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Sea-level Variations and their Interactions Between the Black Sea and the Aegean Sea

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Short, tidal, subtidal, seasonal sea-level variations, sea-level differences and interactions have been studied based on data collected at the stations located along the coasts of the south-western Black Sea, the Strait of Istanbul (Bosphorus), the Sea of Marmara, the Strait of Çanakkale (Dardanelles) and the north-eastern Aegean Sea. Short-period oscillations in the Strait of Istanbul, the Sea of Marmara and the Strait of Çanakkale were related to the natural periods of the straits and the Sea of Marmara itself. Tidal oscillations are small in amplitude and vary along the system. Tides are diurnal in the Black Sea and the Strait of Istanbul, mixed, but mainly diurnal at the south of the Strait of Istanbul and in the Sea of Marmara, and semi-diurnal in the Strait of Çanakkale. Long-period oscillations, which are mainly governed by meteorological influences, have a high correlation within a 3–14 day period. Seasonal sea-level fluctuations are in accord with the Black Sea's hydrological cycle. There is a pronounced sea-level difference along the system. The mean sea level at the Black Sea is about 55 cm higher than at the Aegean Sea, but the slope along the system is non-linear, being much steeper in the Strait of Istanbul.

Keywords: sea level; tides; interactions; Strait of Istanbul; Strait of Çanakkale; Sea of Marmara

Introduction

The Sea of Marmara (SOM) and the straits of Istanbul (Bosphorus) and Çanakkale (Dardanelles) create a water passage system (from now on called the Turkish Straits System or TSS) between the Black Sea (BS) and the Aegean Sea (AS) (Figure 1). The SOM is a small inland sea. The width of the Strait of Istanbul (SOI) ranges between 0·7 and 3·5 km with an average of 1·6 km. Its depth ranges between 30 and 110 m with an average of 36 m. The width of the Strait of Çanakkale (SOC), on the other hand, ranges between 1·2 and 7 km with an average of 4·0 km. The narrowest part of the SOC is about 25 km east of its junction with the AS. Its average depth is 55 m, with a maximum of 105 m. Whereas the SOC is connected to the western Marmara basin by a gradually widening junction region, it is terminated at the AS by an abrupt opening (Gunnerson & Özturgut, 1974; Ünlüata *et al*., 1991).

In recent studies, salient aspects of sea-level variations and their variability along the TSS have been partly discovered. However, they are not well documented and far from being fully understood. The present paper reviews previous studies and describes short period, tidal, subtidal, seasonal variations and mean sea levels along the TSS based on the recent data. Their interactions and sea-level responses were also investigated.

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 BS, when they are a part of the seasonal N airstream, are dominant. When not blowing from the NE direction, winds are most often from the SW. In general, onshore winds tend to raise and offshore winds to lower the sea level. The range of sea level thus caused, depends largely upon local conditions. In the SOI, northerly winds are dominant from May to October with a frequency of 60%, while the southerly winds (SW–SE sector) occur 20% of the time, mainly in winter months. Cyclones coming from the AS to the BS in winter change the physical structures of the SOM by reversing surface currents, pulling up water towards northern shores and destroying layer structure at surface. In the months scale, the dominant wind direction is NE–NW except January when SW winds are also important (de Filippi *et al*., 1986).

Short-term effects of wind on sea level are evident. Short-term sea-level increases are due to the intense northerly winds prevailing for limited periods near the SOI. The short-term average sea-level rises of up to

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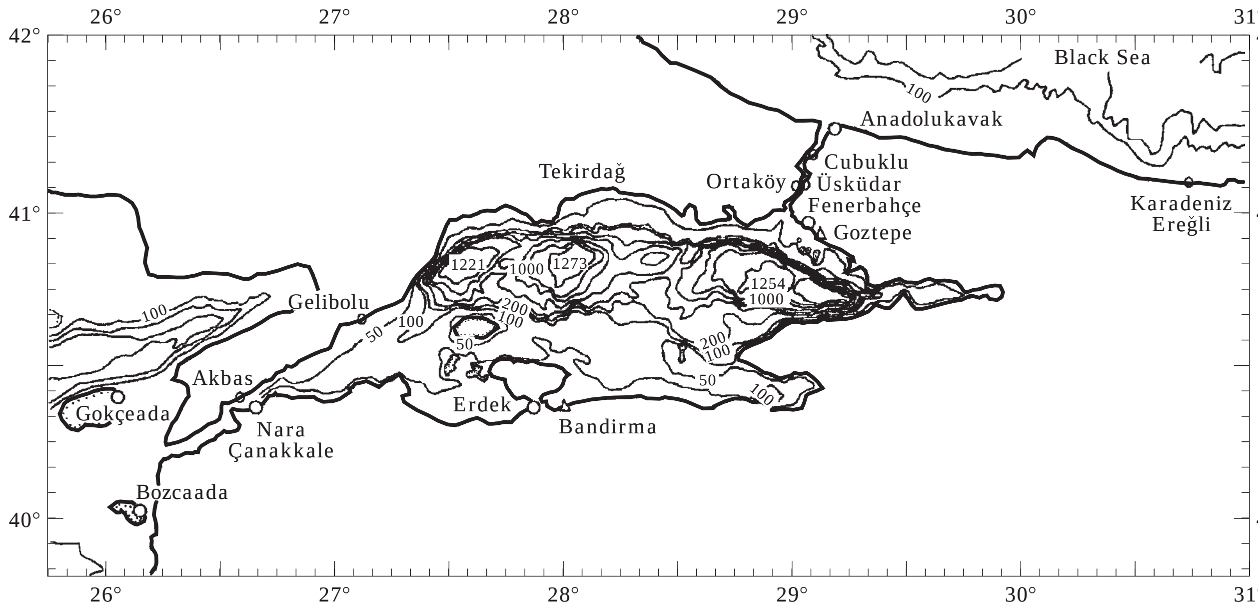

