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Secular Change of the Seasonal Sea Level Variation in the Baltic Sea and Secular Change of the Winter Climate

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Abstract

Using monthly mean sea level data from Stockholm since 1825, the longest unbroken series of such data in the world, we have analysed the secular increase of the seasonal sea level variation in the Baltic Sea. It turns out that changes in winter play a central role, causing a shift of the maximum sea level from July-August to December. We find a secular increase of sea level in December-January of 4 cm, and a secular decrease in February-March of the same amount. Both changes are statistically significant at the 99 % level. The main origin of these changes appears to be changes of wind conditions over the transition area between the North Sea and the Baltic Sea. Using monthly wind data from this area since 1825, we find changes of prevailing southwesterly winds occurring one month in advance of the corresponding sea level changes in the Baltic Sea, the phase difference being due to the time delay in sea level caused by the complicated entrance to the Baltic. In general, during autumn and winter (October-March) there is a 99 % significant monthly agreement between secular increase/decrease of southwesterly winds and secular increase/decrease of sea level as corrected for the phase lag.

Key words: Oceanography, sea level, seasonal variation, climate change

1. Introduction

Sea level has been observed in the Baltic Sea, at Stockholm, since 1774. This constitutes the longest continued sea level series in the world. Some historical information as well as a table of annual means of the sea level has been published by *Ekman* (1988). Analysing these annual means he found a significant secular change of the apparent postglacial land uplift rate between the time periods 1774-1884 and 1885-1984, reflecting a corresponding eustatic change of sea level.

During the first 50 years after 1774 there are some gaps in the Stockholm sea level series. From 1825 on, however, the series is complete. *Ekman* and *Stigebrandt* (1990) analysed the monthly means of this complete series, forming the longest unbroken series of monthly mean sea levels in the world. They discovered a significant secular increase of the seasonal variation of sea level. This secular increase will here be studied in more detail in order to try to understand what has happened during the last two centuries, and to some extent also why. *Ekman* and *Stigebrandt* (1990) also discovered a secular increase of the 14-month sea level variation, hitherto mostly known as the "pole tide"; this will only be dealt with very briefly here.

2. General characteristics of sea level variations in the Baltic Sea

The seasonal sea level variation can be decomposed into an annual variation and a semi-annual one. Both these variations as well as the 14-month variation, and also irregular long-term variations, show a common geographical pattern in the Baltic Sea area, indicating a common origin, most probably wind stress (*Ekman*, 1996; see also *Tsimplis* and *Woodworth*, 1994, and *Tsimplis et al.*, 1994).

The general behaviour of sea level variations in the Baltic Sea has been investigated by *Samuelsson* and *Stigebrandt* (1996) and *Carlsson* (1998). 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. These long-term 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* and *Schinke*, 1994; see also *Ekman*, 1997). For periods around one month, variations of the air pressure over Kattegat may also contribute substantially (*Stigebrandt*, 1990).

What has been said above has important implications for the analysis and interpretation of the long Stockholm series of monthly and annual mean sea levels. First, 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. Second, 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.

Applying this to the secular increase of the seasonal variation, as well as of the 14-month variation, as revealed from the Stockholm data by *Ekman* and *Stigebrandt* (1990), it is clear that these secular increases are valid for the whole Baltic Sea area and should be caused mainly by corresponding secular increases of the wind variations over the Baltic entrance. In a shorter time perspective, covering the present century and concentrating on the last decades, such a coupling between sea level change and atmospheric change has recently been confirmed using sea level and atmosphere data from the whole of northwestern Europe, by *Plag* and *Tsimplis* (1998).

3. *Secular change of the seasonal sea level variation, especially in winter*

The annual and semi-annual components of the seasonal sea level variation in the central Baltic Sea have amplitudes close to 10 cm and 4 cm, respectively (e.g. *Woodworth*, 1984). The total variation has its maximum in autumn and its minimum in spring. The secular increase applies only to the annual component, i.e. the main one, according to *Ekman* and *Stigebrandt* (1990). Applying Fourier analysis to the two 80-year time periods 1825-1904 and 1905-1984 they obtained an increase of the amplitude from 8 cm to 10 cm. Furthermore, applying Fourier analysis to each of the eight 20-year-periods contained in the whole time span 1825-1984, they obtained a statistically significant increase of the amplitude from 7 cm in the early 1800s to about 11 cm in the late 1900s.

In order to get a deeper insight into this process we now compute the seasonal variation "month by month" for the same time periods as above. This simply means that, for each time period, we calculate the average of all January mean sea levels, the average of all February mean sea levels etc. Then we express these monthly averages as deviations from the corresponding average of all annual means, thereby eliminating general sea level trends (like postglacial rebound and eustatic sea level rise). The results are quite interesting.

