Small Publications in Historical Geophysics

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Long-term Changes of Interannual Sea Level Variability in the Baltic Sea and Related Changes of Winter Climate

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1. Background

Annual mean values of the sea level may deviate from normal sea level, i.e. from the regression line of a long sea level series, by more than 10 cm in the Baltic Sea. In two recent studies by Ekman (1996, 1997) it has been revealed that extreme annual mean sea levels in the Baltic Sea are mainly due to extreme sea levels during winters, caused by anomalous winter climate. The effect of winter climate on sea level will here be studied from a novel point of view, concentrating on long-term changes of their interannual variabilities. For this purpose we will use, as before, the long sea level series of Stockholm, commencing 1774 (Ekman, 1988), as well as the long air temperature series of Stockholm, commencing 1756 (Moberg & Bergström, 1997) and the long wind series of Lund, commencing 1741 (Jönsson, 1998).

The general behaviour of sea level variations in the Baltic Sea has been investigated by Samulsson & Stigebrandt (1996). They found that variations on a time scale less than one month are mainly internally driven variations, with maxima in the far north and the far south, and a minimum (nodal line) close to Stockholm in the central part of the Baltic. They also found that variations on a time scale exceeding one month are mainly externally driven variations, with a maximum in the north and a minimum at the Baltic entrance (cf. Ekman, 1996a). Hence, Stockholm is an ideally situated station for investigating long-term sea level changes, these being quite large here in combination with the short-term variations being especially small. Furthermore, such long-term changes recorded at Stockholm represent, to a very large extent, the long-term behaviour of the entire Baltic Sea, and also the adjacent part of the North Sea.

The long-term sea level variations originate from the North Sea and are, predominantly, governed by the wind situation over the transition area between the North Sea and the Baltic Sea, i.e. over the Baltic entrance (Matthäus & Schinke, 1994; see also Ekman, 1997). Hence, Lund in southernmost Sweden is very well situated for studying such long-term wind changes. Moreover, during winter, winds are closely correlated with temperature; Stockholm is reasonably well located for studying corresponding temperature changes.

2. The impact of winter climate on annual mean sea levels

Winters play a central role in influencing annual mean values of the Baltic Sea level, as demonstrated by Ekman (1997). He showed that a special relation is valid for extreme sea level years, which are defined by the annual sea level deviation exceeding twice the standard deviation, or 11.5 cm at Stockholm. This relation may be formulated in two parts:

1. Extreme high water years have persistent winter winds from SW and winter temperatures about 3 - 4 °C above normal, with only about 20 % ice cover in the Baltic Sea.

2. Extreme low water years have persistent winter winds from ENE and winter temperatures 3 - 4 °C below normal, with as much as 85 % ice cover in the Baltic Sea.

This relation, unfortunately, does not work the other way around. Considering e.g. all winters with a temperature deviation exceeding 3 °C, one cannot predict the annual mean sea level from that information only. Nevertheless, of all such years, 85 % (25 out of 30) do show a sea level deviation of the same sign as the temperature deviation.

The central role for the Baltic sea level played by the winter season is partly due to the fact that winds usually are considerably stronger during autumn and winter, and wind stress is proportional to the square of the wind velocity (Carlsson, 1998). An example of winter climate changes causing long-term sea level changes, related to the seasonal sea level variation, is given by Ekman (1998); cf. also Plag & Tsimplis (1998).

Altogether, we should expect some co-variation between annual mean sea levels and winter climate. Because they are more simple to handle, we start by analysing winter temperatures together with the sea levels, leaving winter winds to a later section.

3. Variance analysis of annual sea level and winter temperature

Let us study the interannual variability of the sea level as well as of the winter temperature. As measures of the variability we use their respective standard deviations, $\sigma(H)$ and $\sigma(t_w)$. The sea level data involved are the annual mean sea levels, and the temperature data are the winter mean temperatures, winter being here defined as the three months January - March. To be able to study the long-term changes of the σ values, we divide the whole time span of approximately 200 years into four 50-year-periods, the first period, however, being 60 years. The results of the computations for both annual sea level and winter temperature are given in Table 1.

Table 1 indicates that $\sigma(H)$ as well as $\sigma(t_w)$ decrease from the first period to the third, and then increase from the third period to the fourth. A minor reservation should be made for the earliest period; here the sparseness of sea level data for some early years might exaggerate that figure slightly.

Table 1. Standard deviations of annual sea levels (cm) and of winter temperatures (°C).

