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SHORT AND TIDAL PERIOD SEA-LEVEL VARIATIONS ALONG THE TURKISH STRAIT SYSTEM

TÜRK BOĞAZLAR SİSTEMİNDEKİ KISA VE GELGİT PERİYOTLU SU SEVİYESİ DEĞİŞİMLERİ

BEDRİ ALPAR [1] , HÜSEYİN YÜCE [2]

[1] University of Istanbul, Institute of Marine Sciences and Management, Vefa, 34470 Istanbul, Turkey.
[2] Department of Navigation, Hydrography and Oceanography, Çubuklu, 81647 Istanbul, Turkey.

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Abstract

An analysis of the short-period and tidal sea-level variations is performed based on the measurements taken at the stations along the coasts of the Southwestern Black Sea, Strait of Istanbul (Bosphorus), Sea of Marmara, Strait of Çanakkale (Dardanelles) and Northeastern Aegean Sea. Short-period oscillations observed on the records were related to the natural periods of the straits and the Sea of Marmara itself. Tidal oscillations are small in amplitude and tidal regimes change along the Turkish Strait System.

Introduction

The Sea of Marmara and the straits of Istanbul and Çanakkale build a water passage system between the Black Sea and the Aegean Sea (Figure 1). Two shallow and narrow straits create a couple of control points along this system, which is known as the Turkish Strait System. The average length of the Strait of Istanbul is 31 km with an average width of 1.6 km (ranging between 0.7 and 3.5 km). Its average depth is 36 m, with a maximum of 110 m. On the other hand, the average length of the Strait of Çanakkale is 62 km with an average width of

4.0 km (ranging between 1.2 and 7 km). Its average depth is 55 m, with a maximum of 105 m (Gunnerson et al., 1974; Ünlüata et al., 1990).

Winds :

Short-term effects of wind on sea level are evident in the region which is affected by two distinct seasonal climatic regimes. During the winter, the weather is dominated by an almost continuous passage of cyclonic systems. During the summer, NE winds coming from the Black Sea, when they are a part of the seasonal N airstream, are dominant. When not blowing from the NE direction, winds are most often from SW. In the Strait of Istanbul, northerly winds are dominant from May to October with a frequency of 60%, while the southerly winds (SW-SE sector) occurring 20% of the time mainly in winter months. Cyclones coming from the Aegean Sea to the Black Sea in winter months change the physical structures of the Sea of Marmara. In the months scale, the dominant wind direction is NE-NW except in January when SW winds are also important (de Filippi et al., 1986). In the Strait of Çanakkale, the winds are most frequently from N and NE directions. In July and August, they blow with great persistence during the day. From October to March, the winds coming from the sector between SE and W are rather frequent. They are often strong and may sometimes reach gale force. Transient sea-level variations are due to wind forcing (Yüce, 1994).

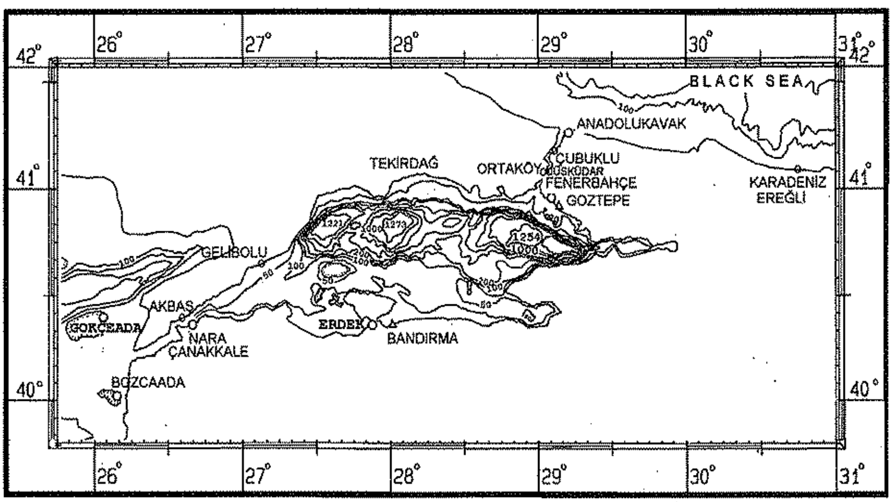

Figure 1. Location map of the permanent and temporary recording stations.