Let us first study the two 80-year-periods, see Table 1. We observe here that the most important changes have occurred during winter, leading to a shift of the maximum from July-August to December. The minimum in April-May is hardly affected. Especially we note the quite considerable increase of the sea level in December-January (+ 4 cm) and the quite considerable decrease of sea level in February-March (- 4 cm).

Table 1. Seasonal sea level variation, expressed as monthly mean sea levels (cm).

Years	J	F	M	A	M	J	J	A	S	O	N	D
1825-1904	2	1	-7	-12	-12	-4	6	6	5	4	5	5
1905-1984	5	-3	-12	-10	-12	-4	5	6	6	5	5	9
Change	3	-4	-5	2	0	0	-1	0	1	1	0	4

Let us now turn to the eight 20-year-periods, making it possible to study the changes in the winter months December-March closer; see Table 2. We find that both the increase of sea level in December-January and the decrease in February-March are of a trend-like character, see also Figure 1. Our data show an increase of the combined December-January sea level from about 3 cm in the early 1800s to nearly 10 cm in the late 1900s, and an equally large decrease of the combined February-March sea level during the same two centuries.

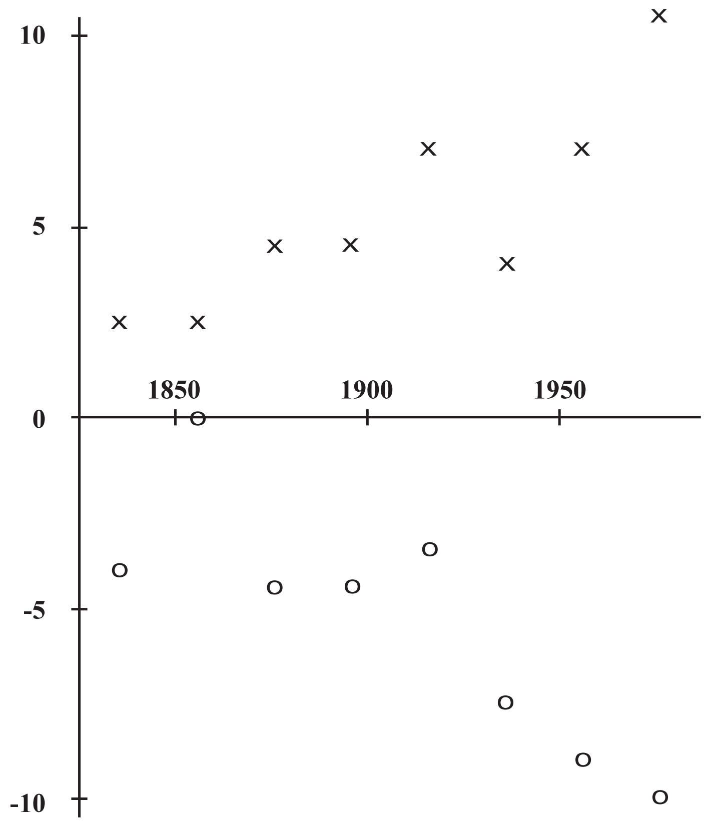

Fig. 1. Mean sea levels (cm) in December-January (x) and February-March (o) for the eight 20-year-periods according to Table 2.

Table 2. Mean sea levels in December-January and February-March, respectively (cm).

Years	D-J	F-M
1825-1844	2.5	-4.0
1845-1864	2.5	0.0
1865-1884	4.5	-4.5
1885-1904	4.5	-4.5
1905-1924	7.0	-3.5
1925-1944	4.0	-7.5
1945-1964	7.0	-9.0
1965-1984	10.5	-10.0

Applying regression analysis to the data of Table 2/Figure 1 we find a December-January sea level increase of

$$\dot{H} = 4.7 \pm 1.2 \text{ cm/century}$$

A t-test with 6 degrees of freedom shows that this is statistically significant at the 99 % level. In the same way we find a February-March sea level decrease of

$\dot{H}$ = - 5.7 ±1.5 cm/century

which is also statistically significant at the 99 % level.

The central role played by the winter season here is in some accordance with the sea level variability being larger during winter (e.g. *Samuelsson* and *Stigebrandt*, 1996) and the fact that extreme monthly mean sea levels are concentrated to winter (*Ekman*, 1996a).

4. Secular change of the dominant wind direction, especially in winter

We now want to investigate whether there has occurred any secular change of the wind situation over the Baltic entrance that may explain the secular increase of the seasonal sea level variation. Because of what we have found in the preceding section we should primarily expect changes of winds during winter.

