Papers

The occurrence of the Chandler effect in the Baltic Sea and in the atmosphere of the adjacent region

OCEANOLOGIA, 41 (4), 1999.
pp. 515–536.

KEYWORDS
Atmospheric fields
Sea level
Pole tide
Seasonal oscillations
North Sea
Baltic

Andrzej Wróblewski
Institute of Oceanology,
Polish Academy of Sciences,
Powstańców Warszawy 55, 81–712 Sopot, Poland; e-mail:wroblew@iopan.gda.pl

Manuscript received 2 July 1999, reviewed 15 September 1999, accepted 22 September 1999.

Abstract

The Chandler effect (CE) has been shown to occur in the atmospheric pressure and geostrophic wind fields over the North and Baltic Seas and contiguous parts of Europe. The atmospheric pressure grid over the area bounded by 50°N–65°N and 0°E–30°E covers atmospheric fields that directly, or indirectly – via the North Sea – affect the variability of sea levels in the Baltic. The variances, amplitudes, phases and the 5% significance isolines of the CE atmospheric field oscillations under investigation and the first EOF of these fields were computed. Their characteristics were compared with an annual and a half-yearly period. Similar characteristics were computed for sea levels. The occurrence of CE is discussed in brief with respect to the North Sea, at six stations typifying the variability of the Baltic Sea level, and for the mean sea level in the Baltic basin. These oscillations in the Baltic Sea level are shown to have varied over a period of many decades. The amplitudes are compared with the oscillations under equilibrium conditions. It has been demonstrated that to a considerable extent, CE in the North Sea and in the zonal circulation force this phenomenon in the Baltic, and that internal forcing is of secondary importance. The wobbles of the Earth's axis of rotation are briefly characterised for the period under scrutiny. The basic computations were performed on the basis of data obtained between 1901 and 1980, *i.e.* reliable series of sea level readings, atmospheric data and variability in polar position.

1. Introduction

The pole tide in the atmosphere and oceans, also known as the Chandler effect (CE), is caused by variations in the Earth's rotational axis with respect to its mean geographic pole. The free oscillations of this pole have a variable period of around 14 months and an amplitude that ranges from $0.002''$ to $0.30''$ (Vondrák 1985). However, the circumstance eliciting the forcing of these movements has not yet been discovered. This forcing has sometimes been explained by earthquakes (O'Connell & Dziewonski 1976), variations in atmospheric angular momentum (Barnes *et al.* 1983) and the influences of global water storage (Hinnov & Wilson 1987). It is also thought that interannual changes in the global atmospheric masses are caused by the Earth's asymmetry – the northern hemisphere being mostly land and the southern hemisphere largely ocean. As the heat capacities of the two hemispheres are different, it is this effect which gives rise to the forcing (Hameed & Currie 1989).

Some authors have discerned CE in atmospheric pressures and winds, *e.g.* Maksimov (1952, 1960), Lamb (1972), Bryson & Starr (1977) and O'Connor (1986), but the forcing of CE oscillations in the atmosphere still remains to be explained. The possibility that the atmospheric pressure field is directly forced by the polar wobble has been discarded as unrealistic (Starr 1983). One plausible explanation, however, could be that such forcing is caused by non-linear interaction between the quasi-biennial oscillation and the movements of Icelandic lows with an annual period (Angel & Korshover 1974). Another type of forcing has been suggested: the movement of Icelandic lows is capable of eliciting the pole tide in the atmospheric pressure (Maksimov *et al.* 1967).

In marine dynamics CE is detectable principally in the form of sea level oscillations, *e.g.* Trupin & Wahr (1990). Such oscillations, due to CE, have been found several times greater in the North and Baltic Seas than those induced by centrifugal force under equilibrium conditions (Haubrich & Munk 1959, Miller & Wunsch 1973). The search for the eliciting circumstance has yielded diverse results: CE is thought to force sea levels, for example, by means of the zonal component of the wind over the North Sea (O'Connor 1986, Tsimplis *et al.* 1994), or the atmospheric pressure (Thompson 1980). Wunsch (1986) expressed the view that forcing is a random resonance of a bunch of long topographic Rossby waves in the North Sea and the direct influence of polar motion. The sea surface temperature has been found to display frequency peaks very near to CE (Naito 1983). The models used to estimate the pole tide in the deep ocean suggest the phenomenon should be explained in accordance with equilibrium theory (O'Connor & Starr 1983, Carton & Wahr 1986, Dickman 1988), but in the North Sea and Baltic this is clearly not the case.

So far only a few basic papers on the occurrence of CE in the Baltic have been published. One of them characterises data for Świnoujście between 1811 and 1943 (Haubrich & Munk 1959). Computations performed on data from over a dozen measurement stations between 1901 and 1930 have demonstrated the nature of the phenomenon (Maksimov & Karklin 1965). In addition, the long series of measurements from Stockholm between 1825 and 1984 has been analysed (Ekman & Stigebrandt 1990).

The aim of the present paper is to analyse the occurrence of CE in the Baltic at the various tide gauges and with respect to the mean level of this sea. The computations also include the characteristics of CE in atmospheric fields and in the North Sea, as these data are significant with regard to the forcing of sea level changes in the Baltic. Covering a set of uniformly long measurement series, the computations were performed simultaneously for the Baltic basin, the North Sea and atmospheric fields. The fundamental computations were based on the mean monthly values for 1901–1980. This particular period was chosen because of the dense grid of atmospheric measurements in Europe and the high reliability of sea level records. Detailed information on the variability of the Earth's axis of rotation is also available for this period.

2. Measurement data

In the present paper CE in the atmosphere over northern Europe was analysed statistically at grid nodes extending from 0° to 30°E and from 50°N to 65°N. The sub-grid covering the Baltic and the North Sea is delimited by co-ordinates 0°E–20°E and 50°N–60°N (Fig. 1). The computation was based on mean monthly atmospheric pressures. The grid nodes were located at every 5° of latitude and every 10° of longitude (Vose *et al.* 1992). Monthly mean sea levels in the North Sea were represented by data from Vlissingen and Esbjerg, and in the Baltic Sea by data from Kungholmsfort, Stockholm, Nedre Gävle, Ratan, Oulu and Helsinki (Spencer & Woodworth 1993). The measurement period was 1901-1980 and the basic time series for computations contained 960 items. The characteristics of the polar wobble during the period under investigation were gleaned from published data (Vondrák 1985). The geographical locations of the atmospheric pressure grid and tide gauges are shown in Fig. 1.

