

## VARIATIONS OF SEA LEVEL AT VARNA TIDE GAUGE 1928 – 2025

### VARIAÇÕES DO NÍVEL DO MAR NO MARÉLOGO DE VARNA 1928 – 2025

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#### Abstract

The sea level changes and global sea level rise are slow but permanent changes. They should be evaluated as a sign of ongoing climate changes. The Black Sea is a semi-enclosed sea, with the only connection to the world's oceans being the narrow strait of Bosphorus. Sea level observations in the Bulgarian part of the Black Sea are carried out mainly at the Varna and Burgas tide gauge stations. The most representative of them, with the most complete set of measurements, is the Varna station. The series of observations spread to a period of 97 years (1928-2025). All sea level data from the tide gauge station are corrected for the Earth vertical movements at the site. As a result of the analysis is to determine mean sea level and its changes, as well as the influences of long-term and seasonal tides. Only monthly data are available for this time interval. The monthly data series were analyzed using a least squares regression model. The model includes mean sea level, trend, decadal, annual, semiannual variations of sea level. The mean sea level was determined and a sea level of 1.3cm trend of about 1.4mm per year has been established. Hourly data since May 2013 are available for the tide gauge station. About 90,000 hourly values are available for the observation period 5.2013-12.2024. The period is sufficient to distinguish between multiple daily and semi-daily tides, as well as to establish the influence of the annual and semi-annual tides. The analysis is aimed to

#### Resumo

*As alterações do nível do mar e a elevação global do nível do mar são mudanças lentas, mas permanentes. Devem ser avaliadas como um sinal das mudanças climáticas em curso. O Mar Negro é um mar semi-fechado, com a única ligação aos oceanos do mundo sendo o estreito de Bósforo. As observações do nível do mar na parte búlgara do Mar Negro são realizadas principalmente nas estações maregráficas de Varna e Burgas. A mais representativa delas, com o conjunto de medições mais completo, é a estação de Varna. A série de observações abrange um período de 97 anos (1928-2025). Todos os dados do nível do mar da estação maregráfica são corrigidos para os movimentos verticais da Terra no local. Como resultado da análise, busca-se determinar o nível médio do mar e suas variações, bem como as influências das marés de longo prazo e sazonais. Apenas dados mensais estão disponíveis para esse intervalo de tempo. As séries de dados mensais foram analisadas utilizando um modelo de regressão de mínimos quadrados. O modelo inclui o nível médio do mar, a tendência e as variações decenais, anuais e semestrais do nível do mar. O nível médio do mar foi determinado e uma tendência de elevação do nível do mar de 1,3 cm, de cerca de 1,4 mm por ano, foi estabelecida. Dados horários desde maio de 2013 estão disponíveis para a estação maregráfica. Cerca de 90.000 valores horários*



determine the influences of long-periods and short-periods tides. The least squares harmonic analysis was used to for data series of hourly sea level values. The influences of about seventy statistically significant short-term tidal have been identified. Obtained results from the harmonic analysis from hourly data for the annual and semi-annual tides were compared with those from the linear regression model -monthly data.

**Keywords:** Mean Sea Level. Sea Level Trend. Harmonic Analysis. Tidal Constituents. Linear Regression Model.

*estão disponíveis para o período de observação de maio de 2013 a dezembro de 2024. O período é suficiente para distinguir entre múltiplas marés diárias e semidiárias, bem como para estabelecer a influência das marés anuais e semianuais. A análise visa determinar as influências das marés de longo e curto período. A análise harmônica de mínimos quadrados foi usada para as séries de dados de valores horários do nível do mar. As influências de cerca de setenta componentes de maré de curto prazo estatisticamente significativos foram identificadas. Os resultados obtidos da análise harmônica a partir de dados horários para as marés anuais e semianuais foram comparados com os do modelo de regressão linear - dados mensais.*

**Palavras-chave:** *Nível Médio do Mar. Tendência do Nível do Mar. Análise Harmônica. Componentes de Maré. Modelo de Regressão Linear.*