In order to perform this investigation we need a wind series equally long as the sea level one, preferably located close to the Baltic entrance. Fortunately, such a series is available. This is the wind record of Lund, in southernmost Sweden, dating back to 1741. It has recently been compiled and published by *Jönsson* (1998), in the form of seasonal and annual mean winds.

The wind is given as a vector, with a direction and a magnitude. The direction α is the azimuth, counted from north towards east - south - west, of the dominating wind. The magnitude s 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.

The long-term sea level in the Baltic Sea is high when there are prevailing winds around southwest, $\alpha \approx 235°$, and low when there are prevailing winds around northeast, $\alpha \approx 65°$, with a dominance corresponding to $s \approx 0.5$ or larger (*Ekman*, 1997). We therefore proceed in the following way. For each of the 20-year-periods in section 3 we count the number of January months etc. with dominating winds between south and west, i.e. $180° < \alpha < 270°$ and $s > 0.5$, as well as the number of January months etc. with dominating winds between north and east, i.e. $0 < \alpha < 90°$ and $s > 0.5$. Then we take the difference w between these two numbers, and look for possible secular changes in w for the various months.

To start with, we study the seasonal variation of the wind difference number for the two 80-year-periods, see Table 3. The general agreement with the seasonal variation of sea level in Table 1 is obvious, partly with a sea level phase lag of one month to be commented upon later. We note, however, that sea level seems to react less to the wind difference number in summer than in autumn and winter. This is due to the fact that winds usually are considerably stronger in autumn and winter, and wind stress is proportional to the square of the wind velocity (*Carlsson*, 1998). The sea level minimum in spring is more pronounced than the wind difference minimum; this is probably due to the fact that water density effects caused by temperature and salinity also have their minimum at that time of the year. For the reasons mentioned, we henceforth concentrate on the six autumn and winter months (October-March).

Table 3. Seasonal wind variation, expressed as monthly wind difference numbers.

Years	J	F	M	A	M	J	J	A	S	O	N	D
1825-1904	8	5	0	-3	1	7	18	21	13	7	3	6
1905-1984	11	5	6	5	4	15	21	17	21	10	12	11

Before proceeding, we should check if there is a general "background" trend in the wind difference number. Such a trend might be anticipated since *Jönsson* and *Fortuniak* (1995) have found a general decrease in northeasterly winds from the total set of the Lund wind data, compensated by an increase in southeasterly and southwesterly winds. The check shows that a trend is clearly visible, see Table 4 summing results from the six autumn and winter months. We find a general increase of persistent southwesterly winds, such winds being particularly common after 1885. (We may note that this coincides in time with the onset of the present global warming and eustatic sea level rise, but the relationship here is uncertain.) Applying linear regression to these data and dividing by 6, we obtain an average monthly secular increase of the wind difference number for October-March of

$$\dot{w} = 1.6 \pm 0.55 \text{ wind units/century}$$

which is significant at the 97 % level. This general trend should be eliminated to find "residual" secular changes for individual months.

Table 4. Wind difference number, sum of autumn and winter months (October-March).

Years	O-M
1825-1844	4
1845-1864	3
1865-1884	6
1885-1904	16
1905-1924	16
1925-1944	10
1945-1964	11
1965-1984	20

We are now ready to deal with the changes of the wind difference number (reduced for the general trend) between the two 80-year-periods; see Table 5.

Comparing Table 5 and Table 1 we observe that wind changes seem to be followed by changes of sea level one month later. Therefore, at the bottom of Table 5 we have included the sea level changes from Table 1, but here taking into account the sea level phase lag of one month; this phase lag will be explained below. From Table 5 we now find that changes of the wind difference number correspond excellently to changes of the sea level. Taking the phase shift into consideration, 5 1/2 of the 6 months (1/2 because of a zero value) exhibit the same sign for the changes in wind and in sea level. Performing a linear regression of the sea level change with respect to the wind change we obtain

$$\Delta H/\Delta w = 1.1 \pm 0.20 \text{ cm/wind unit}$$

A t-test with 4 degrees of freedom tells us that this is significant at the 99 % level. See also Figure 2!

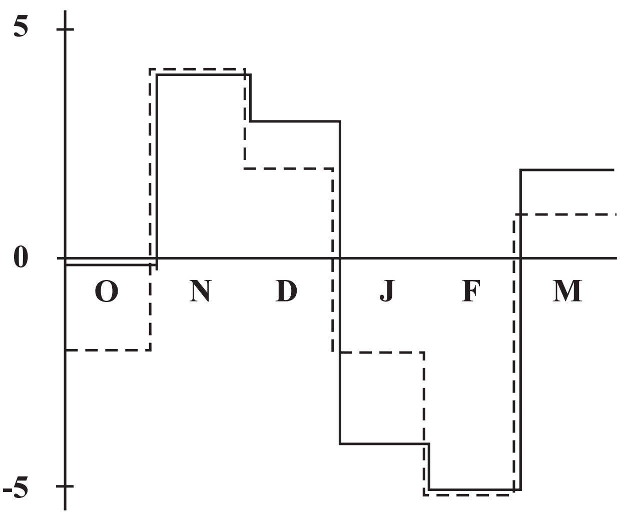

Fig. 2. Changes of monthly wind difference number (dashed line) and monthly mean sea level (continuous line, cm) for October-March, between the two 80-year-periods, according to Table 5. (Sea level phase lag of one month is eliminated.)