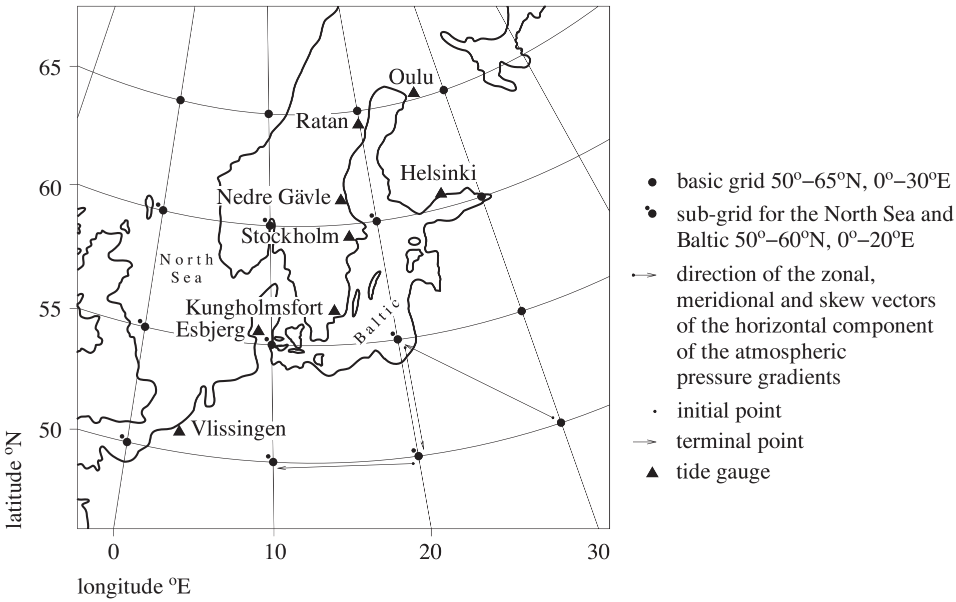

Fig. 1. Geographical location of the atmospheric pressure grid and tide gauges

3. The wobble in the Earth's axis of rotation and the equilibrium tide

Serious deviations in the occurrence of CE in the Baltic Sea and North Sea from equilibrium conditions have been reported in the literature. In order to give the reader some idea of CE forcing, the polar wobble during the period under scrutiny will now be outlined on general terms. There is a linear dependence between the total polar amplitude a integrated according to $\int_0^t (a - a_0)dt$, where a_0 is the mean amplitude, and the phase of the wobble. The phase determines the location of the wobble period in time. This relationship can be represented by the reciprocal dependence $-f = 0.816 + 0.0037/a$. However, this model does not yield reliable results for low amplitudes. During the period under analysis both the phase and the amplitude of the free oscillations of the Earth's axis of rotation were subject to considerable variation. The annual polar wobble affects the Chandler wobble, and the Chandler motion characteristics were computed on the assumption that the amplitude and phase of the annual polar changes were constant. In the early years of the 20th century the values of the phase were around 30°. In 1923–1940, a change occurred and phase values were now around 135°. During this change, the minimum amplitude was $0.05''$. In the computation period amplitudes varied within the interval $0.05''$–$0.30''$ with a standard deviation of $0.07''$ and a mean value for a 95% confidence interval of $0.16'' \pm 0.02''$. The phase changes are explained by oscillations in the CE amplitude calculated from measurement data. For various time intervals between 1901 and 1980 it was found that the period of oscillations ranged from 12.72 to 13.80 months. Some of these characteristics were obtained from plots included in the paper by Vondrák (1985) in which the occurrence of CE is analysed and modelled. The polar wobble characteristics indicate that the action of the related centrifugal force is a function of time with a large variability. The potential V of the centrifugal force of the Earth's rotation is given by the following formulae (*cf.* Lisitzin 1974):

$$V = -\frac{1}{2}\,\omega^2\,a^2\sin^2\Theta, \tag{1}$$

where
ω – angular velocity of the Earth's rotation,
a – average radius of the Earth,
Θ – co-latitude.

$$W_p = \Delta V = -\frac{1}{2}\,\omega^2\,a^2\,2\sin\Theta\,\cos\Theta\,\Delta\Theta, \tag{2}$$

$$\Delta\Theta = x\cos\lambda + y\sin\lambda, \tag{3}$$

where
W_p – potential of the Chandler deforming force,
x, y – rectangular co-ordinates of the current pole position in relation to its average position,
$\Delta\Theta$ – radius vector of the polar movement,
λ – longitude,

$$\Delta V = -\frac{1}{2}\,\omega^2\,a^2\,(x\sin\lambda + y\sin\lambda)\sin 2\Theta. \tag{4}$$

According to the equilibrium tide-generating force formula, the sea level deformity is

$$\xi = \frac{\Delta V}{g}\,(1 + k - h)\,, \tag{5}$$

where
ξ – sea level deformity,
k, h – tidal effective Love numbers,
g – acceleration due to the Earth's gravity.

Equations (1)–(5) have been combined to yield a short formula for Stockholm (Ekman & Stigebrandt 1990)

$$\xi = 5.5\,\gamma\,\sin(2\Theta)\,d\Theta, \tag{6}$$

where

γ = 0.68 (equivalent to $1 + k - h$),

Θ – co-latitude of the Stockholm latitude 59.3°N,

$d\Theta$ – 0.18$''$, the amplitude of the polar motion at the upper limit of the 95% confidence interval.

Assuming the Stockholm tide gauge to be representative of the Baltic (Wróblewski 1998a), the mean pole tide for equilibrium conditions in the Baltic is 0.6 cm.

4. Computations of atmospheric fields

The monthly mean atmospheric pressures at particular stations were interpolated into a regular geographical grid, the basis for interpolation for the period 1901–1980 being a dense network of stations. Nevertheless, it is obvious that the data were more accurate for grid nodes situated near measurement stations than for those interpolated on the basis of remote measurements. Another source of data inaccuracy is the weak and changeable CE forcing, which gives rise to variable phases and amplitudes, which are often concealed in the random atmospheric oscillations. Under these circumstances, the signal recorded at particular atmospheric stations at different frequencies of the CE band could be distorted by interpolation and the Fourier algorithm. CE was not computed from the mean signal in the whole band because of the possibility that noise oscillations with amplitudes near the significant level might be added. The highest peak in the CE band was therefore taken into consideration in the computations. However, this approach also has the disadvantage of diminishing the real occurrence of the phenomenon. These remarks should therefore be borne in mind when reading the computation analysis.

The Finite Fourier Transform was the principal tool in the search for the CE amplitude in the random oscillations. In the computations the annual period was a harmonic component of the basic period, which characterises its influence on the CE phase and amplitude. The significance of the amplitudes was assessed by the bootstrap method (Efron & Gong 1983), while the EOF method was applied to obtain a general presentation of the fields. The atmosphere was analysed for the zonal, meridional and skew horizontal components of the atmospheric pressure gradients and for the atmospheric pressures. In further analysis, these gradient fields can be regarded as geostrophic circulation fields, once the influence of the Coriolis force has been taken into consideration. The directions of the assumed gradients are shown in Fig. 1.