Short-term sea-level increases are due to the intense northerly winds prevailing for limited periods near the Strait of Istanbul. The short-term average sea-level rises up to 20 cm at the northern approaches of the Strait of Istanbul are due to the northerly winds (Ünlüata et al., 1990). The influence of southerly winds is more pronounced in the southern entrance of the Strait of Istanbul with an average sea-level increase. Consequently, the range of sea-level changes thus caused depends largely upon local conditions, being much more marked in bays and inlets than in more open places and may be as much as 30 cm.

Sea level changes:

Characteristics of the sea-level variations along the Turkish straits and the Sea of Marmara have only been partially studied in the past by Möller (1928), Smith (1946), Bogdanova (1965), Damoc (1971), Gunnerson and Özturgut (1974), De Filippi et al. (1986), Büyükay (1989), Ünlüata et al. (1990), Yüce (1986, 1991, 1993), Yüce and Alpar (1994, 1997).

Short-period oscillations:

In the Black Sea, the effect of deflecting forces on the short-period oscillations can not be ignored and Defant (1961), after filtering tidal constituents from the sea-level records, observed seiches with specific periodicities of 6.4 and 5.5 hours for Constanta and Bourgas, respectively. These natural periods differ considerably from those of the tidal forces for Black Sea and any influence from the Strait of Istanbul is hardly to be expected. On the other hand, the short-period oscillations with natural periods of one and three hours are known for the Strait of Istanbul and the Sea of Marmara, respectively. The amplitude of seiches in the Strait of Istanbul is as high as 10 cm. In the Strait of Çanakkale, the short-period oscillations with periodicities of 90 minute and 11.0 hours are attributed to the natural periods of the seiches in the Strait of Çanakkale and Aegean Sea, respectively (Yüce, 1994).

Tidal oscillations:

The tides of the Black Sea are nothing else than the forced oscillations of the water-masses by the tide-generating forces. There is an amphidromy (clockwise) for semi-diurnal tides. Tidal amplitudes are very small (3-9 cm) and there is not any influence of the Strait of Istanbul on them (Defant, 1961). The Sea of Marmara, on the other hand, is also almost entirely isolated from the Black Sea tides and it is not large enough to generate its own tides. Semi-diurnal tidal pattern of the Black Sea is only effective in the northern part of the Strait of Istanbul where tides are mixed but mainly semi-diurnal. Semi-diurnal tides of the Black Sea mainly dissipate along the Strait of Istanbul and at its south end, tides become mainly diurnal with a spring range of 2.5 cm. (Yüce, 1986; Yüce and Alpar, 1994). Tidal oscillations are mainly masked by fluctuations caused by winds and the magnitude of surface water flow from the Black Sea to the Aegean Sea. This type of small basins generally co-oscillate with neighboring seas. However, recent studies show that the Sea of Marmara is not affected from the tidal oscillations of the neighboring seas and not co-oscillate with them in short tidal period ranges. This is due to the presence of two shallow, narrow and intricately configured long straits and a two-layer water exchange system (Yüce, 1993, 1994). Similarly, semi-diurnal tides of the Aegean Sea are reflected by the narrow entrance of the Strait of Çanakkale (Yüce, 1994).

With recent studies, salient aspects of sea-level variations and their variability along the Turkish Strait System are partly known. However they are not well documented and far from being fully understood. The present paper reviews previous studies and describes short-period and tidal sea-level variations along the Turkish Strait System.

Data source and analytical techniques

The hourly sea-level data were collected by means of mechanical OTT float-type temporary tide gauges located at Anadolukavak, Fenerbahçe, Erdek, Nara and Gökçeada (Figure 1) along the Turkish Strait System for the period of 4-23 May 1993. Other historical data obtained from temporary stations were also utilized for time series analyses in frequency and time domain; these stations are positioned at Karadeniz Ereğli (1996); Çubuklu (1965-72); Vaniköy (1929-76); Arnavutköy (1934-79); Ortaköy (1989-89); Üsküdar (1966-67); Marmara Ereğlisi - Tekirdağ (1997); Gelibolu (1966-71); Akbaş (1969-75) and Bozcaada (1988-92) (Figure 1). Barometric pressure data at Bandırma were corrected to the sea level and zero degrees temperature for the same observation period.

