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A Common Pattern for Interannual and Periodical Sea Level Variations in the Baltic Sea and Adjacent Waters

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Abstract

Based on annual mean sea levels from 56 reliable sea level stations the interannual sea level variation in the Baltic Sea, the Kattegat, the Skagerrak and the adjacent part of the North Sea is computed. All results are reduced to the same time span, the 100-year-period 1892 - 1991. The interannual sea level variation shows a distinct geographical pattern. The maximum occurs in the inner parts of the Gulf of Bothnia and the Gulf of Finland and the minimum in south-western Kattegat, the maximum being 3 times larger than the minimum. There is also a local maximum in the Oslo Fiord and a local minimum in north-western Skagerrak. In both the Kattegat and the Skagerrak there are fairly steep gradients.

The seasonal sea level variations of periods 12 and 6 months as well as the "pole tide" of period 14.3 months turn out to have patterns almost identical to that of the interannual variation. Thus all sea level variations on the time scale months to years in the Baltic Sea and its transition area to the North Sea are found to obey a common pattern. This indicates that they, to a large extent, should have a common origin, presumably wind stress.

The ratio between the maximum and the minimum - the enhancement factor e - is, however, different for different sea level phenomena. This factor is e = 3 for the interannual variation, e = 2 for the seasonal variation of 12 months, e = 4 for the seasonal variation of 6 months and also e = 4 for the "pole tide". It is suggested that the high values of e represent phenomena essentially caused by wind stress, and the lower e values phenomena caused by wind stress as well as salinity (and temperature) variations. A closer investigation should be undertaken of the driving mechanism(s) behind the common sea level variation pattern revealed here; this might contribute to the understanding of the relation between the Baltic Sea and the North Sea.

Key words: geodesy, sea level, interannual variation, seasonal variation, pole tide.

1. Background

It is well known that annual mean values of the sea level in the Baltic Sea may deviate by the order of 10 cm from the long term mean sea level. It is also known that

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such interannual sea level variations tend to be larger in the north than in the south of the Baltic Sea. This can be seen already from the tables in *Blomqvist* and *Renqvist* (1914). However, no systematic computation of this phenomenon seems to have been made.

We will here make a consistent computation of the interannual sea level variation within the Baltic Sea, the Kattegat, the Skagerrak and the adjacent part of the North Sea. This should give a clear picture of the geographical distribution of its "amplitude" within the area. Comparisons will then be made with the seasonal sea level variation and the "pole tide", revealing that all these sea level variations obey a common pattern, the existence of which does not seem to have been realized before.

2. *The interannual variation: computations*

The sea level stations used for computing the interannual variation are 56 stations in Russia, Finland, Sweden, Norway, Denmark, Germany, Poland and the Baltic countries (Latvia) that have reliable records spanning at least 60 years; see Figure 1, and also Table 1 in section 3. No less than half of these stations have records of about 100 years; one station, Stockholm, about 200 years. Most of them are mareographs recording continuously and operated by the national hydrographic services, but a few of them are other controlled tide gauges where daily readings have been performed.

The annual sea level data have been obtained mainly from the national hydrographic services (in the Nordic countries) and the Permanent Service for Mean Sea Level. The main exceptions from this are the oldest stations. Thus the data for Stockholm are those published by *Ekman* (1988); this is the longest continued sea level series in the world. It was first analysed by *Nordenskiöld* (1858), who could then estimate the interannual variations for the first time. The German data for Swinemünde, nowadays Swinoujscie, are the same as in *Montag* (1964); see also *Seibt* (1881, 1890). The German data for Kolberg, now Kołobrzeg, and Pillau, now Baltijsk, are from *Anderson* (1897) and *Hahn* and *Rietschel* (1938). The data for the Russian station Kronstadt are taken from *Bogdanov et al.* (1994); cf. also *Bonsdorff* (1891). Further information on the stations used can be found in *Ekman* (1996).