The amplitudes of the CE atmospheric pressure oscillation and their significance were computed for every node in the grid. The isoline of the 5%

significance level determined by the bootstrap method is presented in Fig. 2. From latitude 50°N to 59°N it is nearly parallel to the 0° line of longitude. At about latitude 60°N the isoline takes a more latitudinal course. The probable reason for the spatial distribution of the 5% isoline and other isolines around 55°N–60°N is the link with the trajectories of the centres of Icelandic depressions approaching central and northern Europe from the North Atlantic. CE atmospheric pressure amplitudes increase from south to north. The computed amplitude maxima are located in the vicinity of latitude 65°N. This is in agreement with the geographical occurrence of CE amplitudes in the measured sea levels, which in the Baltic Sea increase along the long axis of the basin from south to north. The equilibrium sea level CE amplitude in the northern hemisphere reaches a maximum of 0.81 cm at latitude 45°N, from which it decreases to 0 cm at the pole (Lisitzin 1974). Comparison of the equilibrium and measured CE amplitudes indicates that atmospheric forcing of CE is taking place in the Baltic Sea. The basic grid of atmospheric pressure has a mean CE amplitude of 0.67 hPa, which is lower than the mean amplitude of 0.91 hPa computed for the latitude belt 50°–60° (N and S) by Maksimov (1960) on the basis of measurements made in 1901–1913 and 1922–1933.

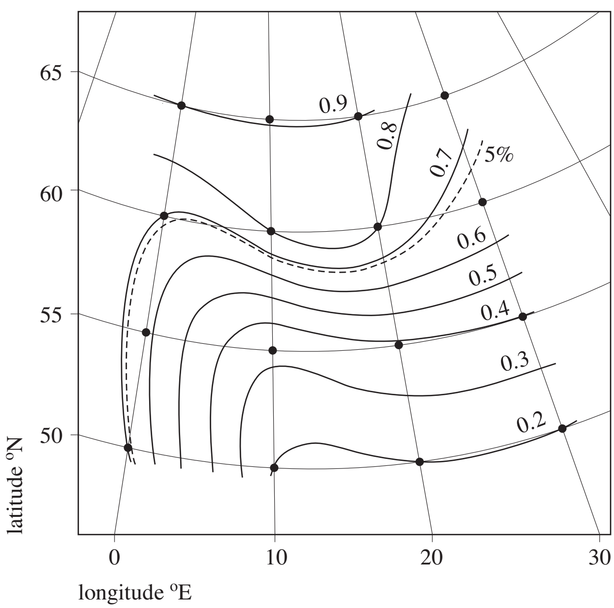

Fig. 2. Amplitudes [hPa] of the Chandler effect oscillations of atmospheric pressures at the grid nodes. Significance isoline 5% computed by the bootstrap method. Measurements 1901–1980

Table 1. Mean values of the Chandler effect and seasonal oscillations computed for monthly means of atmospheric pressure for records of 1901–1980

Characteristics	CE			Sa		Ssa	
	Amplitude	Phase [degree]	Period [months]	Amplitude	Phase [degree]	Amplitude	Phase [degree]
atmospheric pressure [hPa]							
basic grid	0.67	–138	14.64	1.95	42	0.67	–53
sub-grid	0.66	–127	14.83	1.40	33	0.59	–30
I EOF atmospheric	0.36	–143	15.00	0.41	153	0.40	–6
pressure (two peaks)	0.34	–152	14.33				
zonal gradients [hPa]							
basic grid	0.28	33	14.77	1.39	–138	0.34	14
sub-grid	0.30	33	14.77	1.36	–113	0.32	24
I EOF of zonal gradients	0.41	33	14.77	1.93	–168	0.36	5
meridional gradients [hPa]							
basic grid	0.38	12	14.44	1.49	–11	0.44	57
sub-grid	0.46	28	14.33	1.36	21	0.53	57
I EOF of meridional gradients	0.40	29	14.33	1.75	–9	0.37	87
skew gradients [hPa]							
basic grid	0.39	40	14.57	2.78	–19	0.40	–66
sub-grid	0.45	75	14.55	2.57	174	0.42	–88
I EOF of skew gradients	0.32	73	14.55	2.34	–179	0.23	–15

Table 2. Mean variance of the Chandler effect, annual and semi-annual oscillations as percentages of the total variance. Computations for monthly means of atmospheric pressure records from 1901–1980

Periodic oscillations	Basic grid [%]	Sub-grid [%]
Chandler effect	1.3	1.2
annual period	9.1	5.3
semi-annual period	1.2	0.9

The mean values computed from all the nodes of the atmospheric field grids and their first EOFs are given in Tables 1 and 2. On average, the CE amplitude at all the atmospheric pressure nodes is 34% of the Sa amplitude for the basic grid and 47% for the sub-grid. But the range of percentages of CE amplitudes at particular points in comparison with annual amplitudes is large: 8–105%. The amplitudes of CE oscillations are almost the same as those of Ssa tides. The variances of these atmospheric pressure oscillations are small in comparison to the total variance of the field (Table 2). The Sa period comprises 9.1% of the total variance with respect to the basic grid; the figure relevant to the sub-grid is 5.3%. CE and Ssa oscillations make up about 1% of the total variance for both grids. These results point to the largely turbulent nature of the atmospheric pressure oscillations. Nevertheless, Maksimov (1960) has suggested that at higher latitudes even small amplitudes should be an important factor in climatic variability for oscillations greater than Sa. With respect to the basic grid fields of the zonal, meridional and skew gradients, the mean percentages of CE amplitudes in comparison with Sa amplitudes are 20, 26 and 14% respectively. The CE and Ssa amplitudes of the first EOFs of particular fields (except for atmospheric pressure) and their values for mean fields are very similar. The mean CE periods of all the fields occur in the 14.33–15.00 month range. The isolines of CE in gradient fields and the EOF amplitude spectra of these fields are shown in Figs. 3–8. The CE isolines representing the highest values are located around the North Sea, Danish Straits and Baltic Proper. These computation results are in agreement with the general climatic characteristics of the sub-grid, which is located in the west-wind zone of cyclonic activity. In this region, groups of depressions frequently move eastwards from the North Atlantic to the European continent. The variable winds of the zonal circulation over both seas adjacent to the Danish Straits give rise to the well-known exchange of water through the Straits. The more random variability of the atmosphere in this area is presented in Table 2 as a smaller variance of the annual period in the sub-grid.