Table 5. Monthly wind difference numbers (reduced) for autumn and winter (October-March), as well as a comparison between their changes and corresponding changes of monthly mean sea levels from Table 1 (phase lag of one month eliminated).

Years	O	N	D	J	F	M
1825-1904	5	1	4	6	3	-2
1905-1984	3	5	6	4	-2	-1
Change	-2	4	2	-2	-5	1
Change, Table 1	0	4	3	-4	-5	2

The largest wind changes occur in November-December (increase) and January-February (decrease). To study this closer, one might use again the eight 20-year-periods. However, those results become less conclusive, mainly because the amount of data for each 20-year-period, using only two months, becomes somewhat too small.

Let us finally briefly return to the general trend above, i.e. the general increase of persistent southwesterly winds. This should contribute to a general sea level increase. Applying the ratio 1.1 cm/wind unit, found from the study of the individual months, to the general wind trend of 1.6 wind units/century, we can estimate this sea level increase to 1-2 cm/century.

5. *Discussion of results*

As mentioned earlier, southwesterly winds of sufficient duration cause a high sea level in the Baltic Sea and the adjacent part of the North Sea. However, it will normally take several weeks until the high North Sea water has been able to enter into the Baltic through the narrow and shallow Danish straits, including Öresund between Denmark and Sweden (*Stigebrandt*, 1984; *Matthäus* and *Schinke*, 1994). Therefore, long-term sea level in the Baltic Sea will appear with a time delay of more than half a month relative to the driving winds over the Baltic entrance (cf. also *Samuelsson* and *Stigebrandt*, 1996).

A secular increase of southwesterly winds in certain months should, consequently, cause a secular increase of the sea level in the Baltic Sea, although probably not in the same months but rather with a phase lag of one month. This is precisely what can be seen in our results above. The sea level changes fit to wind changes one month earlier as shown in Table 5 and Figure 2. Especially, this means that the secular sea level increase in December-January is preceded by a secular southwesterly wind increase in November-December, and the sea level decrease in February-March is preceded by a southwesterly wind decrease in January-February.

We noticed above that when looking in more detail at the wind changes the results become less conclusive. As mentioned this is partly due to the small amounts of data involved then, but we must also bear in mind that our treatment of winds is rather crude (there are e.g. no wind velocities included). Moreover, the neglected atmospheric pressure over Kattegat may contribute. To perform a more detailed investigation one probably would need to take these effects into account.

Based on the results obtained above we can now explain some unexplained effects seen in the sea level records used in two recent studies of vertical crustal movements. *Liebsch* (1997), analyzing the sea level series of Wismar and Warnemünde at the German Baltic coast, commencing about 1855, finds a season-dependent sea level trend with the maximum trend in December and the minimum trend in March. *Schmidt* (1998), analyzing the sea level series of Esbjerg at the Danish North Sea coast, commencing about 1890, finds a similar effect, with maximum in November and minimum in February. Both these observations reflect (the later part of) the secular change of the seasonal sea level variation described in *Ekman* and *Stigebrandt* (1990) as well as above, and can be nicely explained by the secular change of the prevailing southwesterly winds; see Table 5 and Figure 2. It should be noted that the one-month-difference between Esbjerg at the North Sea and Wismar-Warnemünde at the Baltic Sea is in good agreement with the phase lag discussed above.

6. Conclusions

The secular increase of the seasonal sea level variation in the Baltic Sea during the last two centuries is mainly due to secular changes in winter, causing a shift of the maximum sea level from July-August to December. We have found a significant secular increase of sea level in December-January and a significant secular decrease in February-March. The main origin of these appears to be changes of wind conditions over the transition area between the North Sea and the Baltic Sea, occurring one month in advance of the corresponding sea level change in the Baltic Sea. The phase difference is due to the time delay in sea level caused by the complicated entrance to the Baltic. During the six autumn and winter months (October-March) there is a significant monthly agreement between secular increase/decrease of southwesterly winds and secular increase/decrease of sea level as corrected for the phase lag. Finally, there is also a smaller but significant general "background" increase of southwesterly winds; this should cause a small corresponding increase of sea level.

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