworth, 1994) that the seasonal variation in sea level, which is the dominating one in the Baltic Sea, shows a minimum in spring and a maximum in autumn. A normal sea level year at Stockholm, calculated as the average of the 100 years of the standard period 1892 - 1991, has a monthly distribution according to Table 1 and Figure 1, with the minimum in May and the maximum in September/December. Fourier analysis according to Ekman & Stigebrandt (1990) shows an annual amplitude of 10 cm and a semi-annual one of 4 cm, with a significant increase in the annual amplitude from 8 cm in the 19th century to 10 cm in the 20th.

Let us now investigate the monthly sea level distribution during the extreme years, starting with the high level years, to see if it differs in any systematic way from the normal one. For each high water year has first been found its normal mean sea level as the level corresponding to the regression line. Then the deviations of the monthly means from this level have been determined. The resultant values are presented in Table 2, bold figures indicating maximum monthly means; the averaged sea level distribution is also illustrated in Figure 2.

The results are striking. The seasonal maximum is no longer in autumn, but in winter (February). It is often very pronounced, the maximum monthly deviation for individual years usually reaching 40 cm, sometimes 50. Only one year (1899) does not follow the rule, still keeping to the ordinary maximum time in autumn. The seasonal minimum generally appears at its ordinary time, in spring (May - June).

Years within brackets indicate, as mentioned, insufficient amount of data. In 1775 there are only about two readings each month. In 1822 there are no data at all; the estimated figure for March comes from the historical information of the Bomarsund tide gauge in Ekman (1995), which is supported by the data from Swinemünde (Seibt, 1890; Montag, 1964) and København (Simonsen, 1949).

4. Investigation of low water years

We now turn to the low water years, investigating them in the same way as the high water ones. The resultant values are given in Table 3, bold figures here indicating minimum monthly means; the averaged sea level distribution is also illustrated in Figure 3.

Table 1. Monthly mean sea levels during a "normal" year (average of the 100 years 1892 - 1991) in cm.

Year	J	F	M	A	M	J	J	A	S	O	N	D
"Normal"	5	- 2	-11	-11	-13	- 5	5	6	7	5	5	9

Table 2. Monthly mean sea levels during extreme high water years in cm.