Spectral estimates were computed for the hourly, half hourly and 10-minute sampled sea-level records. To calculate the power spectral densities, consecutive 50% overlapping segments of each data set were taken if the sea-level time series is long enough. Trend and mean were removed from each segment. *Hamming* window was applied to each segment to have an optimum power spectral density estimator. The tapered segments were then subjected to *Fast Fourier Transform (FFT)* analysis (Jenkins et al., 1968) to calculate the power spectra, utilizing the *Seaspect Software* (Lascaratos et al., 1990). Because of the shortage of the simultaneous sea-level data, the spectral computations were made using one segment over the simultaneous data. Hence the error bounds (B_{min} and B_{max}) of the power spectrum confidence intervals computed in this study are 0.27 and 39.49, respectively. However, most of the stations were checked over available longer data series and no essential discrepancies were found; consequently the results were plotted as power spectrum against frequency. A linear least squares tidal analysis Caldwell (1991) was applied to apparently good data from all stations, in order to calculate the harmonic constituents.

Results and discussion

Sea-level records obtained along the Turkish Strait System demonstrate that the area is one of low tidal amplitude. The short-term representative data from Erdek tide gauge, show small amplitude tidal and non-tidal fluctuations superimposed on the long-period oscillations (Figure 2). The data have pronounced diurnal fluctuations with a minor semi-diurnal component. The long-period oscillations in the records are due to long-period tidal constituents and the meteorological influences which can be identified by examining the variations in MSL. The barometric pressure variations show inverse barometric effect (Figure 2).

The energy spectra are almost red for sea-level stations in the Strait of Istanbul and the Sea of Marmara. Sea-level fluctuations are dominated by long-period energy inputs, with secondary contributions from semi-diurnal and diurnal constituents. The long-period sea-level oscillations are meteorologically induced, and their frequency is related to large-scale cyclic atmospheric patterns in the region. Long-period oscillations are also dominant in barometric pressure.

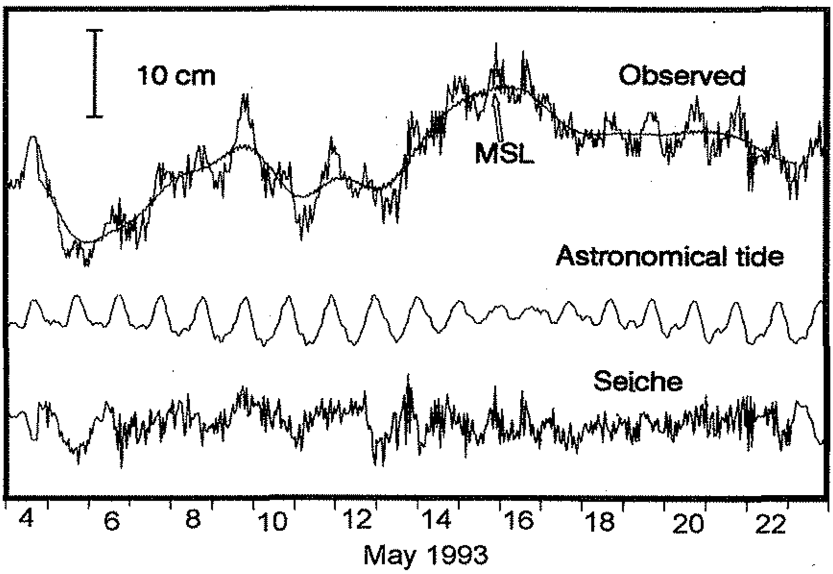

Figure 2. Sample records of observed sea-level, predicted tides and short-period tidal free residuals (seiches) from Erdek for the period of 4-23 May 1993. The mean sea levels are superimposed on the observed data.