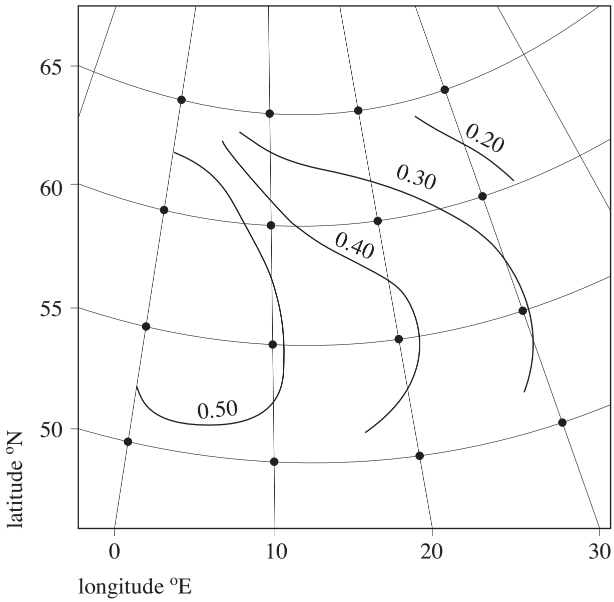

Fig. 3. Amplitudes [hPa] of the Chandler effect oscillations of the meridional gradient field. Measurements 1901–1980

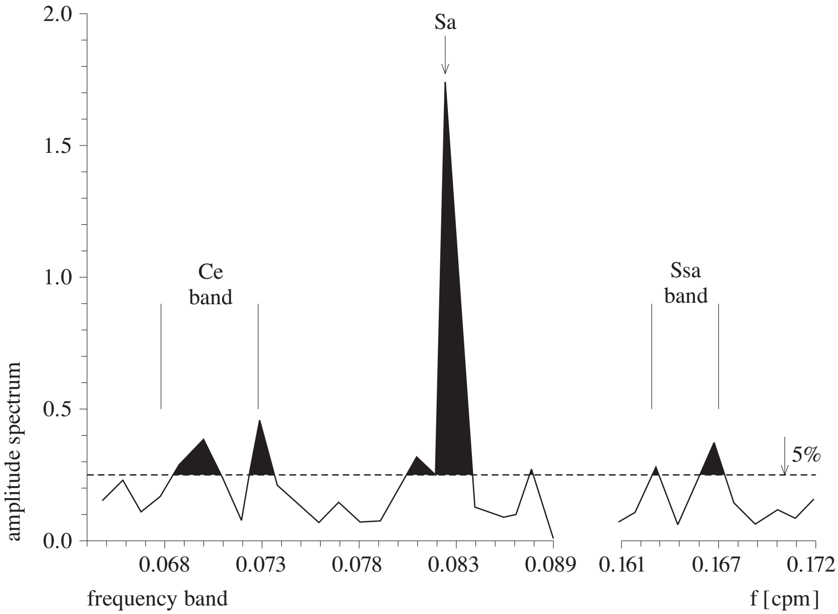

Fig. 4. Amplitude spectrum of the Chandler effect, annual and semi-annual oscillations of the first EOF computed from meridional gradients. Measurements 1901–1980

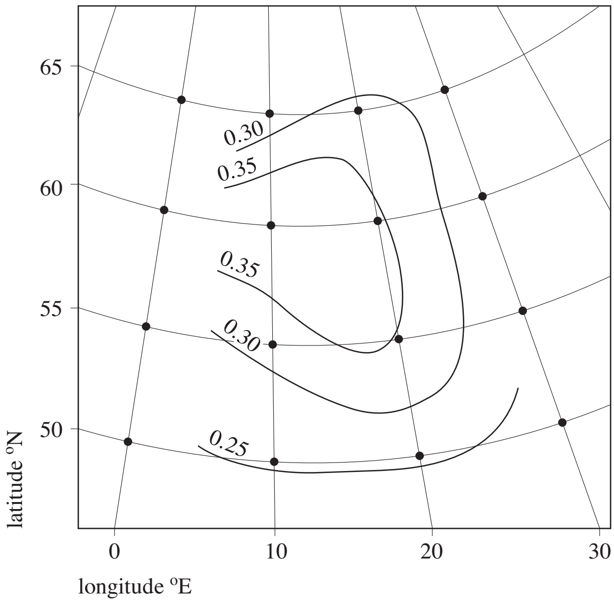

Fig. 5. Amplitudes [hPa] of the Chandler effect oscillations of the zonal gradient field. Measurements 1901–1980

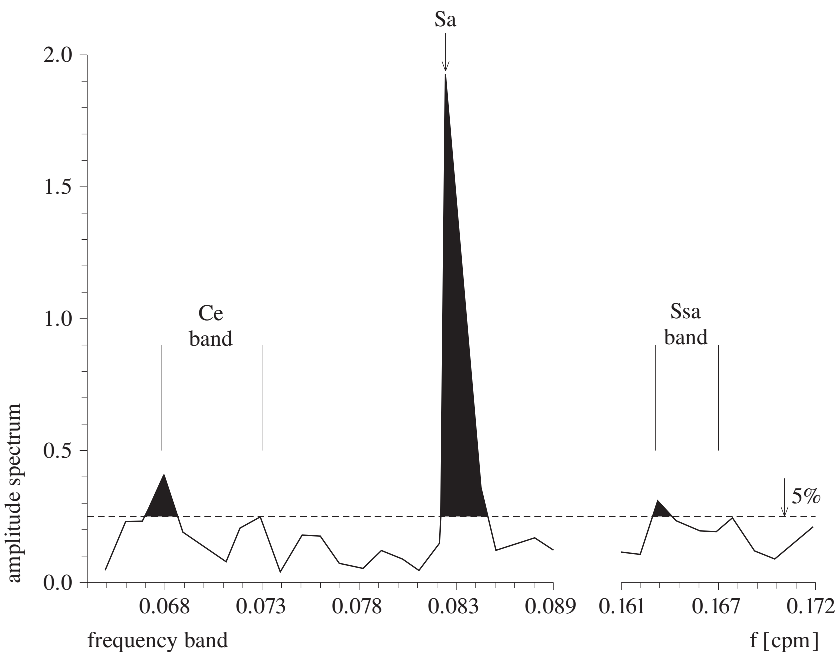

Fig. 6. Amplitude spectrum of the Chandler effect, annual and semi-annual oscillations of the first EOF computed from zonal gradients. Measurements 1901–1980

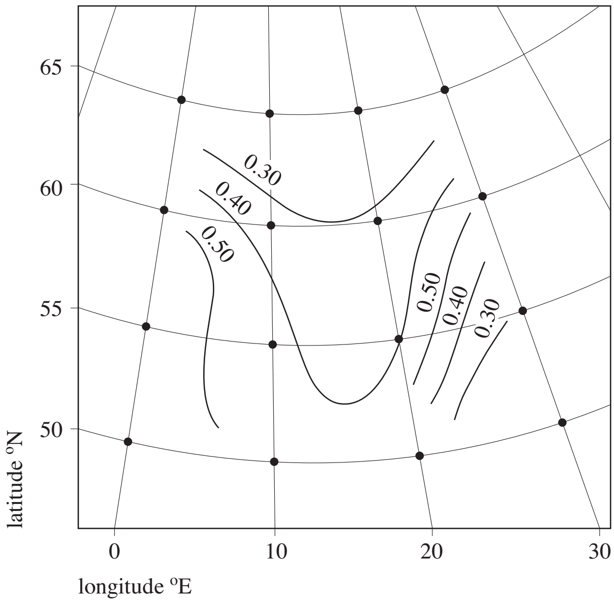

Fig. 7. Amplitudes [hPa] of the Chandler effect oscillations of the skew gradient field. Measurements 1901–1980