FIGURE 1. Location map of the recording stations. Contours shown represent depth in metres.

20 cm at the northern approaches of the SOI are due to the northerly winds (Ünlüata *et al*., 1991). The influence of southerly winds is more pronounced in the southern SOI with an average sea-level increase.

Power spectra of wind stress and barometric pressure at the Kumköy meteorological station located near the BS entrance of SOI (Figure 1) shows peaks near 3, 4, 5, 7, 11, 15 and 20 days. The observed spectral peaks correspond to the passage of a cyclonic system (Büyükay cited by Ünlüata, 1991).

In the SOC, winds from the N and NE are most frequent. In July and August they blow with great persistence during the day. In some years, they begin in late June and may continue during part of September. From October to March, the winds from the sector between SE and W are rather frequent. They are often strong and may sometimes reach gale force (Yüce, 1994).

Sea-level changes

Characteristics of the sea-level variations along the TSS 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*a*,*b*) and Yüce and Alpar (1994, 1997).

Short period and tidal oscillations The short-period oscillations of 1 and 3 h are reported for SOI and SOM, respectively. The amplitude of seiches in the SOI is as high as 10 cm. The short-period oscillations with periodicities of 90 min and 11 h in the SOC are attributed to the natural periods of the seiches in the SOC and the AS, respectively (Yüce, 1994).

Tidal influences have little effect on sea levels in the area and are masked by fluctuations caused by wind stress, i.e. sea breeze, and the magnitude of surface water flow from the BS to the AS. The SOM is also almost entirely isolated from the BS tides and it is not large enough to generate its own tides. The semi-diurnal tidal pattern of the BS is only effective in the northern part of the SOI where tides are mixed, but mainly semi-diurnal. Semi-diurnal tides of the BS mainly dissipate along the SOI and at its south end tides became mainly diurnal with a spring range of 2·5 cm (Yüce, 1986; Yüce & Alpar, 1994). Tidal oscillations are mainly masked by fluctuations caused by winds and the magnitude of surface water flow from the BS to the AS. This type of small basin generally co-oscillates with neighbouring seas. However, recent studies show that the SOM is not affected by the tidal oscillations of the neighbouring seas and does 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*a*,*b*, 1994). Similarly, semi-diurnal tides of the AS are reflected by the narrow entrance of the SOC. Towards the north along the SOC, the tidal amplitudes are dissipated. The mean spring tidal ranges are 19·0 and 5·5 cm for central (Akbas) and northern (Gelibolu) parts, respectively. Transient sea-level variations are due to wind (Yüce, 1994).

TABLE 1. The differences between the highest and lowest monthly mean sea levels and their occurrence times along the system (after Yüce & Alpar, 1994, 1997)

Region	Seasonal high	Seasonal low	Difference (cm)
Northern end of SOI	May–June	October–November	19
Southern end of SOI	June–July	February–March	23
Southern SOM	October	January–February	18
North-eastern Aegean	October	January	12

SOI, Strait of Istanbul; SOM, Sea of Marmara.

Long-period (subtidal) variations Subtidal sea-level fluctuations on the SOI, which indicates significant variability in the 3–14 day period range, have been reported by Gunnerson (1974), de Filippi *et al.* (1986), Ünlüata *et al.* (1990) and Yüce and Alpar (1994, 1997). These fluctuations were related to the variations in the barometric pressure and winds. The passage of cyclones produces synoptic fluctuations in subtidal sea level and causes an upward skewness in subtidal sea level (Alpar, 1993).

Although recent studies show that the SOM is not affected by the tidal oscillations of the neighbouring seas, there are some interactions in the low frequency band. The high frequency subtidal sea-level fluctuations in the SOM were generally driven by the wind. Coastal sea-level response to wind forcing shows variations in the SOM, and the characteristic of barotropic response depended on their time scales. For time scales shorter than 5 days, sea levels were driven by the local wind. Between 5 and 15 days, in which most of the cyclone forcing occurred, the response of the local and non-local forces was coupled, and mainly driven by a north–south wind. The N–S wind sets up a large surface slope between the north and south parts. For longer time scales greater than 15 days, the non-local contribution is important. The phase differences between sea level and N–S wind for northern and southern parts of the SOM have nearly linear trends against frequency, implying constant time lags of about 2 and 3 h respectively (Yüce & Alpar, 1997).