Years	$\sigma(H)$	$\sigma(t_w)$
1774 - 1834	7.4	2.5
1835 - 1884	5.8	2.1
1885 - 1934	4.7	1.8
1935 - 1984	6.2	2.4

Table 2. Significance levels from F-tests for annual sea level and winter temperature. Periods refer to the time periods above (1 = 1774 - 1834 etc.).

Per.	$\alpha(H)$	$\alpha(t_w)$
1 - 3	99	98
3 - 4	94	95

We now apply F-tests to the standard deviations squared, i.e. we determine probability levels α satisfying the confidence interval

$$F_{1-\alpha/2}(f_x, f_y) < \sigma_x^2/\sigma_y^2 < F_{\alpha/2}(f_x, f_y)$$

where f is the number of degrees of freedom. x and y denote the time periods, first 1 and 3, and then 3 and 4, respectively. There are 48 degrees of freedom (50 - 2 overdeterminations, from linear regression) for the third and fourth periods, but this does not hold for the first period. In that case there are 30 degrees of freedom for the sea level data (many years missing), and 59 for the temperature data.

The results are presented in Table 2. We find that the changes from the first period to the third as well as from the third period to the fourth are statistically significant at the 94 - 98 % level, and this holds for annual sea level as well as for winter temperature. (Here we have reduced the 99 % sea level figure somewhat to compensate for the mentioned sparseness of some of the older sea level data). Hence, the columns of Table 1 most probably reflect real changes in both sea level and winter temperature.

It should be mentioned here that a corresponding co-variation of the ice extent variability as tabulated by Seinä & Palosuo (1996) is hard to find; especially the first period does not fit. A possible explanation of this is the larger uncertainty in the ice data before 1846, which often had to be estimated from less reliable information. Moreover, the ice extent is very sensitive to climatic fluctuations (Omstedt & Nyberg, 1996) and, therefore, probably difficult to reconstruct with the accuracy needed here.

The long-term changes in sea level and winter temperature should originate from corresponding changes of the wind conditions over the Baltic entrance and southern Scandinavia. For obvious reasons it is difficult to define a useful σ value for winds. What can be done instead is to count the number of large residuals (deviations) in some reasonable sense.

4. Large residuals in annual sea level, winter temperature and winter winds

Let us count, for both sea level, winter temperature and winter winds, the number of large residuals during the four 50-year-periods. The somewhat vague concept of large residuals will be specified below for each data type.

As a large residual in annual sea level we define

$$|\Delta H| > 8 \text{ cm} \approx 1.5\, \sigma(H)$$

where σ is an average value over the whole time span. In a similar manner we define a large residual in winter temperature as

$$|\Delta t_w| > 3° \text{ C} \approx 1.5\, \sigma(t_w)$$

σ again being an average value over the whole time span.

For winds the situation is a little more complicated. The winter wind in Jönsson (1998) is given as a vector, with a direction and a magnitude. The direction α_w is the azimuth, counted from north towards east - south - west, of the dominating wind. The magnitude s_w is a number between 0 and 1, 1 corresponding to all winds coming from the dominating direction, 0 corresponding to the lack of such a direction. Over the Baltic area there is a tendency to a bi-directional wind situation, with one primary maximum and one secondary maximum in the wind direction; we will use the primary maximum only. We now have to distinguish between northeasterly and southwesterly winds. Based on Ekman (1997) we take as a large residual for northeasterly winds

$$s_w > 0.4 \qquad (0° < \alpha_w < 90°)$$

and as a large residual for southwesterly winds

$$s_w > 0.6 \qquad (180° < \alpha_w < 270°)$$

The winter wind data refer to the three months December - February. Deviating annual sea levels in the Baltic are mainly coupled to high/low water during January - March (Ekman, 1996), i.e. one month later. However, long-term sea level in the Baltic Sea will normally appear with a time delay of nearly one month relative to the driving winds over the Baltic entrance, due to the narrow and shallow character of the Danish straits, including Öresund between Denmark and Sweden (Stigebrandt, 1984; Matthäus & Schinke, 1994). Therefore, it is fully relevant to use wind data refering to a winter one month in advance of that for the sea level.

Now we simply count the numbers of years fulfilling the conditions for annual sea level, winter temperature and winter winds above. The results are given in Table 3, both the numbers themselves (Table 3a) and, to be more easily comparable, their percentages (Table 3b). See also Figure 1! The co-

Table 3a. Number of large residuals in annual sea levels, winter temperatures and winter winds.