Stations or years that are not listed in Table 1 have been considered less reliable because of information in national hydrographic publications and/or comparisons with adjacent sea level stations.

As a measure of the interannual sea level variations we choose the standard deviation of the apparent land uplift as determined from annual mean sea levels during 100 years. (Alternatively one might use the standard deviation of an annual mean; the two quantities differ by a proportionality factor only.) The annual means are corrected for the lunar nodal tide of period 18.6 years whereafter linear regression is applied to give the apparent land uplift and its standard deviation; the apparent uplift rates are treated in *Ekman* (1996).

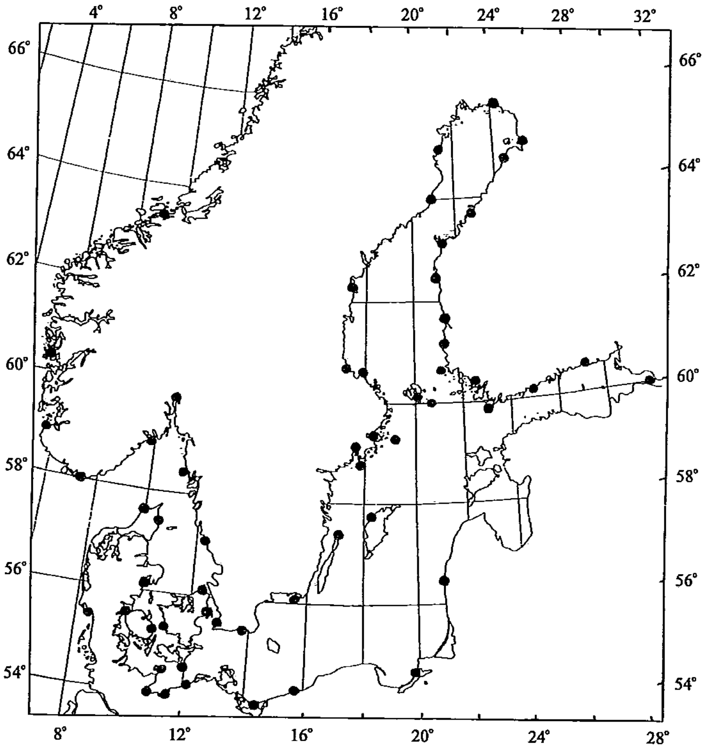

Fig. 1. Sea level stations in the Baltic Sea area (with series spanning 60 years or more).

In order to be comparable with each other, the results must refer to the same time period. Otherwise, changes with time due to climatic changes may be introduced. Let us take a look at Stockholm where the standard deviation has been as follows for different 50-year-periods:

s(1835 - 1884) = 0.57 mm/yr
s(1885 - 1934) = 0.47 mm/yr
s(1935 - 1984) = 0.61 mm/yr

The difference between the two last values is shown by an F test to be significant at the 93 % level, thus probably reflecting a real change from smaller to larger interannual variations in the Baltic sea level. A corresponding problem in the determination of apparent land uplift is well known; a significant secular change of this due to climatic change was shown by *Ekman* (1988) and *Woodworth* (1990).

As a standard period for the computations we select the 100 years 1892 - 1991, being common for many stations and avoiding extreme high water and low water years at the ends of the period. Any sea level station not containing these years is reduced to the standard period by comparison with a reference station containing all years. This presupposes that sea levels at different stations are closely correlated. This is the case in the Baltic Sea area, as found already by *Forssman* (1876). The reduction is made simply according to

$$s = (s_r/s_r')s' \qquad (1)$$

where s = standard deviation for the standard period of the station in question, s_r = the same of the reference station, s' = standard deviation for the actual period of the station in question and s_r' = the same of the reference station.