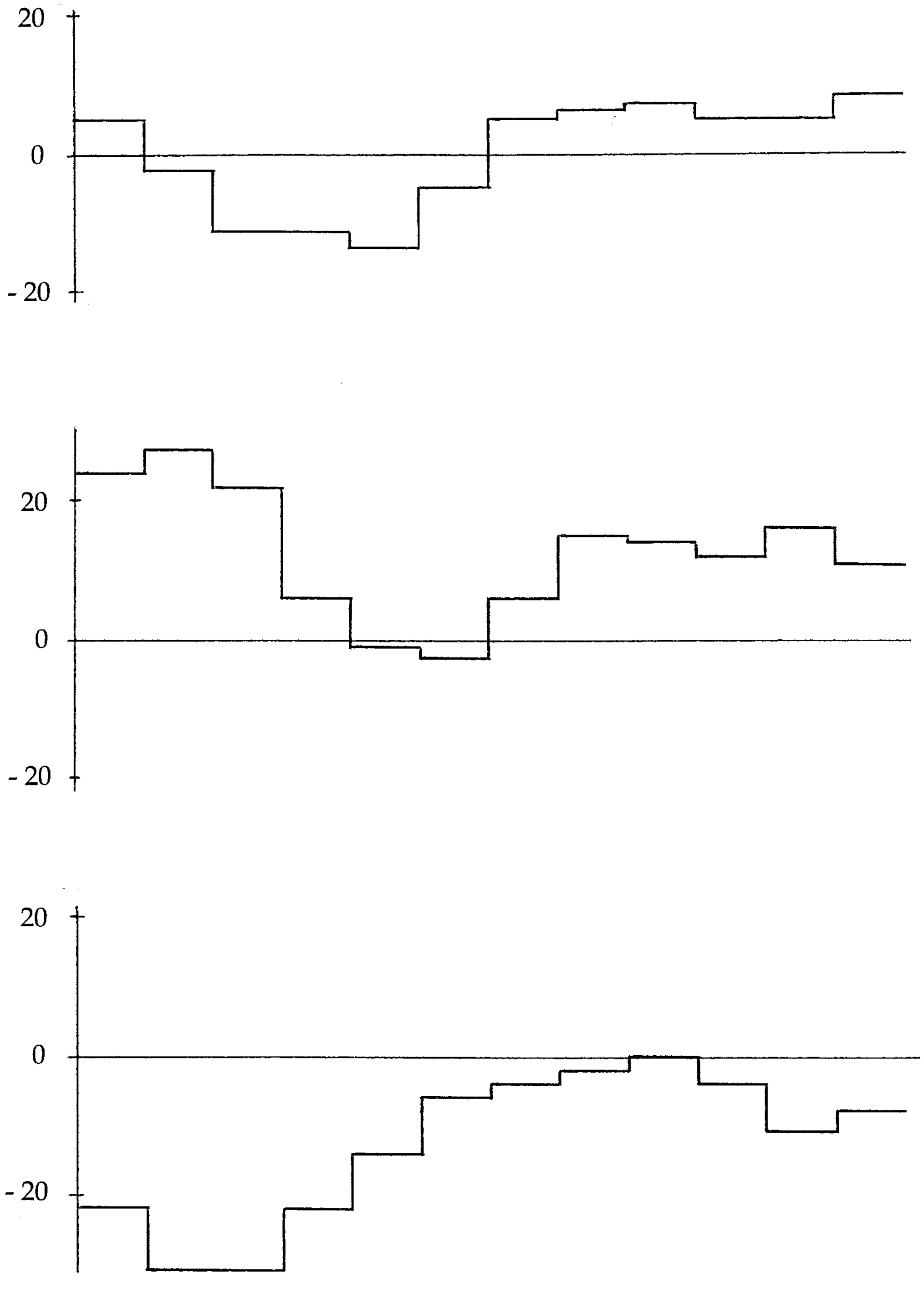
Year	J	F	M	A	M	J	J	A	S	O	N	D
(1775)	17	- 9	26	16	18	- 3	0	26	18	12	16	0
1807	**35**	24	4	- 9	- 4	5	18	- 2	15	16	16	20
(1822)			**45**									
1863	15	**41**	0	- 1	1	- 3	14	19	17	7	20	28
1899	30	9	9	10	-11	0	- 7	12	20	22	**35**	19
1903	8	**38**	17	22	- 1	- 8	7	30	22	5	13	- 2
1989	39	**48**	23	- 6	0	- 5	1	16	0	12	7	13
1990	26	39	**53**	11	-10	- 7	11	5	9	13	4	0
Average	24	27	22	6	- 1	- 3	6	15	14	12	16	11

Table 3. Monthly mean sea levels during extreme low water years in cm.

Year	J	F	M	A	M	J	J	A	S	O	N	D
1804	- 6		-34	-33	-15	6	7	14	15		-43	-35
1831	-26	-27	**-42**	-37	-10	-13	-12	-11	-12	- 6	27	1
1875	-15	-16	**-35**	-13	- 2	2	- 8	-11	- 3	-11	-20	-18
1941	-27	**-30**	-19	-28	-26	-17	- 4	5	9	- 6	-22	6
1947	-35	**-50**	-26	0	-19	-10	- 3	- 9	-11	8	4	6
Average	-22	-31	-31	-22	-14	- 6	- 4	- 2	0	- 4	-11	- 8

Table 4. Differences between, and means of, averaged monthly mean sea levels during extreme high and low water years (in cm).

	J	F	M	A	M	J	J	A	S	O	N	D
Diff.	46	58	53	28	13	3	10	17	14	16	27	19
Mean	1	- 2	- 4	- 8	- 8	- 4	1	6	7	4	2	2



Figures 1 - 3. Seasonal variation in sea level during "normal" years, extreme high water years and extreme low water years, respectively (according to Tables 1 - 3; in cm).

Again, the results are striking. The seasonal minimum is no longer in spring, but in winter (February - March). Thus the minimum of the low water years occurs at the same time of the year as the maximum of the high water years. The minimum is often very pronounced, reaching nearly the same values as the maximum but with the opposite sign, i.e. - 40 cm, sometimes - 50. There is only one year (1804) that does not quite follow the rule, but this year also lacks data from two months. The seasonal maximum generally appears at its ordinary time, in autumn (September).

It is also instructive to compare the averaged monthly means of the high water years with those of the low water years. This is done in Table 4. We clearly see the three winter months January - March standing out, with a difference 3 - 4 times those of the other quarters of the year. We also note that the mean of the two extreme groups (high and low) forms a nearly "normal" result, fairly close to the one of Table 1.