Years	H	t_w	s_w
1774 - 1834	18	13	16
1835 - 1884	7	10	10
1885 - 1934	4	4	8
1935 - 1984	13	12	11

Table 3b. The same as above but expressed as percentage.

Years	H	t_w	s_w
1774 - 1834	42	33	36
1835 - 1884	17	26	22
1885 - 1934	10	10	18
1935 - 1984	31	31	24

Table 4. Number of large residuals in northeasterly and southwesterly winter winds, respectively.

Years	NE	SW
1774 - 1834	10	6
1835 - 1884	4	6
1885 - 1934	1	7
1935 - 1984	1	10

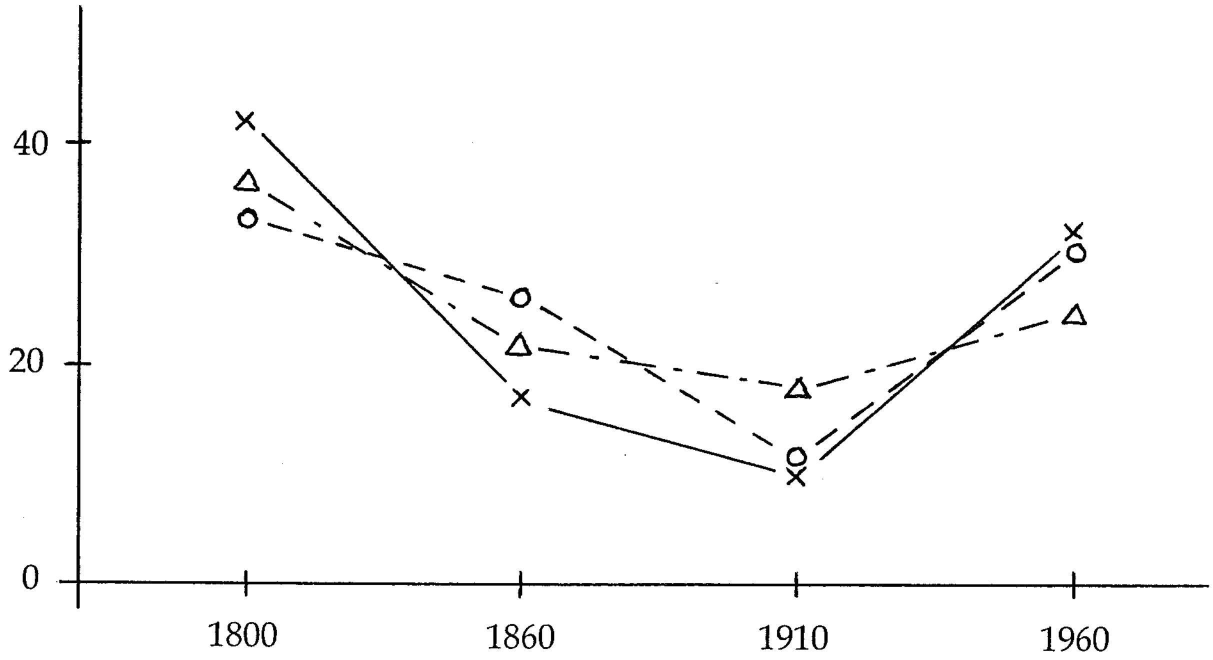

Figure 1. Number of large residuals in annual sea levels (x), winter temperatures (o) and winter winds (Δ), expressed as percentage (from Table 3b).