As the main reference station we select Stockholm since it is situated close to the middle of the Baltic Sea and has the longest record, covering the years of all the other stations. Although the level of the Baltic Sea is correlated with the level outside the Baltic, the correlation weakens when we reach the transition area between the Baltic Sea and the North Sea. Therefore, we adopt Smögen (with a few missing years extrapolated from Hirtshals) as a reference station for the Kattegat, the Skagerrak and the adjacent part of the North Sea. For the few stations at the Norwegian Sea, Bergen is used instead, although this might be questioned.

3. The interannual variation: results

The results are listed in Table 1. Based on this table the map in Figure 2 is drawn, showing a distinct geographical pattern. We find that the interannual sea level variation increases by a factor 3 as we go from western Kattegat through the Baltic proper into the Gulfs of Bothnia and Finland. The maximum standard deviation, 0.24 mm/yr, is found at Kemi and Kronstadt in the innermost parts of the Gulfs of Bothnia and Finland. The discrepancy between an annual mean sea level and the regression line may here reach 17 cm. The minimum standard deviation, 0.08 mm/yr, occurs at Fredericia in south-western Kattegat, where the corresponding discrepancy between an annual mean and the regression line does not exceed 6 cm.

In the transition area between the Baltic Sea and the North Sea we find fairly steep gradients in the pattern of the interannual sea level variation. A marked feature in the Kattegat is that the interannual variations are significantly larger along the Swedish coast (0.14 mm/yr) than along the Danish coast (0.08 mm/yr). In the Skagerrak there is a local maximum in the Oslo Fiord (0.16 mm/yr) while there is a local minimum (0.08 mm/yr) at the southern tip of Norway. At the adjacent North Sea coasts the variations are small at the Norwegian coast but larger at the Danish one.

Table 1. Sea level stations in anti-clockwise order around the Baltic with coordinates, time spans, and interannual sea level variations 1892 - 1991, expressed as standard deviations *s* in mm/yr of the apparent land uplift. (The figures may be converted to standard deviations of an annual mean (cm) by multiplying by 28.8.)

Mareograph	Lat.	Long.	Years	*s*
Kronstadt	59 59	29 47	1841 - 1916	0.24
Hamina	60 34	27 11	1929 -	0.24
Helsinki	60 09	24 58	1904 -	0.23
Hanko	59 49	22 58	1888 -	0.21
Turku	60 25	22 06	1922 -	0.22
Degerby (Åland)	60 02	20 23	1924 -	0.20
Lemström (Åland)	60 06	20 01	1889 -	0.20
Lypyrtti	60 36	21 14	1858 - 1922	0.19
Rauma	61 08	21 29	1933 -	0.21
Mäntyluoto	61 36	21 29	1913 -	0.22
Kaskinen	62 23	21 13	1927 -	0.22
Vaasa	63 06	21 34	1913 -	0.22
Pietarsaari	63 42	22 42	1915 -	0.23
Raahe	64 42	24 30	1923 - 1975	0.23
Oulu	65 02	25 26	1913 -	0.24
Kemi	65 44	24 33	1920 - 1976	0.24
Furuögrund	64 55	21 14	1916 -	0.23
Ratan	64 00	20 55	1892 -	0.22
Draghällan	62 20	17 28	1898 -	0.21
Gävle	60 41	17 10	1896 -	0.20
Björn	60 38	17 58	1892 - 1976	0.20
Stockholm	59 19	18 05	1774 -	0.20
Grönskär	59 16	19 02	1849 - 1930	0.20
Södertälje	59 12	17 38	1869 - 1969	0.19
Landsort	58 45	17 52	1887 -	0.19
Visby (Gotland)	57 39	18 18	1916 -	0.17
Ölands norra udde	57 22	17 06	1887 -	0.18
Kungsholmsfort	56 06	15 35	1887 -	0.17
Ystad	55 25	13 49	1887 - 1986	0.15
Klagshamn	55 31	12 55	1930 -	0.13
Varberg	57 06	12 13	1887 - 1981	0.14
Smögen	58 22	11 13	1895 -	0.13
Oslo	59 54	10 45	1914 -	0.16
(Nevlunghavn	58 58	9 53	1927 - 1965	0.12)
Tregde	58 00	7 34	1928 -	0.08
Stavanger	58 58	5 44	1914 -	0.10
Bergen	60 24	5 18	1883 -	0.12
Heimsjø	63 26	9 04	1928 -	0.16
Narvik	68 26	17 25	1906 -	0.20
Esbjerg	55 28	8 27	1889 -	0.16
Hirtshals	57 36	9 57	1891 -	0.13
Frederikshavn	57 26	10 34	1893 -	0.11
Århus	56 09	10 13	1889 -	0.09
Fredericia	55 34	9 46	1890 -	0.08
Slipshavn	55 17	10 50	1890 -	0.09
Korsør	55 20	11 08	1890 -	0.10