5. Interference between externally and internally driven extremes

None of the extreme sea level years at Stockholm exceeds 2.4 σ. This is fairly close to what we would expect statistically from a 200-year-series, namely 2.7 σ.

In the southernmost part of the Baltic Sea there is another very old sea level station, Swinemünde, (Seibt, 1890; Montag, 1964). The same limit as in Stockholm, 2.4 σ, turns out to apply to Swinemünde - with one exception: The year 1899 deviates by as much as 3.0 σ. This calls for an investigation of the geographical distribution of the 1899 sea level in the Baltic Sea area to understand how such a situation arises.

The investigation was made in the following way. All reliable stations with series spanning 60 years or more, i.e. the stations of Ekman (1996), and containing the year 1899, were used. The deviation of the 1899 annual mean of each station from its respective regression line was determined. For those stations which started operating only a few years before 1899, a correction (of the order of 1 cm) was introduced on the basis of comparisons with neighbouring stations with longer series, in order to compensate effects due to the year 1899 being close to one end of the regression. The results of all stations are shown in Table 5 and illustrated in the map in Figure 4.

From Figure 4 we find that an 1899 sea level exceeding 3.0 σ is restricted to the southwesternmost part of the Baltic Sea, just inside the Baltic entrance, with Gedser reaching 3.2 σ. This should, statistically speaking, occur only once in 700 years. The whole central part of the Baltic Sea has between 2.5 σ and 2.0

Table 5. Deviation of the annual mean sea level of 1899 from normal mean sea level, expressed both as the deviation Δl in cm and as the factor k in $k\sigma$.

Station	Lat.	Long.	Δl	k
Kronstadt	59 59	29 47	11.5	1.7
Hanko	59 49	22 58	12.4	2.1
Lemström (Åland)	60 06	20 01	13.1	2.3
Lypyrtti	60 36	21 14	11.5	2.1
Ratan	64 00	20 55	10.5	1.6
Draghällan	62 20	17 28	12.0	2.0
Björn	60 38	17 58	11.6	2.0
Stockholm	59 19	18 05	12.2	2.2
Grönskär	59 16	19 02	11.9	2.1
Södertälje	59 12	17 38	12.5	2.2
Landsort	58 45	17 52	13.1	2.4
Ölands norra udde	57 22	17 06	13.9	2.6
Kungsholmsfort	56 06	15 35	13.4	2.7
Ystad	55 25	13 49	11.3	2.6
Varberg	57 06	12 13	4.3	1.0
Smögen	58 22	11 13	2.9	0.8
Esbjerg	55 28	8 27	3.7	0.8
Hirtshals	57 36	9 57	5.2	1.4
Frederikshavn	57 26	10 34	2.6	0.8
Århus	56 09	10 13	4.6	1.8
Fredericia	55 34	9 46	3.7	1.5
Slipshavn	55 17	10 50	7.2	2.7
Korsør	55 20	11 08	7.5	2.5
Hornbæk	56 06	12 28	7.6	1.9
København	55 41	12 36	8.3	2.3
Gedser	54 34	11 58	10.9	3.2
Marienleuchte	54 30	11 15	9.8	3.0
Travemünde	53 58	10 52	9.8	2.9
Wismar	53 54	11 28	11.1	3.0
Warnemünde	54 11	12 05	10.1	2.7
Swinemünde	53 55	14 16	12.2	3.0
Neufahrwasser	54 24	18 41	14.2	2.6
Pillau	54 39	19 54	14.3	2.6