If compared to the other simultaneous data sets, the sea-level variations for Nara and Gökçeada have higher tidal amplitudes, semi-diurnal in nature. A numerical analysis of the energy distribution shows the contributions in different frequency bands (Table 1). They are expressed as percentages of the total energy in the hourly-sampled records. These ratios confirm quantitatively, low frequency energy inputs (<0.8 cpd) in the Sea of Marmara are more important if they are compared to those in the Black Sea, the Strait of Çanakkale and the Aegean Sea. Diurnal constituents are more dominant in the Sea of Marmara while semi-diurnal's are more significant for the Strait of Çanakkale and the Aegean Sea.

Short-period oscillations:

The power spectra of the high frequency band of the sea-level records for Anadolukavak, Fenerbahçe, Erdek, Nara and Gökçeada (4-23 May 1993) were calculated (Figure 3). There are some periodicities around 3.1 hours for Erdek, Gelibolu and Nara corresponding to the southwestern part of the Sea of Marmara. For a small rectangular closed basin where the long axis of the basin runs parallel to the lines of latitude, the natural period of the free standing waves (seiches) is determined by the equation:

$$T = \frac{2L}{\sqrt{gh}}$$

The length of the basin is L, the mean depth of the basin is h, and g is the gravitational acceleration. For Sea of Marmara, substituting the values of 240 km and 200 m for the variables L and h respectively, we obtain the natural period of oscillation as 3.01 hours (7.97 cpd) and this corresponds well with the spectral calculations presented in Figure 3.

Table 1. Energy distribution percentages in the sea-level records over different frequency bands

Frequency band : Station name	Low	Diurnal	Semi-diurnal	Other
Karadeniz Ereğli	42.4	23.5	23.8	10.3
Anadolukavak	50.8	10.1	6.7	32.4
Fenerbahçe	73.4	16.7	4.7	5.3
Erdek	75.6	15.2	1.1	8.1
Tekirdağ	83.3	16.4	3.2	2.4
Gelibolu	75.3	6.9	10.3	7.6
Nara	28.6	4.8	59.9	6.7
Gökçeada	5.4	2.9	89.3	2.4
Bozcaada	34.8	11.7	35.5	18.1

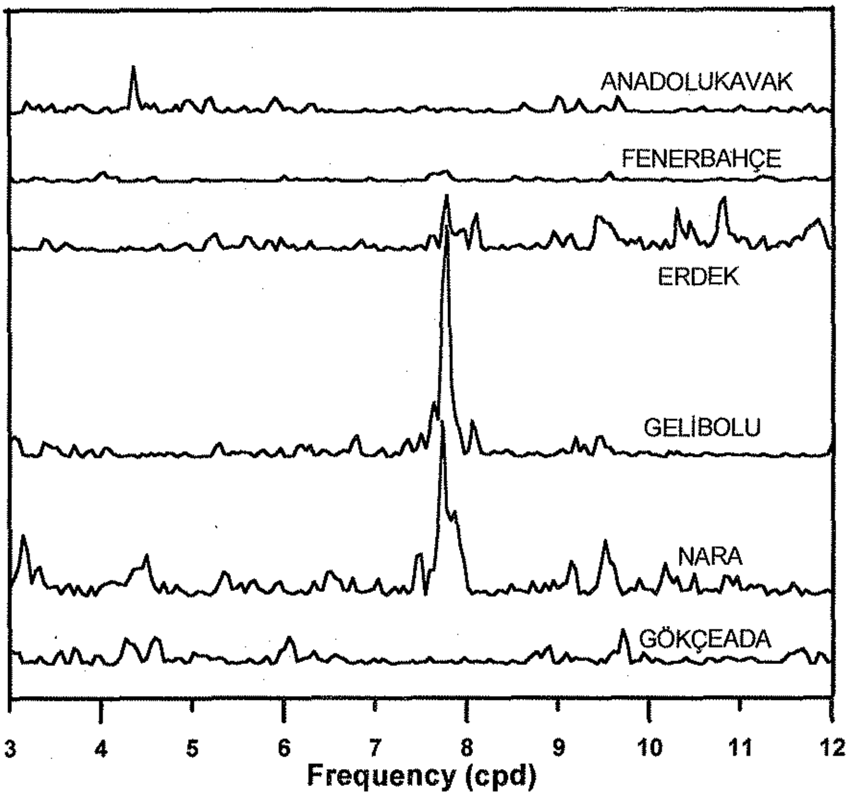

Figure 3. Linear power spectra of the short-period sea-level fluctuations along the Turkish Strait System. The spectral computations were made using only one segment over the simultaneous data between 4-23 May 1993.