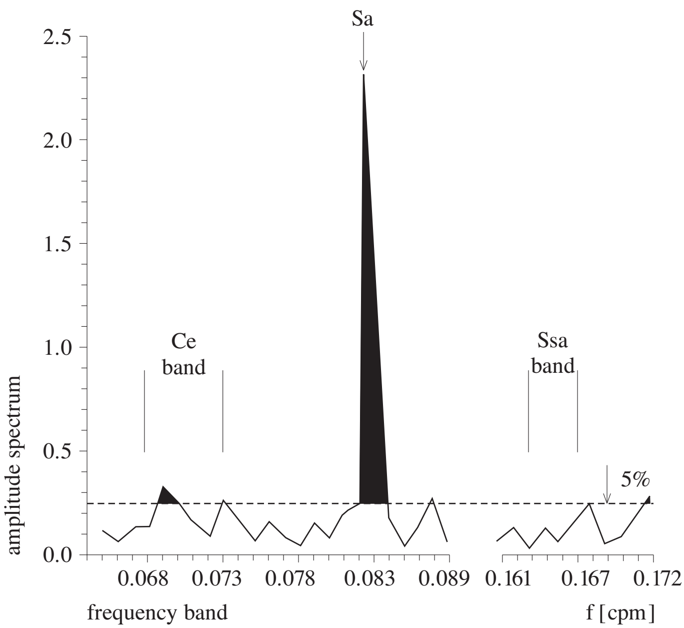

Fig. 8. Amplitude spectrum of the Chandler effect, annual and semi-annual oscillations of the first EOF computed from skew gradients. Measurements 1901–1980

It is worth mentioning that the main feature of the pole tide in the North Sea is its growth in amplitude and phase shift north-eastwards along the Dutch, German and Danish coasts. The atmospheric trace of this phenomenon is the CE rise in the zonal gradient field along these coasts from Vlissingen to Esbjerg. These characteristics of the winds are reflected by the isolines of the gradients. Local winds and other insufficiently understood phenomena are thought to be responsible for the occurrence of CE in the North Sea mean sea level. The mean level of the North Sea forces oscillations of the Baltic Sea level for seasonal and longer periods. From the point of view of these oscillations the Baltic Sea can be regarded as a fjord. The influence of the atmosphere on the Baltic Sea level exerts a double forcing there: a local one due to zonal winds determining the exchange of water through the Straits, and a more comprehensive one due to wind and atmospheric pressure fields forcing the mean level of the North Sea. Thus CE in the Baltic should in part be forced by the principal factors influencing seasonal and long-term sea level oscillations in that basin. The relevant computations will be carried out in the next part of the paper.

5. Sea level computations

Computations for sea levels were carried out on the basis of records from two tide gauges in the North Sea and six others in the Baltic. In the North Sea, the tide gauges at Vlissingen (Holland) and Esbjerg (Denmark) represented the earlier-mentioned rise in CE amplitude north-eastwards

Table 3. The occurrence of the Chandler effect and seasonal oscillations in series of tide gauge readings in the Baltic. Computations for monthly mean sea levels 1901–1980.

Tide gauge	CE		Sa		Ssa	
	Amplitude [cm]	Phase [degree]	Amplitude [cm]	Phase [degree]	Amplitude [cm]	Phase [degree]
Kungholmsfort	2.8	42	8.0	–66	3.4	75
Stockholm	3.2	40	9.4	–59	4.3	63
Nedre Gävle	3.1	37	10.5	–54	4.7	57
Ratan	3.7	40	11.0	–46	4.6	59
Oulu	4.1	46	11.1	–44	4.0	55
Helsinki	3.7	40	10.7	–58	4.2	64
mean sea level in the basin	3.1	40	9.2	–57	3.9	64