Mareograph	Lat.	Long.	Years	*s*
Hornbæk	56 06	12 28	1891 -	0.14
København	55 41	12 36	1889 -	0.12
Gedser	54 34	11 58	1892 -	0.12
Marienleuchte	54 30	11 15	1882 - 1944	0.12
Travemünde	53 58	10 52	1855 -	0.12
Wismar	53 54	11 28	1849 -	0.13
Warnemünde	54 11	12 05	1856 -	0.13
Swinemünde	53 55	14 16	1811 - 1944	0.14
Kolberg	54 11	15 34	1825 - 1944	0.15
Pillau	54 39	19 54	1840 - 1944	0.19
Liepaja	56 32	20 59	1865 - 1936	0.21

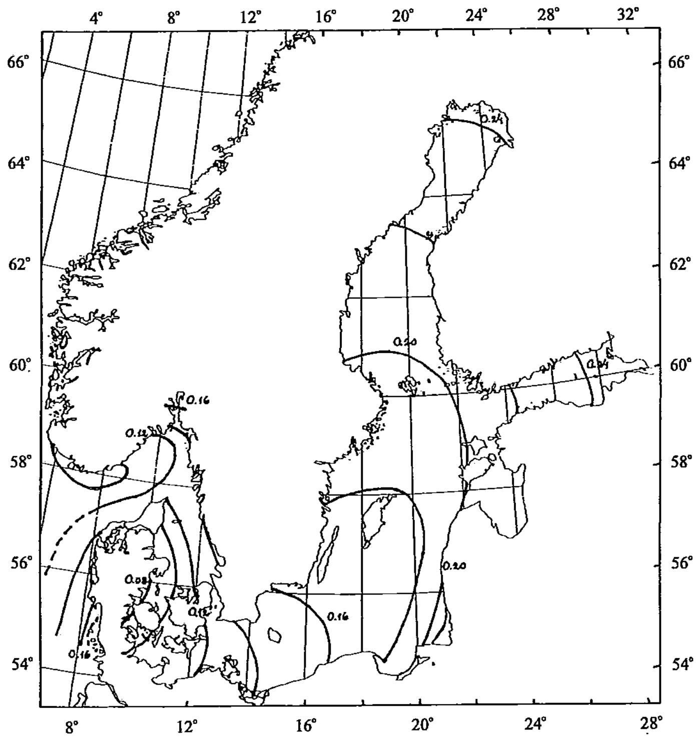

Fig. 2. The interannual sea level variation in the Baltic Sea area 1892 - 1991; standard deviations in mm/yr of the apparent land uplift (alternatively standard deviations of an annual mean (cm), if multiplied by 28.8).

4. *Comparisons with the seasonal variation*

Using monthly means it is possible to study the seasonal variation in sea level, applying harmonic (Fourier) analysis. The seasonal sea level variation is composed of two different variations: the annual one with a period of 12 months and an amplitude of about 10 cm, and the semi-annual one with a period of 6 months and an amplitude of around 3 cm. The total seasonal variation was first estimated by *Forssman* (1876), the separated ones by *Pattullo et al.* (1955).