Due to the length of the sampling interval in the analysis, the shortest period of oscillation that can be resolved is two hours. Consequently, the short-period oscillations smaller than two hours do not appear in the analysis. In order to examine higher frequency oscillations more detailed, 30-min sampled records (21 day in length) from Anadolukavak, Ortaköy and Gelibolu were analyzed and their power spectra were calculated using one 1024-point-segment over the whole data (Figure 4). Short-period oscillations with periods of 1.03, 2.15, 1.29, 1.18, 1.59 and 1.45 h were clearly identified for Anadolukavak; while they are shorter in magnitude and placed at periods of 1.55 and 1.34 h for Ortaköy and at periods of 2.14, 1.48 and 1.16 h for Gelibolu. The value of 1.48 exactly fits with the theoretical model for the Strait of Çanakkale, for L=62 km and h=55 m.

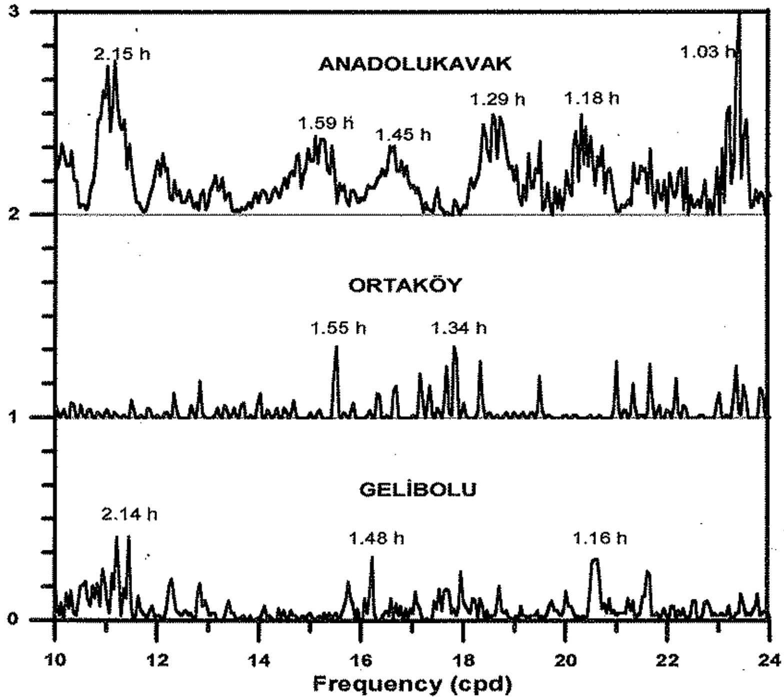

Figure 4. Linear power spectra of half-hourly-sampled historical data from Anadolukavak, Ortaköy and Gelibolu. The spectral computations were made using only one segment with 1024 points long beginning from December 28, 1991 for Anadolukavak; March 22, 1984 for Ortaköy and February 14, 1970 for Gelibolu, respectively.

In order to examine the shorter period oscillations less than one hour, 10-minute-sampled sea-level time series measured at Çubuklu and Tekirdağ using Aanderaa sea level recorder of the type WLR5 were analyzed. For Çubuklu, it was deployed on June 22, 1989 and measured at a 10-minute sampling rate interval until the recovery July 30, 1989. Based on the analysis performed, short-period oscillations with periods of 90 and 32 minutes were clearly identified. On the other hand, for Tekirdağ, the measurement period was between January 30 and March 4, 1997. The short-period oscillations with periods of 91.4, 53.3, 39.4, 32.4 and 24.4 minutes were identified. The oscillations with 53.3-min periodicity may fit well with the NS theoretical model for the Sea of Marmara, which gives 55.8 min for L=74 km and h=200 m.

Tides:

The amplitudes of the M_2, S_2, K_1 and O_1 principal components (semi-diurnal lunar, semi-diurnal solar, soli-lunar diurnal and main lunar diurnal), form numbers, mean spring ranges and mean neap ranges (Defant, 1961) have been calculated (Table 2). The amplitudes were calculated by applying the nodal corrections to the output from the linear least squares tidal analysis.