## 1 INTRODUCTION

Sea level change and global sea level rise are slow but persistent changes. They should be evaluated as a sign of ongoing climate changes. The Black Sea is a semi-enclosed sea, with the only connection to the world's oceans being the narrow Bosphorus Strait. The influence of climate changes in such an environment will be grater. Mean sea level plays significant role in scientific research and practice, especially in relation to the definition and implementation of the International Height Reference System (IHRs), while tidal observations provide key information for multidisciplinary scientific research and applications [1,2,3,4]. Observations to record the current level of the Black Sea and determine the mean values of the measurements are carried out by a network of tide gauge stations located in the coastal waters of the Republic of Bulgaria. Nowadays Bulgaria has five coastal sea level stations operated from years which were modernized in the period of 2009-2013 and equipped with radar sensors, communication and data management system. Two of them (Varna and Burgas) are between five oldest sea level stations in Europe [5] where the automatic sea level recording started in 1928 and radar sensors and computer data storage were installed in 2013. The new technologies applied allowed data recording every minute which gives new opportunities for data analysis.

## 2 USED DATA

Used data at this study is from sea level monitoring at the Varna tide gauge station on the Bulgarian Black Sea coast. The tide gauge station has been operating since 1928 is located at the port. During this early period, observations were made by a mechanical tide gauge and the data were pick out manually from diagrams. Since 2013, the tide gauge was replaced with a radar tide gauge, and data is transferred automatically at minute intervals. There is a substantial data series from 1152 monthly sea level data, for period from 1928 to 2025. There are some missing data due to technical difficulties, repair work, and other reasons. The missing data were filled using Caterpillar SSA software [6]. In the analysis, the filled data have lower weights (1/10) compared to the measured ones. Further processing of data series includes data correction for vertical movements of the earth's crust in the area of the tide gauge station. Data series are referenced in European vertical reference frame EVRF2007. The available data of hourly sea level values is about 90260 hourly values out of 102312 possible. Filling in data gaps is not necessary.

### 3 APPLIED METHODS USED IN DATA PROCESSING

Harmonic analysis, presents sea level as a sum of harmonics with at known frequency. The longer the series of observations the more tidal influences are determined. The unknown parameters are the amplitude -  $A_n$  and the phase shift -  $\omega_n$  of the tidal component.

The applied harmonic analysis using the least squares has some of the advantages. they are ability to process data series with missing values, estimate Rms for the obtained parameters.

From performed least squares harmonical analysis, the amplitudes and phases of multiple daily and semi-daily tides, as well as the influence of seasonal - annual and semi-annual tides, were estimated. A software package described in [7] was used to process the hourly sea level data.

The model used for least squares harmonic analysis is:

$$x^{mod}(t_i) = \sum_{q=1}^{n_{allc}} (E_{iq} a_q) + \bar{x} + \dot{x}(t_i - t_{ref}) \quad (1)$$

$$(t_i - t_{ref}) = (t_1 + t_n)/2$$

$n_{allc}$  all constituents,  $a_q$  complex amplitudes of constituent  $q$ ,  $E_{iq}$ - exponential function.

$\bar{x}$ - mean value of  $x$ ,  $\dot{x}$ ,- trend for reference time  $t_{ref}$

Linear regression model by least squares was used to process monthly mean sea level data. The model parameters corresponding to the mean sea level, the trend of change, annual, semi-annual, nodal tide, and others tidal influences. The conducted analysis, estimates mean sea level and its trend, as it reflects the constant changes in water mass.

From the sea level variations in time we can evaluate the impact of climate change on our surrounding environment. Linear regression models for processing monthly mean sea levels are presented in [8]. The least squares regression model applied for Analysis of monthly sea level data is:

$$X(t) = a_0 + a_1 t + \sum_{n=1}^3 [A_n \cos(w_n - \varphi_n)] + e(t) \quad (2)$$

$n_{allc}$  all constituents,  $a_q$  complex amplitudes of constituent  $q$ ,  $E_{iq}$ - exponential function.  
 $\bar{x}$ - mean value of  $x$ ,  $\dot{x}$ ,- trend for reference time  $t_{ref}$

The model includes parameters assessing the mean sea level, the trend of change, annual, semi-annual, nodal tide, and others tidal influences.

The monthly data series includes 1152 values, for the purposes of analysis the missing data were filled in. Using the software package described in [6].

