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Research Article

CONTRIBUTION OF LONG-TERM TIDE COMPONENTS TO SEA LEVEL VARIATIONS

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Abstract

Some long-term sea level fluctuations at the Świnoujście gauging station reflect periodicities consistent with long-term components of the tidal forces of the moon and the sun as well as the planets. This paper presents results of a spectral analysis of monthly-normalized sea level values. Their relations with the long-term tidal force potential were determined. They can be the primary cause of sea level fluctuations.

INTRODUCTION

Average sea level is the reflection of interactions of all the factors that influence water level fluctuations in the sea and the result of factors determining its water balance as well as factors creating global geophysical changes. The Baltic Sea is a world ocean region characterized by the longest series of water level elevation data. This sea area has a high concentration of gauge stations that are relatively uniformly distributed along the coasts. Of these, the Świnoujście gauge ($\varphi = 53^o56'$ N and $\lambda = 14^o17'$ E) has the longest series of data, documented by measurements that originated in 1811 (Skóra and Wiśniewski 1988).

The aim of the present paper is to describe long-term changes of sea level (such as long-term components of tidal forces of the moon, sun, and the planets) consistent with corresponding periodicity of the tidal force. This undertaking was prompted by the fact that the primary causes of long term cyclic fluctuations of sea level have not been analyzed very often to date.

MATERIALS AND METHODS

In earlier studies carried out by Montag (1967), Dziadziuszko and Jednorał (1987) and Wiśniewski (1978), the measurement data from the Świnoujście station were checked and their homogeneity was estimated. The mean error of calculation of the average annual sea level at Świnoujście was within the range of ±4mm[1].

Real observation data were used repeatedly in statistical compilation and various methods were applied to filter time series and smooth and estimate the spectrum [3 to 8 and 13 to 18]. Harmonic analysis and spectral analysis of the time series were performed for seasonal and long-term fluctuations (Kożuchowski 1996, Wiśniewski 1978). Next the directional coefficient of linear regression was calculated, and the interpretation of time series using spectral analysis was repeated.

Although static tidal theory cannot explain the real values of tides in the World Ocean, it does impact the explanation of their genesis (Skóra and Wiśniewski 1988). With this approach, Table 1 presents important components of the long-term variation of lunar and solar tidal force. The components presented are from Maksimov (1970) and adapted from the division of the potential of the tidal force into 385 harmonic components from Doodson (1921).

[1] Mareographs decrease the amplitude of fluctuations and readouts do not take into consideration the difference of water density. Additionally, mareographs does not do measurements during freezing. Error due to the impact of temperature and humidity on the paper readout tape and watch mechanism is also possible.

Table 1

Some important components of long-term variation in the tidal force of the moon and the sun (According to Maksimov (1970) and Doodson (1921)).

Argument number	Argument ψn	Coefficient (V_n)	Period (days)
058554	3h-p	0.00427	121.8
057565	2 h +N'	-0.00181	177.8
057555	2h	0.07287	182.6
056554	$h-p_1$	0.01176	365.1
—	—	—	18.05 years
055565	N'	0.06552	18.61 years
—	—	—	1600 years
055555 of the moon	0^o	0.50458	constant deformation
055555 of the sun	0^o	0.23411	constant deformation

Legend:

- "Saros" period = 18.05 years is the cycle of divergence of lines in the centre positions of the earth, sun and moon;
- Petterson's cycle = 1600 years is the cycle of divergence of lines of perihelium and perigeum position. Taking into consideration all the mean parameters of the sun and moon, the turn rates of particular arguments of forces for the mean solar day are:

p= the length of the moon perigeum = 0.11140408^o
h= the mean length of the sun = 0.98564734^o
p_1=the length of the sun perihelium = 0.00004707^o
N'=-N, where N is the length of rising of the moon's node orbit = 0.05295392^o

To calculate the wave magnitude of the long-term tide in the ocean, the equation of static tide theory is as follows [16]:

$$W=V(1-3\sin^2\varphi)\cos\psi \ [cm^2/s^2] \quad (1)$$

$$\Delta H = \frac{W}{g} (1 + k - h) \ [cm] \quad (2)$$

where:
W - potential of the force causing the wave,
V - wave coefficient,
ψ - wave argument,
ΔH - amplitude of water level fluctuations as a result of long-term tidal wave
(1+k-h) - multiplier expressing the elastic features of the earth’s crust = 0.670,
φ - latitude.