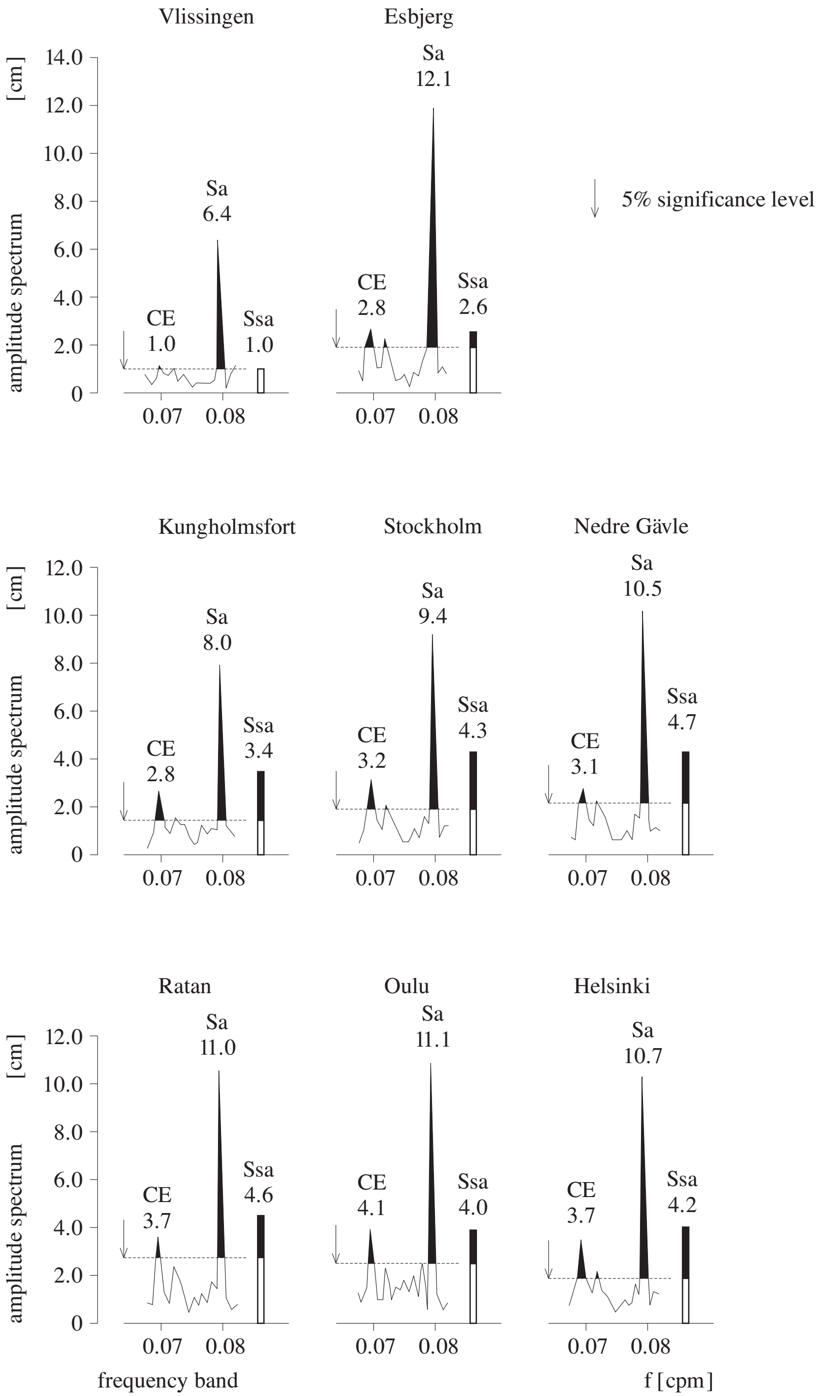

Fig. 9. Amplitude spectra of the Chandler effect and seasonal oscillations in the North Sea and the Baltic Sea. Measurements 1901–1980

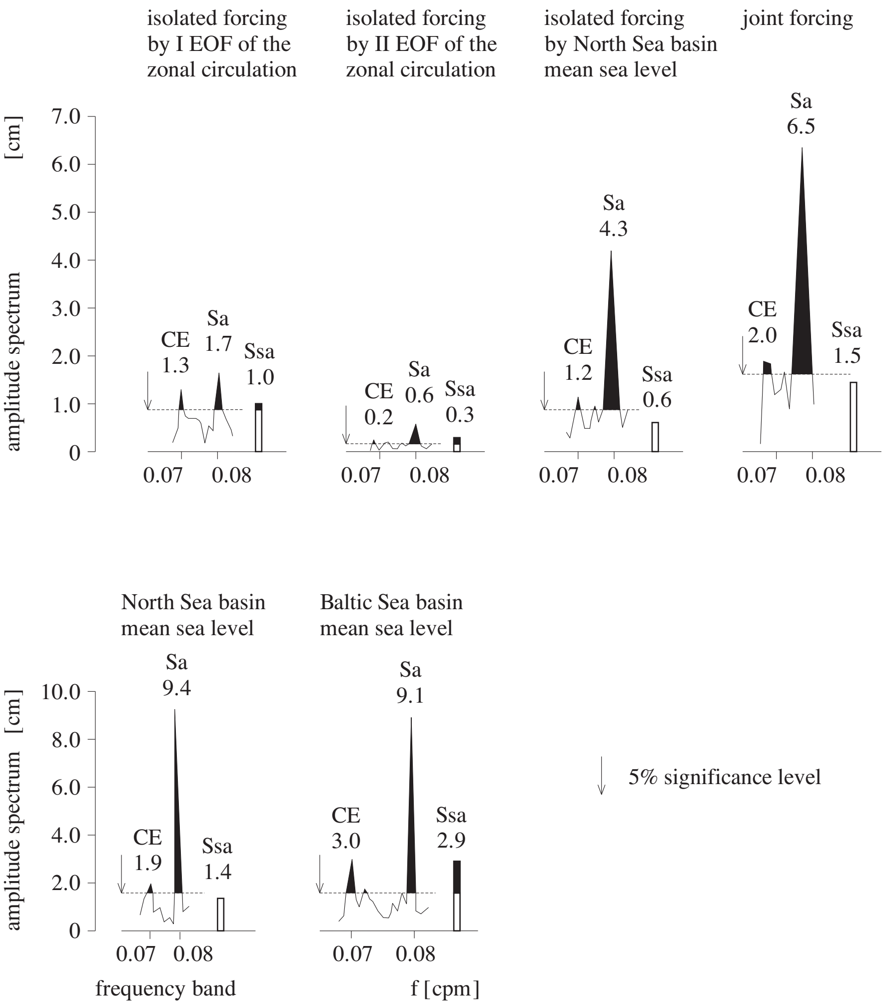

Fig. 10. Forcing of the Chandler effect and seasonal oscillations in the Baltic by the North Sea basin mean level and zonal circulation. Measurements 1928–1969

along the Dutch, German and Danish coasts. The mean sea level in the Baltic was computed by the EOF method from records of six tide gauges characterising the oscillations in that sea (Wróblewski 1992). The results of those computations are shown in Table 3 and in Figs. 9 and 10. The CE amplitude at Kungholmsfort is 2.8 cm at latitude 56°06′N and rises to 4.1 cm at Oulu (lat. 65°02′N). The CE amplitude of the mean Baltic Sea level was calculated at 3.1 cm. On the assumption that the area of the Baltic Sea is 392 000 km^2 (Ehlin & Mattisson 1976), the amplitude of the Baltic Sea volume due to the Chandler effect was calculated at 12.2 km^3. The CE oscillation period for all the computed series and mean sea level is 14.33 months, and is very regular in occurrence. The discrepancy among the periods, which is evident in the mean atmospheric fields and even more so in the readings from the various grid nodes, does not show up in the sea levels. Under equilibrium conditions the CE amplitude for Stockholm, a measurement station representative of the Baltic, has already been computed according to formula (6) and is 0.6 cm. The volume amplitude is 2.4 km^3. The phase differentiation, conspicuous in the North Sea – it varies from –2° at Vlissingen to 22° at Esbjerg, is less obvious in the Baltic; there the phase is 40° for the mean sea level and lies within the 37–46° interval at particular tide gauges. The respective variances of CE, the annual and half-yearly periods are 2.3, 20 and 3.5% of the basin mean sea level total variance.

It is clear from the data in Table 4, which characterises the investigated variability in the Baltic Sea for three periods of 30 years each, that the annual period has the most stable amplitude and phase. However, the difference between extreme amplitudes is 3.8 cm – 33% of the maximum amplitude. The corresponding phase differences –16° and 25% – are not so obvious. For the half-yearly period the relevant differences are 3.9 cm and 64% for amplitude and 46° and 55% for phase. CE has a practically stable period of 14.40 months, amplitudes similar to Ssa variability and almost identical phases for the first two computation periods. In the final period, the phase changed signs, and differed by 168° in comparison with the phase of the previous period. The difference in extreme amplitudes was 2.2 cm, that is, 42% of the maximum amplitude. The very large phase change indicates that CE is the least stable of the oscillations examined. The criterion for assessing the occurrence of CE was the appearance of the maximum amplitude in the band where this effect occurred. Because

Table 4. The occurrence of the Chandler effect and seasonal oscillations in the mean sea levels of the Baltic for long-term measurement sries. Computations for the mean monthy sea levels of the Baltic Sea basin 1896–1985

Measurement	CE		Sa		Ssa	
period	Amplitude [cm]	Phase [degree]	Amplitude [cm]	Phase [degree]	Amplitude [cm]	Phase [degree]
1896–1925	3.0	76	7.7	–53	6.1	84
1926–1955	5.2	53	9.2	–65	2.2	57
1956–1985	2.0	–88				
	3.8	–115	11.5	–49	4.2	38
	2.5	74				

of the phase change of the maximum amplitude, the characteristics of the periods adjacent to that amplitude have been presented. The phase of only one of the three periods, its amplitude (2.5 cm) being much smaller than the maximum, was comparable with those of the previous computation periods. The computations illustrated in Table 4 give some idea of the difficulties involved in assessing the characteristics of CE which, because of the irregularity and weakness of their amplitudes, are very often not much above the noise level or are concealed within it.