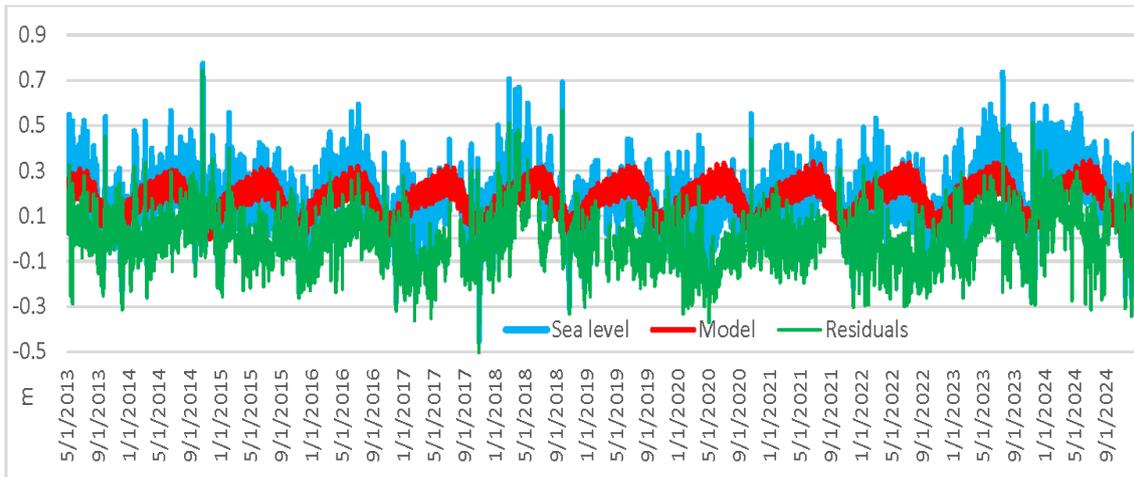
## 4 RESULTS

### 4.1 Harmonic analysis and results

Period of observations includes hourly sea level values for 05.2013-12.2024. Total of 68 tidal influences of varying periodicity have been identified. The determined mean sea value is 17.4 cm and a trend of 3.4 mm/year. The estimated mean sea level and trend values are not related to permanent changes, they are included as parameters in favor to determine tidal influences (Figure 1.).

**Figure 1**

*Hourly sea level data for period 5.2013-12.2024 for tide gauge station Varna*



The semi-annual tide SSA amplitude is 3.08 cm and phase of  $251.122^\circ$  has been determined.

The estimated value of the annual tide SA has been determined. The amplitude is the greater than all others tides - 8.5 cm and its phase is  $134.814^\circ$ .

The lunar tide was having also been estimated: Mm, the lunar monthly constituent (27.55 days), Mf, the lunar fortnightly constituent (13.66 days) MSf, the lunar synodic fortnightly constituent (13.77 days).

At the Table 1 is presented some of the results obtained, since the remaining tidal components have very small amplitudes - respectively, their influence on sea level change is smaller. The remaining tidal influences are respectively diurnal with index 1 and semi-diurnal with index 2.

**Table 1**

*Tidal constituents solved by harmonic analysis*

	PE	Amplitudes	Amplitudes	Phase	Phase
	%	[cm]	[cm] $3\sigma$	[ $^\circ$ ]	[ $^\circ$ ] $3\sigma$
'SA'	75.05	8.506	0.096	134.814	0.645
'SSA'	9.82	3.077	0.095	251.122	1.792
'M2'	5.54	2.310	0.095	9.122	2.359
'K1'	2.64	1.595	0.097	48.923	3.486
'S1'	2.33	1.500	0.135	248.820	5.165
'S2'	1.47	1.191	0.096	12.098	4.610
'O1'	0.66	0.795	0.097	45.450	7.019

'MSF'	0.62	0.776	0.096	218.047	7.072
'P1'	0.49	0.687	0.096	41.484	7.970
'MF'	0.33	0.561	0.096	120.539	9.776
'MSM'	0.32	0.553	0.096	294.998	9.936
'MM'	0.22	0.465	0.096	36.040	11.786
'N2'	0.20	0.441	0.095	6.904	12.326
'K2'	0.09	0.295	0.096	2.279	18.666
'PSI1'	0.04	0.190	0.096	356.766	28.969
'PI1'	0.02	0.152	0.096	72.394	35.962
'Q1'	0.02	0.144	0.098	30.819	38.895
'T2'	0.02	0.130	0.096	29.887	42.224
'NU2'	0.01	0.100	0.095	1.613	54.579
'PHI1'	0.01	0.095	0.096	46.933	58.310
'NO1'	0.01	0.093	0.087	24.095	53.601
'OO1'	0.01	0.091	0.085	52.253	53.597
'BET1'	0.01	0.090	0.097	42.217	61.885
'J1'	0.01	0.087	0.098	107.720	64.267
'L2'	0.01	0.084	0.094	42.948	63.972
'H2'	0.01	0.077	0.095	241.412	71.469