RESULTS

At Świnoujście, semi-annual and annual oscillations were clearly found among the fluctuations of the average water level. All the oscillations significantly exceeded the 0.95 confidence level. Other possible oscillations were 3-year, 5.6-year, 11-year, 18-year, and 90-year. The oscillations are presented graphically in Figure 1.

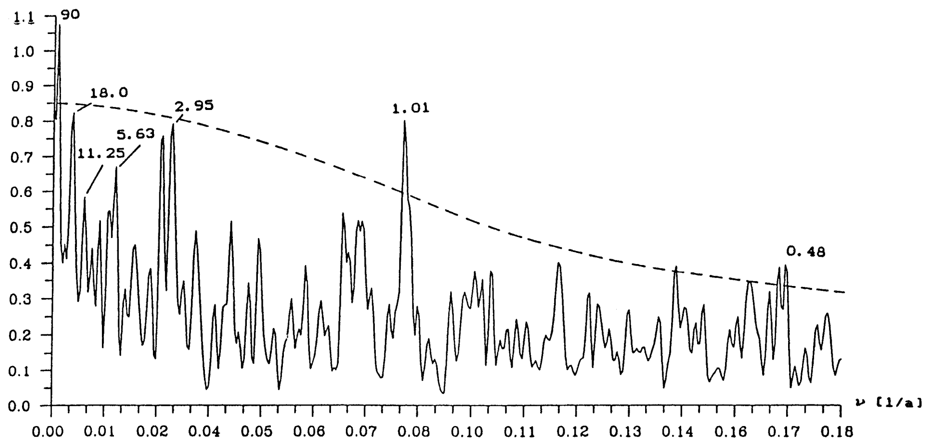

Fig.1. Spectrum of monthly-normalised sea level values in Świnoujście. Dashed line – significance level (α=0.05) for deviations from red noise (after Kożuchowski *et al.* 1996).

Taking into consideration the average water level fluctuations of the Baltic Sea, semi-annual and annual oscillations can be seen clearly. Thus, the interpretation of seasonal fluctuations should not be limited only to the annual radiation cycle. The annual and semi-annual solar tide should be mentioned among the phenomena that affect the annual distribution of mean sea level changes (Wiśniewski 1999).

The annual component of tidal force potential for the World Ocean is characterized by the following equation (Maksimov 1970, Wiśniewski 1978):

$$W_{sa}=153.8(1-3\sin^2\varphi)\cos(h_s-p_s)\ [cm^2/s^2] \quad (3)$$

where:
h_s- the mean length of the sun,
p_s=the length of the sun perihelium.

According to static tidal theory, such sea level fluctuations (ΔH) cannot be significant, and, theoretically the maximum for high latitudes is 21 mm. However, real investigations of periodic fluctuations of tides in oceans and seas proved that these fluctuations are many times greater (Skóra and Wiśniewski 1988). The mean amplitude of this annual oscillation calculated from the authors' data is ΔH_{sa} =58 mm, and the phase is f = 250°. This proves that the maximum oscillation occurs in the middle of September while the minimum is in March.

The semi-annual element of the potential of the solar tidal force (six components of the 057 group [Ssa]) is about 10% of the potential sum of all the 99 long-term components of that force and is expressed by the following equation (Maksimov 1970, Wiśniewski 1978):

$$W_{ssa}=0.08644G_s(1-3\sin^2\varphi)\cos 2h_s \quad (4)$$

where:
G_s- gravitational coefficient of the sun that is 12049 cm^2/s^2, according to Doodson.