The CE of the mean Baltic Sea level is almost in phase with CE in the zonal and meridional gradient fields of the sub-grid. Skew gradients follow 35° after CE (Tables 1 and 3). With regard to the atmospheric pressure field, the CE phase difference is 167°, which indicates that sub-grid atmospheric pressures are not the force eliciting the investigated oscillations in the Baltic. The zonal circulation field has a well-known influence on the external forcing of CE. Internal forcing in particular sub-basins of the Baltic may be due to the meridional circulation field. The Danish Straits act as a low-pass filter for the water masses entering the Baltic from the North Sea. The mean sea levels in both basins are coherent at the 1% significance level for frequencies lower than 0.36 cpm (Wróblewski 1998a) and their CE phase difference is 8°. For the CE frequency this filter is transparent, hence the North Sea does force CE in the Baltic; this has been amply demonstrated by the computations in this paper. Computations in this respect can be performed only for the period 1928–1969, owing to the problems involved in working out the mean level of the North Sea (Wróblewski 1998b). The mean level of the North Sea and the I and II EOF of the set of gradients representing the zonal circulation over the Baltic,

Table 5. A comparison of the occurrence of the Chandler effect in the North and Baltic Seas, and fundamental exciting forces. Computation for monthly means 1928–1969

Measurement series	CE			
	Amplitude	Phase [degree]	Period [months]	Percentage of total variance
mean Baltic Sea level	3.0 cm	–77	14.0	2.3
mean North Sea level	1.9 cm	–89	14.0	1.6
I EOF of the zonal circulations	0.31	–92	14.0	1.0
(two peaks)	0.36	164	13.6	1.4
II EOF of the zonal circulations	0.134	51	14.8	1.1

Danish Straits and the area of the North Sea adjacent to the Straits are assumed to be predictors of the Baltic Sea level. A detailed description of these predictors can be found in the above-mentioned paper on the mean North Sea level. In general, the influence of the wind on CE in the Baltic has already been explained briefly in the previous description of oscillations in the atmosphere. In view of the precision of the calculations and the fact that the time series under consideration was relatively short, weighting functions of a stochastic dynamic system of constant parameters were not applied. Thus, a regression system with the elimination of predictor collinearity has been introduced which, though simpler and more accurate, is devoid of any dynamic reference. Characteristics of the predictand and predictors are presented in Table 5. The multiple regression formula for collinear predictors is

$$\xi_(t) = 2.87\alpha_1(t) - 2.24\alpha_2(t) + 0.57\alpha_3(t) + \varepsilon(t), \tag{7}$$

where

$\xi(t)$ – mean sea level of the Baltic Sea basin (mean = 0),
$\alpha_1(t)$ – I EOF of the zonal circulation,
$\alpha_2(t)$ – II EOF of the zonal circulation,
$\alpha_3(t)$ – mean level of the North Sea basin (mean = 0),
$\varepsilon(t)$ – error of the computations (the mean absolute error = 7.1 cm).

The results given in Fig. 10 show that 40% of the CE amplitude in the mean Baltic Sea level is generated by the isolated influence of the mean North Sea level. The respective proportions of I EOF and II EOF are 43% and 7%. The combined influence of the predictors makes up 67% of the amplitude. The computations covered these fundamental exciting forces for a period of 42 years and, because of the coherence indications described, were more exact for longer periods of the periodicity band analysed.

6. Conclusions

The Chandler effect has been analysed for large atmospheric fields covered by the grid over central and northern Europe and for an area of special importance for the exchange of the water through the Danish Straits. This sub-grid has more random variability and extends over the North Sea, the Baltic Proper and central Europe in the vicinity of these basins. The Chandler effect in Baltic Sea levels and its forcing were also analysed. The fundamental atmospheric fields analysed are the atmospheric pressure, as well as the zonal, meridional and skew horizontal components of the atmospheric pressure gradients.

In the basic grid fields (Table 1), CE occurred at the 5% significance level for many nodes and in general is responsible for 1.3% of the atmospheric pressure field variance oscillations. The annual and semi-annual period variances are 9.1 and 1.2% respectively. Its mean amplitude is 34% of the mean annual pressure oscillation amplitude. In the basic fields the mean phase of CE varies from –138° for the atmospheric pressure to 40° for the skew gradient field. The mean periods occur in the 15.00–14.33 month range. Dissipation of the characteristics at the grid points is much greater.

The atmospheric pressure amplitudes of CE increase from south to north, the maxima occurring at 65°N in the basic grid. This is in agreement with the geographical occurrence of this phenomenon in the measured sea levels but not with the location of the equilibrium sea level oscillations in the northern hemisphere. This result points to the atmospheric forcing of CE in the Baltic Sea. In the sub-grid the trajectories of deep Icelandic lows are the most probable cause of the highest CE amplitudes, and the geographical position of the 5% isoline of the significance of the occurrence of CE in the atmospheric pressure field.

This analysis provides further, well-founded proof that the occurrence of CE in the atmosphere and its variability depend in general on geographical location. At particular grid points the characteristics of CE are very variable and influenced by the noisy oscillations of the atmosphere. Weak and unstable CE forcing by polar movements is the reason why this phenomenon occurs around the noisy level. The characteristics of Sa and Ssa are also very irregular and are affected by turbulent oscillations of the atmosphere.

For the six tide gauges lying on the long axis of the Baltic, the amplitude of the Chandler effect ranges from 2.8 to 4.1 cm, with the amplitude increasing northwards. The phase occurs in the 37° – 46° interval. The corresponding values for the mean sea level in the basin are 3.1 cm and 40°. The equilibrium tide with respect to the mean level of the basin is 0.6 cm. The period – 14.33 months – is the same for all computations. The respective variances of CE, the annual and half-yearly periods are 2.3, 20 and 3.5% of the overall variance of the basin mean sea level.