A comprehensive study of the seasonal variation was performed by *Woodworth* (1984) based on the PSMSL data set, see also *Tsimplis* and *Woodworth* (1994). As in the case with the interannual variation the seasonal variation should be referred to the same time span for all stations; a significant increase of the annual amplitude with time was revealed by *Ekman* and *Stigebrandt* (1990) analysing the long Stockholm series. We now use the tables of *Woodworth* (1984), making here an approximate reduction to the same time span as in the previous section. The result is illustrated in Figure 3.

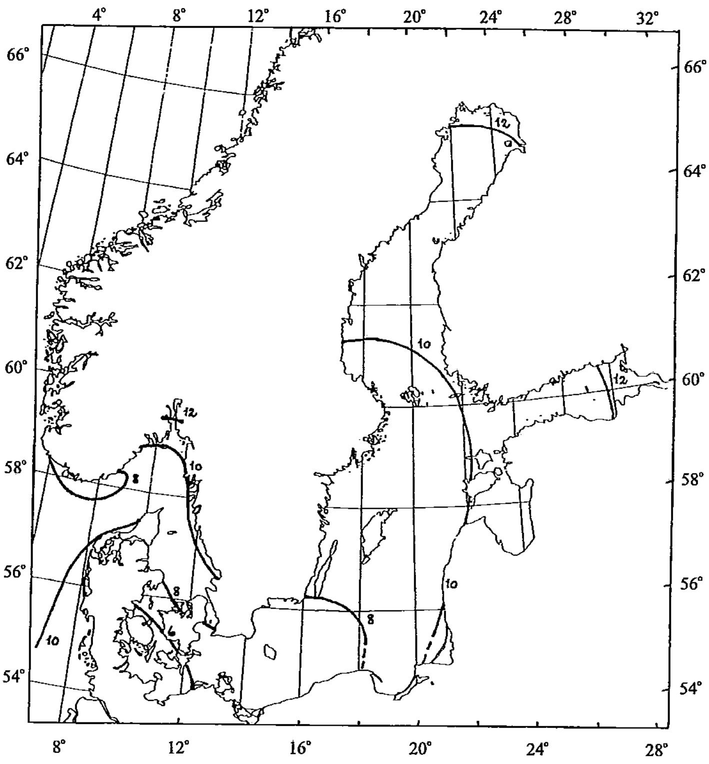

Fig. 3. The seasonal sea level variation of period 12 months in the Baltic Sea area during the present century; amplitudes in cm.

Comparing the main seasonal variation according to Figure 3 with the interannual variation according to Figure 2 we find a striking similarity in their geographical patterns. In both cases the variations show a minimum in western Kattegat and the Belt Sea, increase more or less continuously through the Baltic Sea, and reach a maximum in the inner parts of the Gulf of Bothnia and the Gulf of Finland. The increase is by a factor 2 for the seasonal variation (from 6 to 12 cm) compared to a factor 3 for the interannual one. The variations in the Kattegat are in both cases significantly larger at the Swedish coast than at the Danish one, and in the Skagerrak the local maximum in the Oslo Fiord and the local minimum at the southern tip of Norway are found in both cases.

The considerable similarity between the seasonal and interannual variations is valid not only for the main seasonal variation of 12 months but also for the smaller 6-month-variation; see Figure 4. The enhancement factor in this case is about 4 (the amplitude increasing from 1 cm in western Kattegat to 4 cm in the Gulfs of Bothnia and Finland).