Seasonal variations

Sea-level fluctuations in TSS have large seasonal variability (Yüce, 1986, 1993*a*, 1994; Yüce & Alpar, 1994, 1997). The extreme differences were reported to be 34, 56 and 81 cm for the BS entrance of SOI (Anadolukavak), the SOM entrance of SOI (Üsküdar) and north-eastern Aegean (Bozcaada) for 2 year periods, respectively (Alpar, 1993). The differences between the highest and lowest monthly means and the months they occur are given in Table 1 for different regions along the system.

TABLE 2. Seasonal mean sea-level differences and their standard deviations (the latter ones are shown in parentheses) between Anadolukavak and Ortaköy (Büyükay, 1986)

	Mean sea-level difference	
Season	1985 (cm)	1986 (cm)
Winter (Dec–Feb)	18 (12)	26 (13)
Spring (Mar–May)	26 (7)	34 (8)
Summer (Jun–Aug)	34 (10)	28 (4)
Autumn (Sep–Nov)	35 (10)	—
Annual average	28 (10)	29 (8)

Sea-level differences Möller (1928) estimated mean sea-level differences of 6 and 7 cm, respectively, between the two ends of the SOI and of the SOC. A higher sea-level difference was calculated as 42 cm with a considerable seasonal variation ranging between a minimum value of 35 cm in October–November, and maximum value of 57 cm in June, between Yalta (northern BS) and Antalya (southern coast of Turkey) by Bogdanova (1965).

The other estimates are related to the sea-level measurements in the SOI alone (Gunnerson & Özturgut, 1974; de Filippi *et al*., 1986; Büyükay, 1989). The average sea-level difference between the two ends of the SOI (Anadolukavak and Üsküdar) was found to be 35 cm and the average monthly differences vary between 11 cm (October 1966) and 24 cm (February 1967) based on the data from January 1966 to February 1968 (Gunnerson & Özturgut, 1974; Çeçen *et al*., 1981). An average sea-level difference of 37 cm was determined for the April–August 1984 period (de Filippi *et al*., 1986). Analysing the sea-level data for 1985 and 1986, Büyükay (1986) found the seasonal main sea-level differences between Anadolukavak and Ortaköy (Table 2).

While the average sea-level difference between the ends of SOI is typically of the order of 30–40 cm, the slope of the surface is found to be non-linear

(Gunnerson & Özturgut, 1974; de Filippi *et al.*, 1986). They have also indicated that the surface slope in the southern half (2·9 cm km^{-1} between Üsküdar and Çubuklu) was much steeper than that in the northern half (1·4 cm km^{-1} between Çubuklu and Anadolukavak). They noted the effects of strong south-westerly winds in diminishing, even reversing, the sea surface slope.

Data source and analytical techniques

The 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 TSS for the periods of 4–23 May 1993, and 5 April–3 July 1994. In order to produce sea-level data that are linked to a local datum, they were defined by the zero of the visual tide staff. Sea levels at hourly intervals were abstracted from the analogue records of these stations. Hourly sampled sea-level data from the Erdek (1986–94) was provided by the General Command of Mapping. Other historical data obtained from temporary stations were also utilized for time series analyses in the frequency and time domain; these stations are positioned at Karadeniz Eregli (1996); Çubuklu (1965–72); Vaniköy (1929–76); Arnavutköy (1934–79); Ortaköy (1989–89); Üsküdar (1966–67); Gelibolu (1966–71); Akbas (1969–75); and Bozcaada (1988–92) (Figure 1). The barometric pressure data (5 April–3 July 1994) at Göztepe were corrected according to the sea level and zero degrees temperature.

Spectral estimates were computed for the hourly and half hourly 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 was long enough. Trend and mean were removed from each segment. A 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 (4–23 May 1993, and 5 April–3 July 1994), 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. Most, however, such as Anadolukavak, Fenerbahce, Erdek, Bozcaada and Gökçeada, were checked over available longer data series and few discrepancies were found between their spectra. Hence, the results were plotted as a 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.

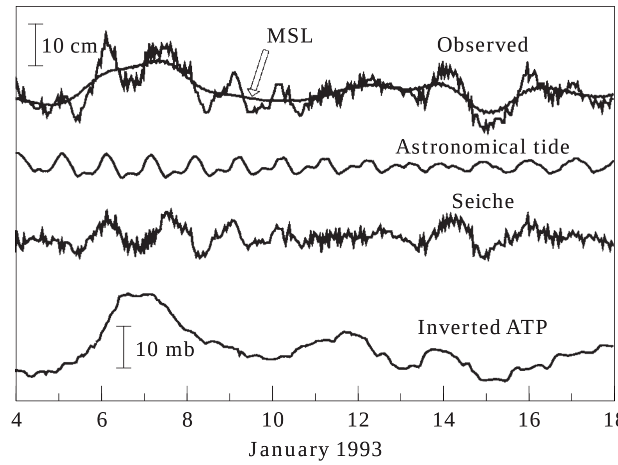

FIGURE 2. Sample records of observed sea level, predicted tides and tidal free residuals (seiches) from Erdek. The mean sea levels (MSLs) are superimposed on the observed data. The comparative barometric pressure (inverted) data from Bandirma are also included.