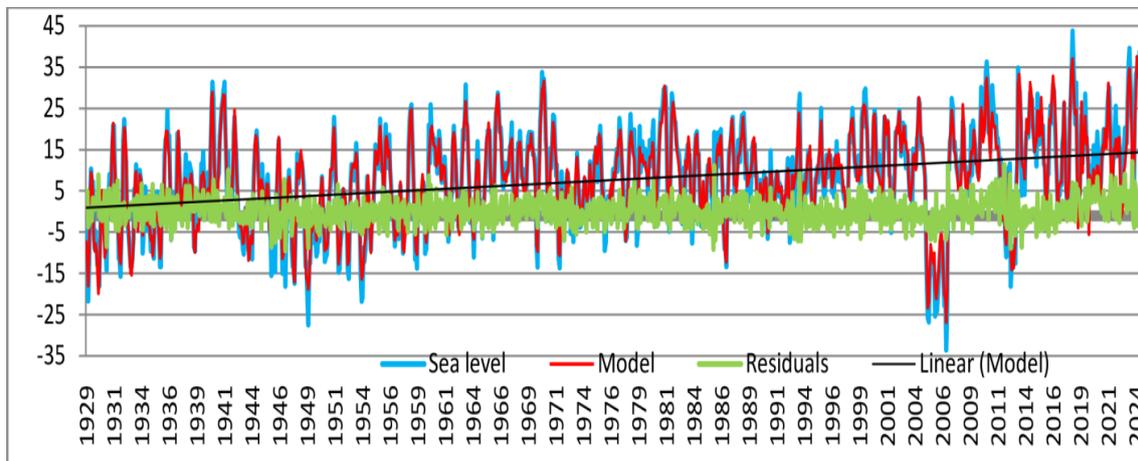
## 4.2 Least squares regression analysis and results

Monthly mean sea level data were estimated from hourly sea level values. The missing values have been filled in. The filled values have a weight coefficient for them in the equation  $-1/10$  compared to those obtained from measurements. The analysis identifies the influences of seasonal and long-term tides, determined the mean sea level for the period and its trend of change. The results of the analysis are presented in the Table 2 and 3. The annual SA tide has been determined, as is expected its amplitude is the largest - 6.72 cm, and its phase is  $305.00^\circ$ .

The semi-annual tide SSA has amplitude, three times smaller -1.84cm and a phase of  $160.72^\circ$ . The two tides represent the seasonal influences associated with monthly sea level data. The nodal tide and the pole tide are defined as significant long-term tides in the analysis of mean monthly sea level data. In Figure 2 is presented monthly sea level data for period 1928-12.2024 for tide gauge station Varna.

**Figure 2**

Monthly sea level data for period 1928-12.2024 for tide gauge station Varna



Nodal tide and pole tide are two types of gravitational forces that influence Earth's tides, they have different origins and effects. The nodal tide is a long-period tide (18.61 years) caused by the Moon's varying declination, affecting tidal amplitudes. The pole tide, results from changes in Earth's spin axis (polar motion), causing a time-dependent gravity signal that needs to be removed from measurements. Its period is about of 12-14 months. The obtained parameters for the nodal tide are amplitude of 2.35 cm and a phase of 60.29° (Table 2).

The pole tide amplitude is 1.16 cm and a phase of 329.03°.

Table 3 presents harmonics determined as significant including nodal tide and Pole tide. Their influence was established by spectral analysis of the observed data series.

**Table 2**

Mean sea level and trend and seasonal tides.