Analysis of CE of the mean Baltic sea level over three 30-year periods has shown that the maximum amplitude is 5.2 cm and the minimum 3.0 cm. The phase varies from 76° to –115°. The oscillation period of 14.40 months was practically stable. The present computations have shown that phases are the most changeable characters of CE variability in the Baltic. It has also been shown that it is difficult to select the appropriate CE phase and amplitude from adjacent data whose significant amplitudes are very similar but whose phases are markedly different.

The sea level forcing (known from the literature) in the Baltic due to zonal circulation winds in the Danish Straits area and the mean level of the North Sea also applies to CE. For the period 1928–1970 the CE phase difference in the levels of the North and Baltic Seas is 8°. The mean Baltic Sea level and the mean zonal and meridional gradient fields of the sub-grid are almost in phase for the period 1901–1980. For this period of sub-grid measurements the skew gradient field has a phase difference of 35°, while for the atmospheric pressure field this difference is 167°. As regards external forcing of CE, only the zonal circulation field has any influence. Internal forcing in particular sub-basins may be due to the meridional circulation field.

Along with the mean North Sea level, the I and II EOFs of the zonal circulation in the Danish Straits area and adjacent basins were regarded as collinear input data. Then the separate and combined influences of these external exciting forces on the CE amplitude were computed by multiple regression. As far as the mean level of the Baltic is concerned, the combined effect of these forces makes up 67% of this amplitude. The separate effect of the North Sea comprises 40%, and the respective effects of the I and II EOFs of the zonal circulation 43 and 7% of the CE amplitude.

References

Angel J. K., Korshover J., 1974, *Quasi-biennial and long-term fluctuations in the centres of action*, Mon. Weather Rev., 102, 669–678.

Barnes R. T. H., Hide R., White A. A., Wilson C. A., 1983, *Atmospheric angular momentum fluctations, length-of-day changes and polar motion*, Proc. Res. Soc. Lond., A387, 31–73.

Bryson R. A., Starr T. B., 1977, *Chandler tides in the atmosphere*, J. Atmosph. Sci., 34, 1975–1986.

Carton J. A., Wahr J. M., 1986, *Modelling the pole tide and its effect on the Earth's rotation*, Geophys. J. Res. Astron. Soc., 84, 121–138.

Dickman S. R., 1988, *The self-consistent dynamic pole tide in non-global oceans*, Geophys. J., 94, 519–543.

Efron B., Gong G., 1983, *A leisurely look at the bootstrap, the jackknife and cross-validation*, Am. Statist., 37, 36–48.

Ehlin U., Mattisson I., 1976, *Volumes and areas of the Baltic Sea and its subbasins, water in the North*, IHP-News, 9 (1), 16–20, (in Swedish).

Ekman M., Stigebrandt A., 1990, *Secular change of the seasonal variation in sea level and of the pole tide in the Baltic Sea*, J. Geophys. Res., 95 (C4), 5379–5383.

Hameed S., Currie R. C., 1989, *Simulation of the 14-month Chandler wobble in a global climate model*, Geophys. Res. Lett., 16 (3), 247–250.

Haubrich R., Munk W., 1959, *The pole tide*, J. Geophys. Res., 64, 2373–2388.

Hinnov L. A., Wilson C. R., 1987, *An estimate of the water storage contribution to the excitation of polar motion*, Geophys. J. Res. Astron. Soc., 88, 437–459.

Lamb H. H., 1972, *Climate: present, past and future*, Methuen & Co. Ltd, London, 613 pp.

Lisitzin E., 1974, *Sea level changes*, Elsevier, New York, 286 pp.

Maksimov I. V., 1960, *Mutational phenomena in the high latitude atmosphere and their role in the formation of climate*, [in] *Problems of the North*, Nat. Res. Council Canada, 1, 103–123.

Maksimov I. V., 1952, *On the 'pole tide' in the sea and the atmosphere of the earth*, Dokl. AN USSR, 86, 673–676.

Maksimov I. V., 1956, *The polar tide in the world ocean*, Dok. AN USSR, 108, 799–801.

Maksimov I. V., Karklin V. P., 1965, *The Baltic polar tide*, Dokl. AN USSR, 161, 580–582.

Maksimov I. V., Karklin V. P., Sarukhangan E. I., Smirnov N. P., 1967, *The migration of the Iceland Low*, Dokl. AN USSR, 177, 3–6.

Miller S. P., Wunsch C., 1973, *The pole tide*, Nature Phys. Sci., 246, 98–102.

Naito I., 1983, *Response of the ocean to the Chandler wobble*, Mar. Geodesy, 7, 345–358.

O'Connell R. J., Dziewonski A. M., 1976, *Excitation of the Chandler wobble by large earthquakes*, Nature, 262, 259–262.

O'Connor W. P., 1986, *The 14-month wind stressed residual circulation (pole tide) in the North Sea*, NASA Tech. Memorandum 87800.

O'Connor W. P., Starr T. B., 1983, *Approximate particular solutions for the poletide in a global ocean*, Geophys. J. Res. Astron. Soc., 75, 397–405.

Spencer N. E., Woodworth P. L., 1993, *Data holdings of the permanent service for mean sea level*, Permanent Service for Mean Sea Level, Birkenhead, 81 pp.

Starr T. B., 1983, *On the dynamic atmospheric response to Chandler wobble forcing*, J. Atmosph. Sci., 40, 929–940.

Thompson K. R., 1980, *An analysis of British monthly mean sea level*, Geophys. J. Res. Astron. Soc., 63, 57–73.

Trupin A., Wahr J., 1990, *Spectroscopic analysis of global tide gauge sea level data*, Geophys. J. Int., 100, 441–453.

Tsimplis M. N., Flather R. A., Vassie J. M., 1994, *The North Sea pole described through a tide-surge numerical model*, Geophys. Res. Lett., 21, 6, 449–452.

Vondrák J., 1985,*Long-period behaviour of polar motion between 1900.0 and 1984.0*, Ann. Geophys., 3 (3), 351–356.

Vose R. S., Schmoyer R. L., Steurer P. M., Peterson T. C., Heim R., Karl T. R., Eischeid J. K., 1992, *The global historical climatology network: long-term monthly temperature, precipitation,sea level pressure and station pressure data*, ORNL/CDIAC–53 Rep., Oak Ridge, 99 + 189 pp.

Wróblewski A., 1998a, *Inter-annual oscillations of Baltic water volumes and sea level*, Oceanologia, 40 (3), 183–203.

Wróblewski A., 1992, *The application of EOF in determining basin mean sea level using computations for the Baltic as an example. In sea level changes: determination and effects*, Am. Geophys. Union IUGG, 23–28.

Wróblewski A., 1998b, *The effect of the North Sea on oscillations of the mean monthly sea levels in the Baltic Sea*, Cont. Shelf Res., 18, 501–514.

Wunsch C., 1986, *Dynamics of the North Sea pole tide reconsidered*, Geophs. J. Res. Astron. Soc., 87, 869–884.