Daily values are obtained from hourly sea-level data by using a two-step filtering operation. Firstly, the dominant diurnal and semi-diurnal tidal components are removed from the quality controlled hourly values. Second, a 119-point convolution filter (Bloomfield, 1976) centred on noon is applied to remove the remaining high-frequency energy and to prevent aliasing when the data are computed to daily values. The 95, 50 and 5% amplitude points are 124·0, 60·2, and 40·2 h, respectively. The Nyquist frequency of the daily data is at a period of 48 h which has a response of about 5% amplitude, thus, aliasing is minimal. The primary tidal periods have a response of less than 0·1% amplitude. Monthly averages were calculated by taking the simple arithmetic mean of daily averages, if seven or fewer values are missing.

Results and discussion

Sea-level records obtained along the TSS demonstrate that the area is one of low tidal amplitude. The short-term representative data from the 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 the

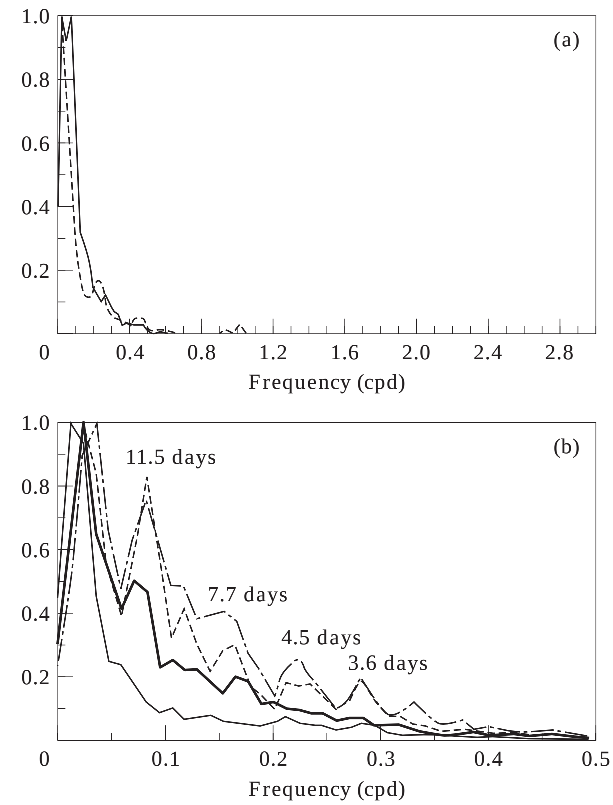

FIGURE 3. (a) Power spectra of Erdek hourly sea level (dashed line) and Bandirma comparative barometric pressure (solid line) data for 1993; the 95% confidence factor, for 30 df., is (B_{min} = 0·724, B_{max} = 1·472) on 8192 points. Spectrum normalization factors are $0{\cdot}7725 \times 10^7$ for sea level and $0{\cdot}2692 \times 10^7$ for pressure. (b) Power specta of 4 hourly sea levels (thin solid line) at Erdek, comparative barotropic pressure (thick solid line) and wind stress components (NE, dashed line; EW, long dashed line) at Bandirma for 1992–93. The 95% confidence factor, for 32 df., is (B_{min} = 0·647, B_{max} = 1·749) on 4352 points. Spectrum normalization factors are $0{\cdot}2051 \times 107$, $0{\cdot}57613 \times 10^6$, $0{\cdot}4245 \times 10^{10}$ and $0{\cdot}8830 \times 10^8$ for sea level, pressure and wind stress components (N–S and E–W), respectively.

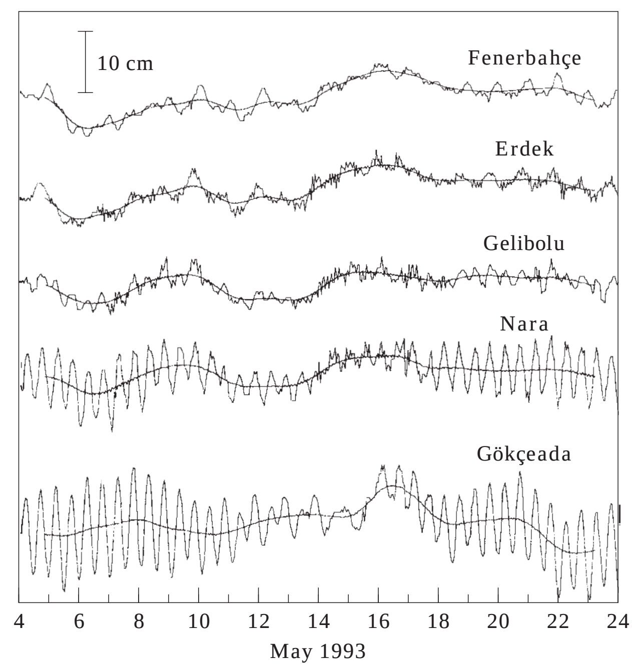

FIGURE 4. Comparison of sea-level fluctuations from Fenerbahce, Erdek, Gelibolu, Nara and Gökçeada for the period 4–23 May 1993. The mean sea levels are superimposed on the observed data. Datum is arbitrary at each of the recording sites.