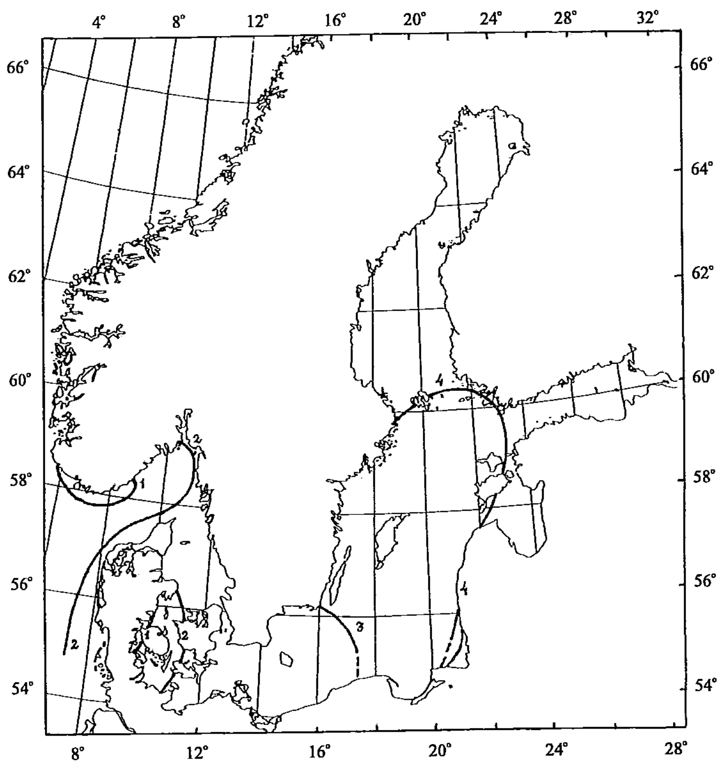

Fig. 4. The seasonal sea level variation of period 6 months in the Baltic Sea area (during the present century); amplitudes in cm.

5. *Comparisons with the "pole tide"*

There is another periodic sea level variation that may be studied using harmonic analysis of monthly means: the "pole tide". Its period is 14.3 months and its amplitude is around 2 cm in the Baltic Sea. The period happens to be the same as that of the polar motion (Chandler period), but the amplitude is much larger than that of the corresponding equilibrium pole tide (which is only about 0.5 cm). This was discovered by *Haubrich* and *Munk* (1959) and *Maksimov* and *Karklin* (1965).

Comprehensive studies of the "pole tide" amplitude were made by *Miller* and *Wunsch* (1973) and *Currie* (1975). Using their tables together with a few results in *Maksimov* and *Karklin* (1965) and *Plag* (1987), and making an approximate reduction to the same time span as earlier, we find a geographical pattern for the "pole tide" remarkably similar to that of the seasonal and interannual variations; cf. Figure 5. The enhancement factor is in this case about 3 (the amplitude increasing from 1 cm in the Kattegat to 3 cm in the Gulfs of Bothnia and Finland). Also here a significant secular increase of the amplitude has been discovered by *Ekman* and *Stigebrandt* (1990) from the long Stockholm series.