Table 2. Tidal harmonic constituents along the Turkish Strait System (amplitudes and ranges are in cm.)

Station name	M_2	S_2	K_1	O_1	Mean Spring Range	Neap Spring Range	Form Number
K.Ereğli	1.12	0.51	0.97	0.52	3.3	1.2	0.914
A.kavak	1.26	0.52	1.00	0.63	3.6	1.5	0.916
Çubuklu	1.01	0.58	0.69	0.73	3.2	0.9	0.893
Vaniköy	0.74	0.46	0.85	0.50	2.4	0.6	1.125
Arnavutköy	0.60	0.38	0.56	0.49	2.0	0.4	1.071
Ortaköy	0.65	0.44	0.93	0.75	3.4	2.2	1.541
Üsküdar	0.57	0.54	1.18	0.68	3.7	2.2	1.676
Fenerbahçe	0.84	0.51	0.96	0.74	3.4	2.7	1.259
Erdek	0.43	0.33	1.17	0.78	3.9	1.5	2.566
Tekirdağ	0.90	1.51	2.73	1.13	7.7	4.8	1.602
Gelibolu	1.78	1.69	0.97	0.98	6.9	0.2	0.562
Akbaş	3.22	2.00	1.00	0.67	10.4	2.4	0.320
Nara	5.50	2.10	1.17	0.85	15.2	6.8	0.266
Gökçeada	6.58	4.92	2.10	0.96	23.0	3.3	0.266
Bozcaada	6.30	3.90	2.40	1.30	20.4	4.8	0.363

Tidal amplitudes are small and vary along the Turkish Strait System. According to the Form number calculated and taking into account the tidal classification procedure given by Amin (1986), tides are diurnal in the Strait of Istanbul, mixed but mainly diurnal at the south end of Strait of Istanbul and in the Sea of Marmara, and semi-diurnal in the Strait of Çanakkale and NE Aegean Sea. The Strait of Çanakkale is partly affected by the semi-diurnal tides of the Aegean Sea. Further north, tidal amplitudes are dissipated. Therefore, along the Strait of Çanakkale towards the Aegean Sea, the mean ranges at spring tide increase rapidly.

Conclusions

The Turkish Straits System, joining two of the world's largest isolated seas with extremely different water mass properties, presents complicated sea-level variations. Short-period oscillations with periods of 1.0-2.2 hours were clearly identified for the northern entrance of the Strait of Istanbul; while they are shorter in magnitude and placed at periods of 1.3-1.6 hours for the southern entrance of the Strait of Istanbul. Short-period oscillations with periods of 90 and 32 minutes were clearly identified in the central part of the Strait of Istanbul. There are some periodicities around 3.1 hours for the southwestern part of the Sea of Marmara. In the Strait of Çanakkale the short-period oscillations have periods between 1.1 and 2.2 hours. These fluctuations are related to the natural period of the respective straits and the Sea of Marmara.

Tidal oscillations are small in amplitude and vary along the Turkish Strait System. They are semi-diurnal in the Black Sea; mixed, but mainly semi-diurnal in the Strait of Istanbul; mixed, but mainly diurnal at the south end of Strait of Istanbul and in the Sea of Marmara; and finally semi-diurnal in the Strait of Çanakkale and the Aegean Sea. Even though there are some interactions in low frequency band, the Sea of Marmara is not affected from the tidal oscillations of the Black Sea and the Aegean Sea.

Özet

Güneybatı Karadeniz, İstanbul Boğazı, Marmara Denizi,Çanakkale Boğazı ve Kuzeydoğu Ege Denizindeki kıyılar boyunca dağılmış olan istasyonlardan alınan su seviyesi kayıtlarına göre, kısa-periyotlu ve gelgit tipi su seviyesi değişimleri incelenmiştir. Kayıtlarda rastlanılan kısa-periyotlu salınımlar boğazların ve Marmara Denizinin doğal salınım periyodu ile ilişkilidir. Gelgit salınımlarının genlikleri küçük olup, gelgit rejimi Türk Boğazlar Sistemi boyunca değişmektedir.

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