long-period tidal constituents and the meteorological influences. The barometric pressure variations at Bandirma show an inverse barometric pressure effect (Figure 2). The results from spectral analyses of sea level (Erdek) and barometric pressure (Bandirma) of the hourly sampled time series are plotted in Figure 3(a). The energy spectra are almost red; sea-level fluctuations are dominated by long-period energy inputs, with secondary contributions from semi-diurnal and diurnal constituents. Other stations in the SOI and the SOM have similar characteristics in frequency domain. Long-period oscillations are also dominant in barometric pressure.

In order to examine these long-period fluctuations more closely, longer sea level and meteorological data sets, for a 2-year period (1992–1993), were chosen from Erdek and Bandirma. Wind stress components were computed from the wind field from usual quadratic law using a drag coefficient of $2{\cdot}5 \times 10^{-3}$, in order to provide a relative measure with which to quantify the effects of wind forcing. All data were then low-pass filtered and resampled to a 4 h interval. The spectral analyses of these data are presented in Figure 3(b). There are distinct peaks greater than 11 days and also between 3 and 8 days. The long-period sea-level oscillations are meteorologically induced and their frequency is related to large-scale cyclic atmospheric patterns in the region.

Short-term comparative records of the sea-level fluctuations for the stations of Fenerbahçe, Gelibolu, Nara and Gökçeada also demonstrate similar long-period characteristics as seen in Erdek (Figure 4). The data for Nara and Gökçeada have higher tidal amplitudes (semi-diurnal). The mean sea levels (MSLs) computed by the application of the Godin's tide killing filter (Godin, 1972) were superimposed on observed data.

A numerical analysis of the energy distribution shows the contributions in different frequency bands (Table 3). They are expressed as percentages of the total energy in the hourly sampled records. These ratios confirm quantitatively that low-frequency

TABLE 3. Energy distribution percentages in the sea-level records over different frequency bands

Station name	Frequency band			
	Low	Diurnal	Semi-diurnal	Other
Karadeniz Ereğli	42·4	23·5	23·8	10·3
Anadolukavak	50·8	10·1	6·7	32·4
Fenerbahce	73·4	16·7	4·7	5·3
Erdek	75·6	15·2	1·1	8·1
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

energy inputs (<0·8 cpd) in the SOM are more important if they are compared to those in the Black Sea, south-west end of the SOM and SOC.

Short-period oscillations The power spectra of the high-frequency band of the sea-level records for Anadolukavak, Fenerbahce, Erdek, Nara and Gökçeada (4 and 23 May 1993) were calculated (Figure 5). The spectral computations were made using one segment over the simultaneous data. There are some periodicities around 3·1 h for Erdek, Gelibolu and Nara, which correspond to the south-western part of the SOM.

The natural period of oscillation of a closed rectangular basin is $T = 2L/(\boldsymbol{g}h)^{1/2}$, where L is the length, h is the mean depth of the basin and $\boldsymbol{g}$ is the gravitational acceleration (9·81 m s^{-2}). For the SOM, substituting the values of 240 km and 200 m for the variables L and h, respectively, gives the natural period of oscillation as 3·01 h, which corresponds well with the spectral calculations.

Due to the length of the sampling interval in the analysis, the shortest period of oscillation which can be resolved is 2 h. Consequently, the short-period oscillations smaller than 2 h do not appear in the analysis. In order to examine the short-period oscillations in more detail, 30 min sampled records (21 days in length) from Anadolukavak, Ortaköy and Gelibolu were analysed and their power spectra were calculated using one 1024-point segment over the whole data. 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 as periods of 1·55 and 1·34 h for Ortaköy and at periods of 2·14, 1·48 and 1·16 h for Gelibolu [Figure 6(a)]. The value of 1·48 fits well with the theoretical model for SOC, which gives 1·43 h for $L = 60$ km and $h = 55$ m (Yüce, 1994).