Mean [cm]	$a_0$	1.30	$3\sigma$	0.47			
Trend mm/yr	$a_1$	1.38	$3\sigma$	0.3			
Frequency	Period	Cosine coef	$3\sigma$	Sine coef	$3\sigma$	Amplitudes	Phase
	[months]	[cm]	[cm]	[cm]	[cm]	[cm]	[°]
0.0833	12	-3.857	0.33	5.508	0.33	6.72	305.001
0.1667	6	1.733	0.33	-0.606	0.33	1.84	160.724
0.0725	14.4	-0.999	0.33	0.599	0.33	1.16	329.031
0.0045	218.2	1.164	0.33	2.04	0.33	2.35	60.291

**Table 3***Least squares linear regression model tidal influences.*

Frequency	Period	Cosine coef	$3\sigma$	Sine coef	$3\sigma$	Amplitudes	Phase
	[months]	[cm]	[cm]	[cm]	[cm]	[cm]	[°]
0.0054	183.67	-1.635	0.33	0.007	0.33	1.63	359.740
0.0844	11.85	1.722	0.33	0.602	0.33	1.82	19.261
0.0113	88.62	-1.271	0.33	0.919	0.33	1.57	324.128
0.0104	96.00	1.049	0.33	0.847	0.33	1.35	38.908
0.0078	128.33	0.416	0.33	1.794	0.33	1.84	76.941
0.0061	164.57	-1.470	0.33	0.753	0.33	1.65	332.868
0.0130	76.80	1.044	0.33	0.139	0.33	1.05	7.594
0.0174	57.60	-1.755	0.33	-2.104	0.33	2.74	230.172
0.0226	44.31	0.597	0.33	2.811	0.33	2.87	78.005
0.0122	82.286	-0.317	0.33	-2.882	0.33	2.90	263.717
0.0547	18.28	-1.589	0.33	-0.433	0.33	1.65	195.256

## 5 DISCUSSION

The analysis of sea level data from the Varna tide gauge station, encompass two data series. Harmonic analysis was used for the hourly sea level series, and linear regression model was used for the monthly data series. The results obtained from the harmonic analysis are comparable to those presented in [9] and [10]. As a result, from an hourly series with a length of approximately 12 years, the influences of seasonal - annual, semi-annual tides have been successfully established. The influences of the tidal components of the lunar tide, Mm, Mf and Msf, respectively, have also been determined.

The mean sea level and trend estimates obtained from the hourly analysis are not related to permanent sea level changes. Their significance in the analysis is to assist in determining tidal influences. Also, a large number of daily, half-day and shorter tides were estimated. The influences of seasonal tides - annual and semi-annual have been successfully determined analysis of the monthly sea level data. The nodal tide as well as the pole tide has been determined. A mean sea level and a trend for the researched period of the order of 1-2 mm/year have been determined. The results obtained at this study are consistent with those of previous presented in [9] and [10]. The established trend does not deviate significantly from the changes in sea level on a global scale reported in [11] and [12].

## 6 CONCLUSIONS

The monthly data series for period of 1928-2024 has been processed. The estimated mean sea level for the period is 1.3 cm, with a trend change of 1.38 mm/year. The seasonal tides annual and semi-annual also have been determined. Amplitudes are 6.72 cm and 1.84 cm, respectively. The long-period nodal and pole tides have been established. A series of hourly data for the period 05.2013-12.2024 was processed. The harmonic analysis method by least squares was applied. About of 68 tidal influences were determined as significant.

The solar annual (SA) and the solar semi-annual tide - SSA have the greatest influence on sea level change. The estimated parameters for SA are amplitude of 8.5 cm with a phase of  $134.814^\circ$ , and for SSA respectively 3.08 with a phase of  $251.122^\circ$ .

The estimated amplitudes for the annual and semi-annual tides, from the analysis of monthly sea level values, are smaller than those determined by the harmonic analysis. The determined trend and mean sea level from the monthly sea level data identifying constant changes in sea level. Continuous sea level observations from tide gauges provide more accurate local sea level data than global altimetry surveys, which cover a larger area with lower accuracy. The sea level observations from tide gauge stations provides more accurate local sea level data than global altimetry surveys, which cover a larger area with lower accuracy. They key role is important to validating climate models and determining global sea level.

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### CONFLICTS OF INTEREST

The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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### **Authors' Contribution**

All authors contributed equally to the development of this article.

### **Data availability**

All datasets relevant to this study's findings are fully available within the article.

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