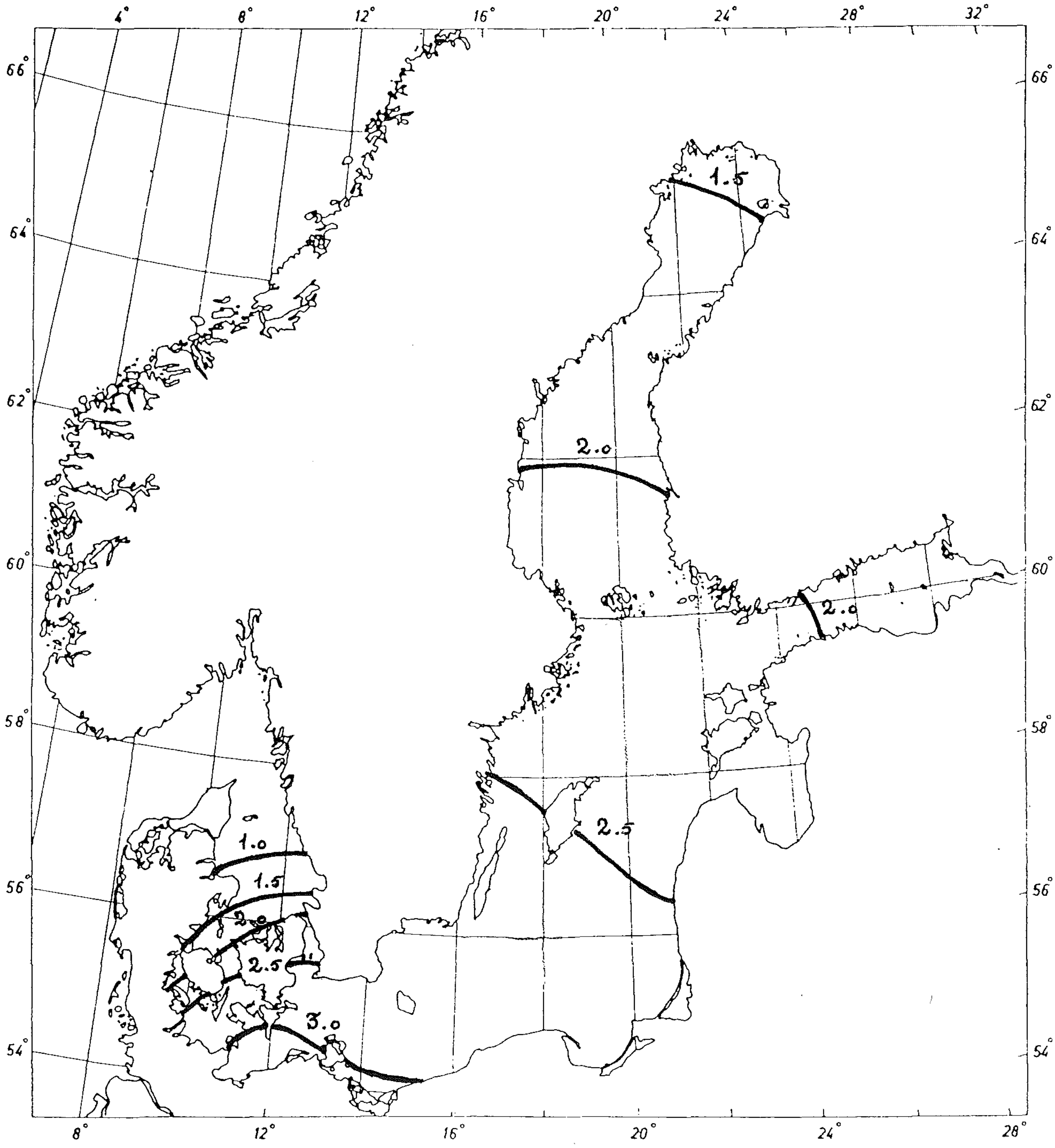


Figure 4. Deviation of the annual mean sea level of 1899 from normal mean sea level, expressed as the factor *k* in *k*σ.

σ, while the northern end only has about 1.5 σ. Outside the Baltic entrance the 1899 sea level hardly exceeds 1.0 σ, leading to a very strong gradient in the entrance itself. The situation can be described as a sea level outside the Baltic 4 cm above normal, then a step of 8 cm in the entrance, leading to a sea level inside the Baltic about 12 cm above normal all over.

This unique sea level distribution can be explained as the result of interference between the externally and internally driven sea level variations. What we see here is probably an externally driven (long-term) high sea level situation (2σ) upon which is superimposed several internally driven (short-term) high sea levels in the south with corresponding low levels in the north.

It is interesting to compare the internal part of the pattern here with the sea level pattern at the time of the great flood along the coasts of the southwestern Baltic in autumn 1872. This flood was investigated in detail by Colding (1881); it was caused by a northeasterly storm. The patterns are quite similar, and Colding notes with surprise a stability of the sea level during the whole storm along a line from Stockholm towards southeast; this seems to be the first observation of the nodal line of the internally driven sea level variations in the Baltic.

An interference between externally and internally driven sea level variations of somewhat the opposite kind may also occur, leading to an almost vanishing annual deviation from normal sea level in the south although the deviation in the north may exceed 2σ. Such situations occurred in 1863 and 1989.