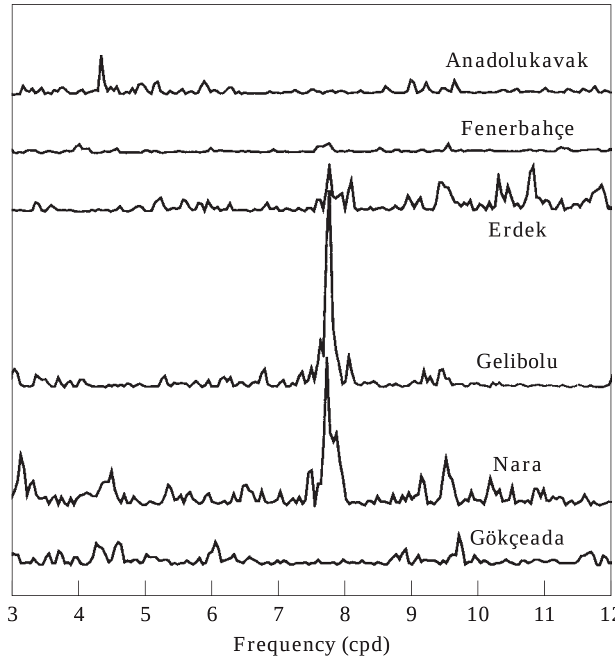

FIGURE 5. Linear power spectra of the short-period (high-pass filtered) sea-level fluctuations from Anadolukavak, Fenerbahçe, Erdek, Nara and Gökçeada. The spectral computations were made using only one segment over the simultaneous data between 4 and 23 May 1993. The 95% confidence factors are 0·27 and 39·49.

In order to examine the shorter period oscillations of less than 1 h, a 39 day record (10 min sampled) from Çubuklu was analysed and its power spectra was calculated [Figure 6(b)]. Short-period oscillations with periods of 90 and 32 min were clearly identified.

Tides The amplitude and phases 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 4). The amplitudes and phases were calculated by applying the nodal corrections to the outputs from the linear least squares tidal analysis. Applying nodal corrections allows the fitted components to be used further from the actual time period used to fit the components.

Tidal amplitudes are small and vary along the TSS. Tides are diurnal in the SOI, mixed but mainly diurnal at the south end of the SOI and in the SOM, and semi-diurnal in the SOC and NE Aegean Sea. The SOC 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.

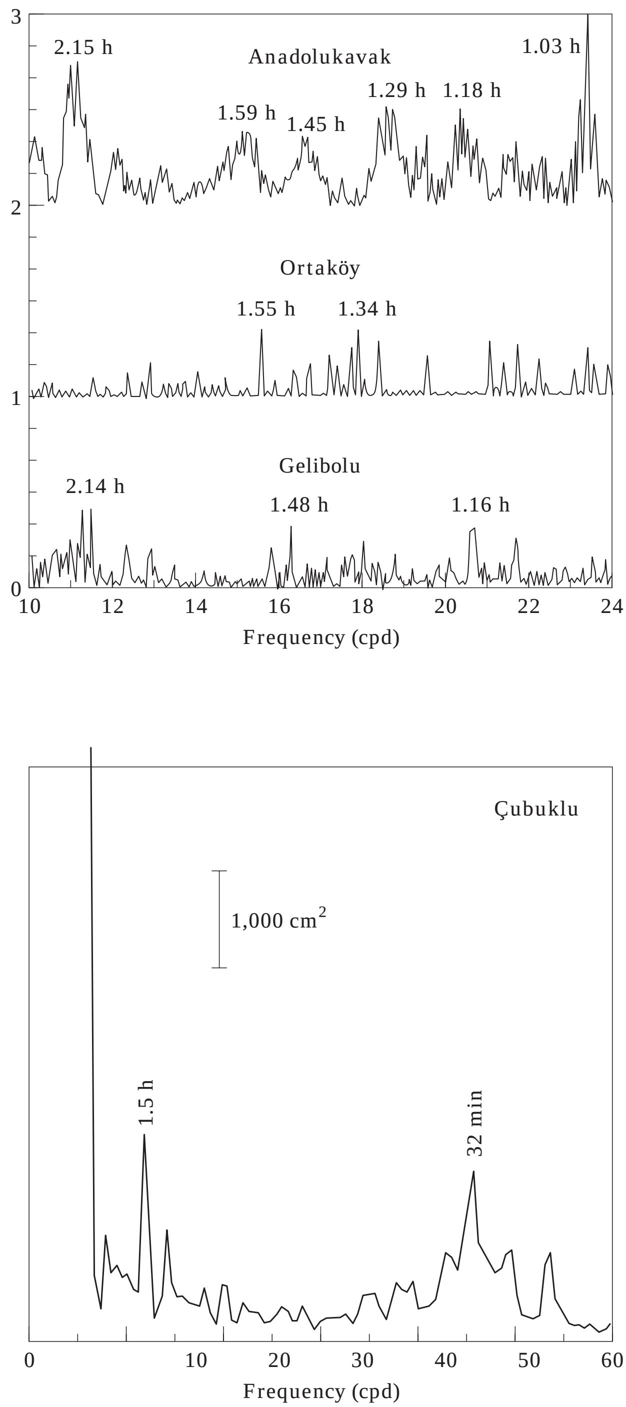

FIGURE 6. (a) Linear power spectra of half-hourly sampled historical data from Anadolukavak, Ortaköy and Gelibolu. The spectral computations were made using only one segment 1024 points long beginning from 28 December 1991 for Anadolukavak, 22 March 1984 for Ortaköy and 14 February 1970 for Gelibolu, respectively. The 95% confidence factors are 0·27 and 39·49. (b) Linear power spectrum of 10 min sampled data from Çubuklu. The spectral computations were made using segments with 512 points beginning from 22 June 1989. The 95% confidence factors, for 40 d.f., are 0·674 and 1·637.