The semi-annual solar tide in the World Ocean is theoretically a standing wave with extremes on the equator and the poles and the node line at 35° latitude. The amplitude is about 50% of the annual oscillation amplitude. Data from observations of this oscillation at Świnoujście indicate that ΔH_{ssa}=31 mm and the phase ψ=31°. Such magnitudes are consistent with the expected characteristics for latitudes of the Polish coast. The maximum of semi-annual oscillation is observed at the end of January and July, whereas the minimum is recorded in April and October.

The total value of annual and semi-annual oscillations corresponds to sea level fluctuations that were actually observed. Low water levels along the Polish coast are observed in March and April, while high water levels are recorded from September to November. The extremes of semi-annual oscillation cause the creation of secondary maximum and minimum values of sea levels. They cause the deepening of the minimum in April and May and strengthening of high water levels in August and September. Insignificant fluctuations of another origin overlap these oscillations.

A 90-year cycle of fluctuations separated by spectral analysis reflected the previously mentioned sea level rise at the beginning of the twentieth century. The cycle is connected with a secular climatic cycle found in the literature by Ernest Brown in the hypothesis on the tidal character of the solar activity at the beginning of the twentieth century. Just as the sun has an influence on the planets (the components of the solar tide), the planets also have an impact on the sun, *i.e.*, there are interactions between them. Maksimov (1970) separated the parallactic and declinational parts of tidal forces on the sun and presented a periodogram of centuries-long change in the Wolf number that suggest an 83-year cycle.

The potential of the moon's tidal force has a component with a change period of 18.61 years (Lisitzin 1956, Maksimov 1970):

$$W_{MN} = -0.03276 G_M (1\text{-}3\sin 2\varphi)\cos N' \qquad (5)$$

where:
G_M- gravitational coefficient of the moon's tidal force of 26160 cm^2/s^2.

Due to the fact that there are also other elements among multiyear components of tidal force, the period of an "18-year" component, the so-called nodal tide[2], is not constant, but ranges from 17 to 21 years. The potential value of the nodal tide is only about ten-fold weaker than semi-twenty-four hour and twenty-four hour tidal oscillation. Therefore, it is assumed that the potential has a significant impact on the water surface of the earth. The calculated amplitude for Świnoujście was ±11 mm.

Eleven-year fluctuations of the average water level depend on the sun's activity. The studies of multiyear changes of hydrometeorological processes have produced numerous descriptions of the 11-year cycles found in many papers. It can be assumed that the multiyear oscillation of the activity of the sun with a prevailing 11-year cycle causes, without any exception, 11-year quasi-periodic oscillations of all the meteorological indexes in the troposphere of the earth.

Six-year fluctuations of the average water level might be connected with the nutational cycle of the earth's axis and caused by the so-called polar tide. The wave of the "polar tide" is assumed to be a wave arising in the ocean as a result of changes in the centrifugal force of the earth connected with fluctuations of the rotation axis of the earth. That deforming force changes due to 14-month free and 12-month forced fluctuations of the rotation axis of the earth. The 12-month motions of the rotation axis of the earth are assumed to be caused by seasonal interactions of meteorological phenomena, mainly the exchange of air masses between oceans and continents and hemispheres. The 14-month cyclic fluctuations are connected directly with earth's shape and its rotation movement. For Świnoujście, the peak is shown at the period of 5.63 years. From earlier analyses of the periogram (Wiśniewski 197), 5-year periodicity is discernable with an amplitude of 7 mm and a phase of 276^o and 7-year periodicity with

[2] In the literature an 18.61 cycle is referred to as a 19-year nodal cycle.

an amplitude of 6 mm and a phase of 100º. In the current analysis, 6-year periodicity has not been seen clearly.

The current analysis also indicated that there are 3-year oscillations with an amplitude of 4.8 mm and a phase of 203º in Świnoujście. Although such periodicity is confirmed in the oceanological and meteorological literature, its origin is not sufficiently explained. Kowalik and Wróblewski (1973, 1974) also demonstrated the existence of such oscillation using a different research method based on the average annual sea levels in Świnoujście Port.