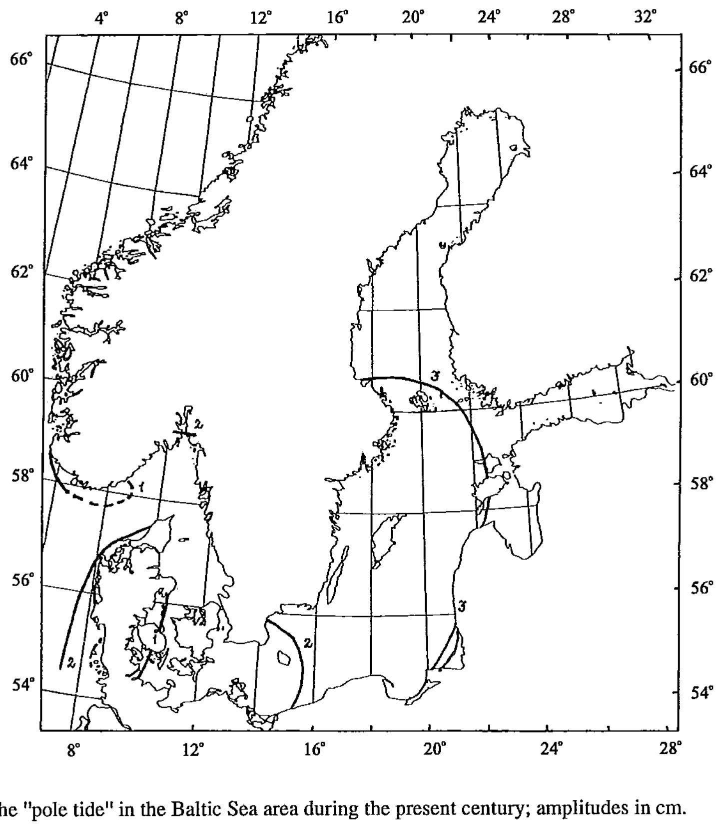

Fig. 5. The "pole tide" in the Baltic Sea area during the present century; amplitudes in cm.

6. *The common pattern - a brief discussion*

The interannual sea level variation, the seasonal sea level variations and the "pole tide" in the Baltic Sea area show a geographical pattern involving a maximum in the inner parts of the Gulf of Bothnia and the Gulf of Finland and a minimum in southwestern Kattegat, the maximum being around 3 times as large as the minimum. There is also a local maximum in the Oslo Fiord and a local minimum in northwestern Skagerrak; in both the Kattegat and the Skagerrak there are fairly steep gradients.

Thus all sea level variations on the time scale months to years in the Baltic Sea and its transition area to the North Sea have been found to obey a common pattern. This indicates that they, to a large extent, should have a common origin.

The interannual variation in the area is mostly ascribed to (air pressure variations and) wind stress, with a possible contribution from salinity variations (*Witting* 1943, *Rossiter* 1967). The seasonal variation is considered to be caused mainly by salinity and temperature variations, with a possible contribution from wind stress (*Gill* and *Niiler* 1973, *Lisitzin* 1974, cf. *Ekman* and *Stigebrandt* 1990). The "pole tide" was earlier believed to be a resonance phenomenon created by the polar motion (*Wunsch* 1974, 1986), or simply a random peak (*Vermeer et al.* 1988), but is nowadays considered mainly as an effect of air pressure or winds (*O'Connor* 1986, *Plag* 1987, *Trupin* and *Wahr* 1990, cf. *Ekman* and *Stigebrandt* 1990). Recently *Tsimplis et al.* (1994) have developed a numerical model for meteorological forcing in the North Sea. Their conclusion is that the "pole tide" as well as the 6 month seasonal variation are due to west-east wind stress, whereas the 12 month seasonal variation is due partly to wind stress and partly to oceanographic causes, i.e. salinity and temperature variations.

The common origin indicated by the common pattern of the different sea level variations in the Baltic Sea area should, therefore, be wind stress. It is interesting, in this context, to study the enhancement factor of the sea level variations, i.e. the ratio between the maximum and the minimum (cf. Figures 2 - 5). Denoting this factor by e, and subtracting the equilibrium pole tide due to polar motion from the observed "pole tide", we have the following values:

Sea level variation	e
Interannual	3
Seasonal, 12 months	2
Seasonal, 6 months	4
"Pole tide"	4

A possible interpretation of the e values could be the following. The "pole tide" and the 6-month-variation, with high values of e (e = 4), are essentially wind stress induced phenomena. The 12-month-variation, with an e value half of that (e = 2), is a phenomenon partly due to wind stress and partly to salinity and temperature variations. The interannual variation, with an e value in between (e = 3), is caused mainly by wind stress, but with some contribution from redistributions of salinity. These two causes may be coupled, as winds affect the inflow of salt into the Baltic.

It may be mentioned here that severe ice conditions during winter reduce the amplitudes of high-frequency variations only (*Omstedt* and *Nyberg*, 1991) and thus do not influence the present investigation.

An obvious field for further research is to investigate in more detail the driving mechanism(s) behind the common sea level variation pattern revealed here. This may contribute to the general understanding of the behaviour of the Baltic Sea and its relation to the North Sea.

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