Long-period (subtidal) variations Short-term subtidal sea-level data along the TSS for the period of 5 April–3 July 1994 are given in Figure 7. Barometric pressure data from Göztepe (GOZ) are also included. Low-frequency fluctuations were clearly observed on the subtidal sea-level data. Spectral analyses (Figure 8) indicate significant variability in the 3–14 day period range. These oscillations may correspond with the cyclone frequency in the region. Part of these oscillations may be attributed to barotropic phenomena (e.g. response to barometric pressure forcing). The cross spectrum of the barometric pressure and the sea-level data (not given here) shows significant coherence for 3·5–6·7 days periodicity band. The obvious inverse relationship between the mean sea-level data and the barometric pressure provides the evidence that the long-period oscillations are mainly induced by meteorological forces.

Although the SOM is not affected from the tidal oscillations of the neighbouring seas, there are some interactions in the low frequency band. The dominant coherent sea-level fluctuations on the SOM occurred at time scales of greater than 6·5 days, and they are coherent over the whole width of the basin (Figure 8). The sea levels, on the other hand, are not coherent between the northern and southern part of the SOM at shorter time scales (Yüce & Alpar, 1997).

Seasonal variations There is a regular fluctuation of sea level along the TSS throughout the year caused by meteorological forces. The seasonal sea-level variations for the northern end of SOI, the northern and southern SOM, and the north-eastern Aegean, each deriving from at least 3 years average of the monthly MSL data between 1987 and 1994, were calculated. In the Black Sea, the range of seasonal fluctuation increases in spring to a maximum in May–July and decreases to a minimum in October and November. The seasonal sea-level variations for the northern end of SOI also reflects the general pattern of the BS, with a maximum in June and minimum in November (Figure 9).

The differential range of the monthly MSLs between the two ends of SOI is highly variable. It is high during the February–July period (between 28 and 56 cm with an average of 40 ± 3 cm) and low (between 19 and 35 cm with an average of 23 ± 3 cm) during autumn and winter. Most rapid variations evidently occur in June and July. During persistent southerly winds in October and November, an opposite relationship may also be observed for short periods. Such surface slope reversals are typically maintained for one or more days; after diminishing southerly winds, the surface slope returns to its

TABLE 4. Tidal harmonic constituents for the stations along TSS

Station name	M_2 amplitude phase	S_2 amplitude phase	K_1 amplitude phase	O_1 amplitude phase	Mean spring range	Mean neap range	Form number
K. Eregli 12/2–20/41996	1·12 70	0·51 73	0·97 152	0·52 83	3·3	1·2	0·914
Anadolukavak 1987–89, 1996	1·26 93	0·52 101	1·00 110	0·63 106	3·6	1·5	0·916
Çubuklu 1989	1·01 —	0·58 —	0·69 —	0·73 —	3·2	0·9	0·893
Vaniköy 1937–39	0·74 295	0·46 316	0·85 120	0·50 103	2·4	0·6	1·125
Arnavutköy 1943	0·60 302	0·38 324	0·56 120	0·49 102	2·0	0·4	1·071
Ortaköy 1989	0·65 310	0·44 333	0·93 160	0·75 110	3·4	2·2	1·541
Üsküdar 14/1–31/7/1967	0·57 —	0·54 —	1·18 —	0·68 —	3·7	2·2	1·676
Fenerbahçe 1992–94	0·84 302	0·51 347	0·96 162	0·74 118	3·4	2·7	1·259
Erdek 1986–94	0·43 294	0·33 328	1·17 138	0·78 106	3·9	1·5	2·566
Gelibolu 2–21/12/1969	1·78 —	1·69 —	0·97 —	0·98 —	6·9	0·2	0·562
Akbas 7–19/3/1970	3·22 —	2·00 —	1·00 —	0·67 —	10·4	2·4	0·320
Nara 22/4–31/7/1994	5·50 139	2·10 177	1·17 355	0·85 337	15·2	6·8	0·266
Gökçeada 21/2–3/7/1994	6·58 135	4·92 149	2·10 21	0·96 350	23·0	3·3	0·266
Bozcaada 1988–92	6·30 119	3·90 139	2·40 4	1·30 338	20·4	4·8	0·363

Amplitudes and ranges in cm; phase lags in degrees and relative to Eastern European time origin (30°E) at 00:00, 1 Jan 1976. The phases of Çubuklu, Üsküdar, Gelibolu and Akbas which are not reliable are not given. M_2, S_2, k_1 and O_1 principle components semi-diurnal lunar, semi-diurnal solar, soli-lunar diurnal and main lunar diurnal, respectively.