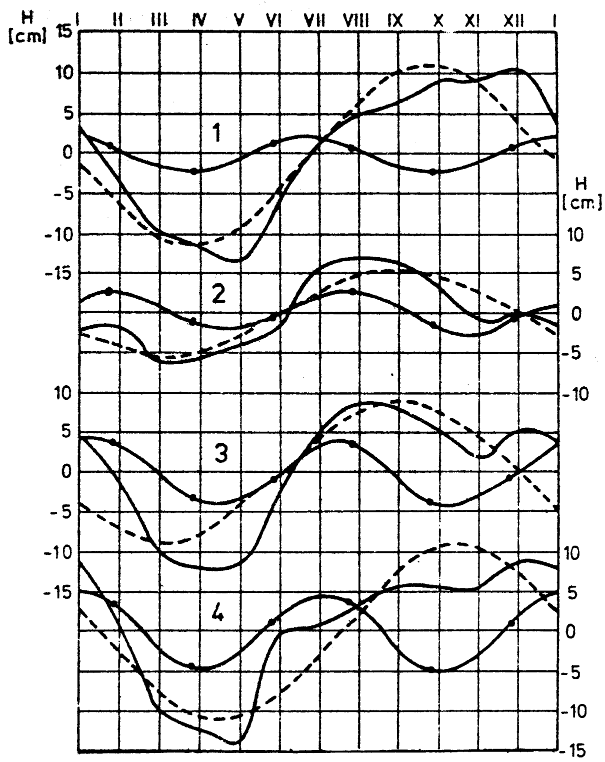

Fig. 2 Annual and semi-annual oscillation in comparison to the curve of real mean sea level (1891-1960) in [cm] at stations: 1. Ejsberg- North Sea, 2. Gedser – Danish Straits, 3. Landsort – central Baltic Sea. 4 . Oulu – Bothnian Sea [19]

monthly mean water level
annual oscillation
semi-annual oscillation

DISCUSSION

The results confirm some results from earlier publications. The 90-year cycle is controversial as it is equal to half of the observational series of about 180 years.

For the 18.6-year cycle, the amplitude of sea level fluctuations in Świnoujście is 17 mm and its phase is 248º. The results confirm earlier studies based on the methodology of Binderup and Frich (Kożuchowski 1994, 1996). In earlier investigations, when the century trend was not reduced, an amplitude of sea level fluctuations of 7 mm was reported (Wiśniewski, 1978). The differences could have been caused by the fact that isostatic motion had not been eliminated. Regardless of this discrepancy, the results confirm that, among the average sea level fluctuations in Świnoujście, there is an 18-year cycle dependent on the nodal tide.

The water level fluctuations at Świnoujście, as noted by Wiśniewski (1978) and Wróblewski (1974), included the 11-year cycle with the amplitude of 17.4 mm and a phase of 35º (1811-1968). However, it is not currently as obvious. In the present analysis, the 11-year cycle is insignificant. There is scant information about the 6-year cycle in the hydrological and meteorological literature, and, to date, nobody has associated it with the polar tide.

Many authors link annual oscillations with the radiation cycle. Only some of them, like Maksimov (1970), Lisitzin (1970), and Wiśniewski (1974, 1978), indicated the necessity of considering the annual and semi-annual potential of tidal forces as well. Figure 2 presents the real mean sea level and its annual and semi-annual oscillations at four chosen stations in the North Sea, Danish Straits, the central Baltic and Bothnian seas that confirmed this thesis.

CONCLUSIONS

Sea level deformations penetrate from the Atlantic Ocean into the Baltic Sea where they are shaped. They are generated by long-term components of the moon and sun's tidal forces. These include semi-annual and annual solar tides (that have an impact on seasonal changes), nodal tides (18.6-year), and polar nutational tides (about 6-year).

Increased solar activity can certainly be considered as one of the interactions in the geophysical planetary scale. The 90-year cycle, the 11-year cycle, and, to a certain extent, also the 3-year cycle, are linked to changes in this activity.

It goes without saying that for research on sea level fluctuations it is necessary to analyze measurements such as those at the Świnoujście gauge. Additionally, studies have to focus on such phenomena as long-term periodicity, climate variability, and geophysical force interactions.

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