6. Conclusions

The investigation of extreme annual mean sea levels at Stockholm 1774 - 1991, deviating more than 2σ from their normal values, has revealed a specific behaviour of the Baltic Sea during such years. The normal seasonal variation of sea level, with a minimum in spring and a maximum in autumn, is during extreme high water or low water years replaced by a variation with a pronounced maximum during winter, for high water years, and correspondingly a pronounced minimum also during winter, for low water years. Of the 13 extreme years during the investigated 200-year-period, no less than 10 - 12 show this specific behaviour. As this behaviour is a long-term phenomenon (sea level variation exceeding one month), its origin must be sought in the relation between the North Sea and the Baltic Sea, especially in the wind conditions over the Baltic entrance. We may suspect that the high water years are related to prevailing (south)westerly winds there during winter, while the low water years are related to prevailing (north)easterly winds there during the same season. If so, we should expect also a relation between extreme sea level years and anomalous winter temperatures. This will be studied in a forthcoming publication.

Repeated short-term extremes, due to the wind conditions over the Baltic itself, may in rare cases interfere with the above long-term extremes to produce especially anomalous sea level years. This seems to be the explanation for the year 1899 showing a deviation of the annual mean from its normal value of more than 3σ just inside the Baltic entrance (but only 1σ just outside it).

References

Bergsten, F (1950): Vattenståndens varaktighet utmed svenska kusten. Geografiska Annaler, 32, 165-178.

Carlsson, M, & Stigebrandt, A (1996): Main characteristics of the long-term sea level variability in the Baltic Sea. Tellus, 48 A (in press).

Colding, A (1881): Nogle Undersøgelser over Stormen over Nord- og Mellem-Europa af 12te - 14de November 1872 og over den derved fremkaldte Vandflod i Østersøen. Dansk Videnskabelig Selskaps Skrifter, Naturvidenskabelig og mathematisk Afdeling, 6/1, 243-304.

Ekman, M (1988): The world's longest continued series of sea level observations. Pure and Applied Geophysics, 127, 73-77.

Ekman, M (1995): Postglacial uplift of the Åland Islands, and the world's oldest preserved sea level gauge. Small Publications in Historical Geophysics, 1, 15 pp.

Ekman, M (1996): A consistent map of the postglacial uplift of Fennoscandia. Terra Nova, 8, 158-165.

Ekman, M (1996a): A common pattern for interannual and periodical sea level variations in the Baltic Sea and adjacent waters. Geophysica, 32 (in press).

Ekman, M, & Stigebrandt, A (1990): Secular change of the seasonal variation in sea level and of the pole tide in the Baltic Sea. Journal of Geophysical Research, 95 C, 5379-5383.

Forssman, L A (1876): Observationer öfver vattenhöjden vid Sveriges kuster. Kongl. Svenska Vetenskaps-Akademiens Handlingar, 13/11, 1-23.

Lisitzin, E (1957): The frequency of extreme heights of sea-level along the Finnish coast. Finnish Marine Research, 175, 12 pp.

Lisitzin, E (1974): Sea level changes. Elsevier Scientific Publishing Co, 286 pp.

Montag, H (1964): Die Wasserstände an den ehemaligen Pegelstationen des Geodätischen Instituts Potsdam bis 1944. Arbeiten aus dem Geodätischen Institut Potsdam, 5, 53 pp.

Nordenskiöld, A E (1858): Beräkning af fasta landets höjning vid Stockholm. Öfversigt af Kongl. Vetenskaps-Akademiens Förhandlingar, 15, 269-272.

Seibt, W (1890): Das Mittelwasser der Ostsee bei Swinemünde. Veröffentlichung des Königl. Preussischen Geodätischen Institutes, 38 pp.

Simonsen, O (1949): Nivellements-nul paa Sjælland, Møn og Lolland-Falster med særligt henblik paa København og Frederiksberg 1845-1945. Doctoral dissertation at the University of Copenhagen, 182 pp.

Tsimplis, M N, & Woodworth, P L (1994): The global distribution of the seasonal sea level cycle calculated from coastal tide gauge data. Journal of Geophysical Research, 99 C, 16031-16039.

Woodworth, P L (1984): The worldwide distribution of the seasonal cycle of mean sea level. Reports of the Institute of Oceanographic Sciences at Bidston Observatory, 190, 94 pp.