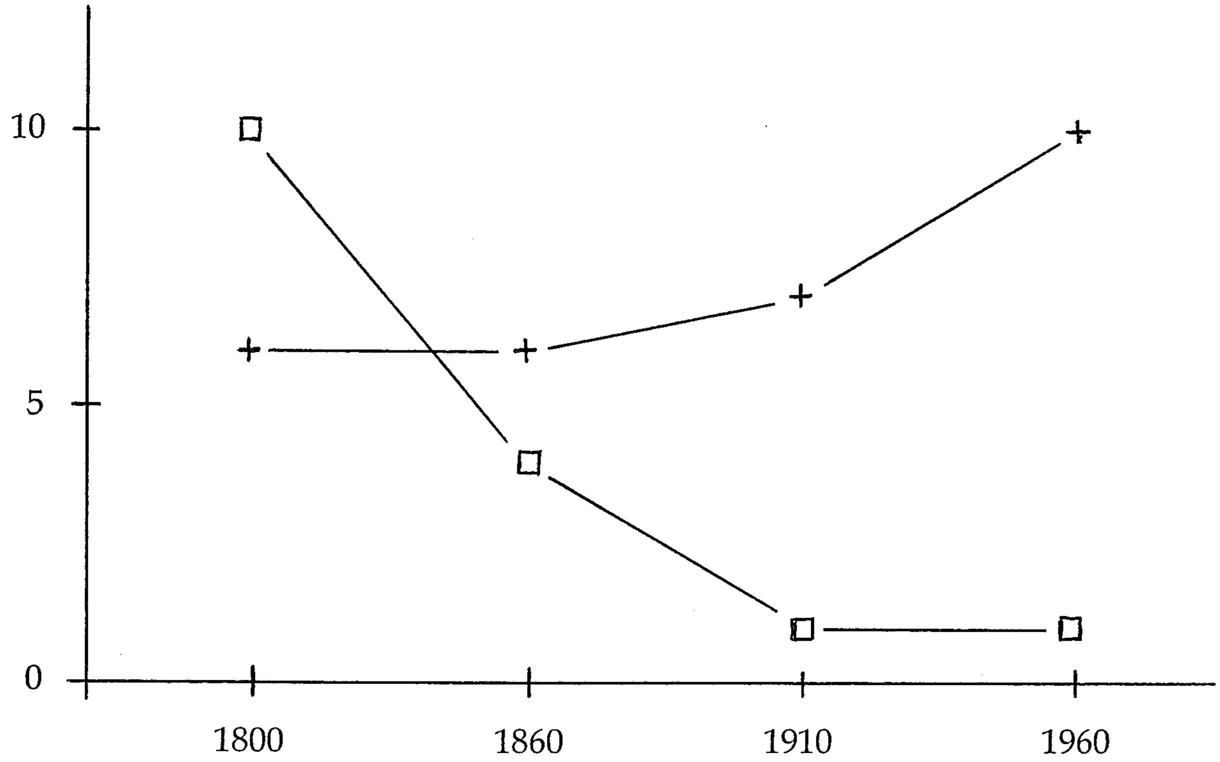

Figure 2. Number of large residuals in northeasterly (□) and southwesterly (+) winter winds, respectively (from Table 4).

variation is striking. This is the case not only between annual sea level and winter temperature, as should be expected from the results of section 3, but also between these quantities and winter winds. Hence, it is clear that long-term changes of winter winds over the Baltic entrance are the main cause of the long-term changes in both annual sea level and winter temperature.

5. A closer study of winter winds

In order to obtain a deeper understanding of the phenomenon, we study the northeasterly and southwesterly winds separately. This means that we split the numbers of the wind column in Table 3a into two columns, one for northeasterly winds and one for southwesterly ones. The results are shown in Table 4.

Table 4 reveals something interesting. See also Figure 2! From the first period to the third we find a marked decrease of persistent northeasterly winter winds, whereas the southwesterly ones keep constant. From the third period to the fourth we find an increase of persistent southwesterly winter winds, while the northeasterly ones keep constant. Thus the significant decrease-increase of the sea level and temperature variabilities demonstrated in the previous sections is actually caused by two different processes: one process of decreasing northeasterly winter winds that cause the decreasing variabilities from the first period to the third, and one process of increasing southwesterly winter winds that cause the increasing variabilities from the third period to the fourth.

It should be mentioned here that Ekman (1998), analysing monthly wind data from 1825 onwards for studying the seasonal sea level variation, finds a special increase of persistent southwesterly winds during early winters. This seems to be related to the second process above.

6. Conclusions

The interannual sea level variability and the interannual winter temperature variability (standard deviations) have both decreased significantly from the end of the 1700s to the beginning of the 1900s; after that they have both increased significantly again. The frequencies of large residuals in not only annual sea levels and winter temperatures, but also winter winds, reveal the same pattern. We have found that the common origin of these long-term changes are two consecutive wind processes over the Baltic entrance: From the end of the 1700s to the beginning of the 1900s there is a rapidly decreasing number of dominating winter winds from northeast, after that there is an increasing number of dominating winter winds from southwest.

In terms of the nowadays so popular North Atlantic Oscillation we note that the extremely long sea level series of Stockholm may be said to partly reflect that oscillation and, therefore, also indicate long-term changes of it.

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