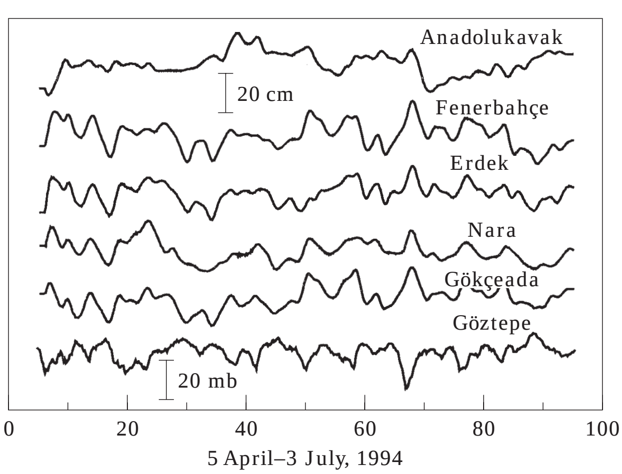

FIGURE 7. Subtidal sea-level records for tide gauges of Anadolukavak, Fenerbahçe, Erdek, Nara and Gökçeada for the period 5 April–3 July 1994. The corresponding representative of barometric pressure data from Göztepe is also included.

normal position. Even when the wind persists, a new equilibrium state may be established so that the surface water may again flow towards the SOM. The major reason for the varying difference is that the response of the sea level to the wind which varies along the SOI, due to its intricate configuration and its exposure to the wind. Winds from the north, occurring 50% of the time, are not only dominant from May to October, but also are the strongest. The northerly winds blowing along the axis of SOI with a duration of 6 days may cause a southward MSL slope along the SOI, which may be as high as 60 cm. Southerly winds, occurring 20% of the time, predominate during the winter months. The persistent southerly winds generally raise the sea level at the northern coasts of SOM, which may be as high as 28 cm above MSL, if the wind duration is more than 3 days.

The seasonal sea-level patterns for the southern SOM and the north-eastern Aegean, on the other

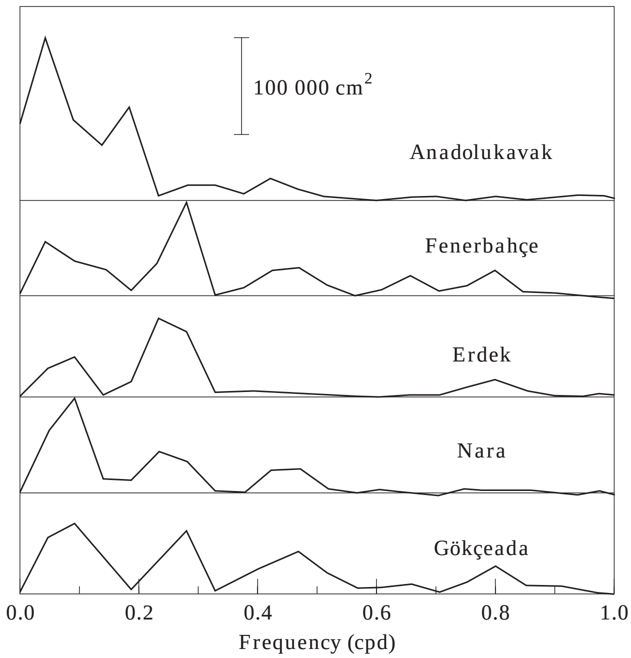

FIGURE 8. Power spectra of the subtidal sea-level data from Anadolukavak, Fenerbahçe, Erdek, Nara and Gökçeada. The spectral computations were made using only one segment over the simultaneous data between 5 April–3 July 1994. The 95% confidence factors are 0·27 and 39·49.

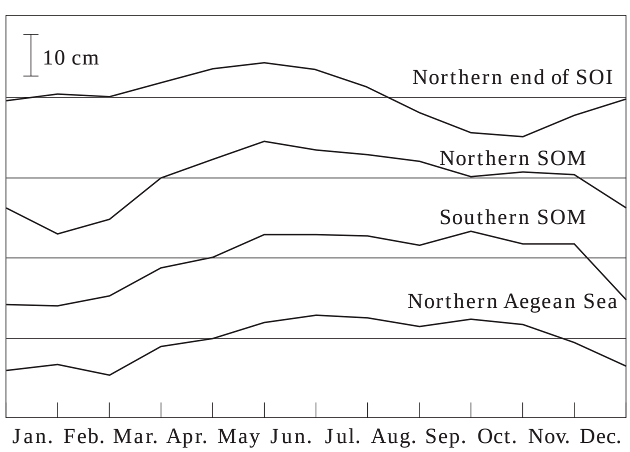

FIGURE 9. Seasonal sea-level variations for the northern end of the Strait of Istanbul (SOI), northern and southern Sea of Marmara (SOM), and north-eastern Aegean. The data used in taking averages cover 3 years of time span at least.

hand, have maxima in late summer–early spring and minima in winter. The range between the extremes varies between 12 and 18 cm, which is mainly caused by the seasonal barometric pressure variations, the BS river runoff effect and the hydrologic regime of the TSS.

The slopes of mean sea levels The historical data which were gathered between 1985–87 along the SOI were reviewed and the average sea-level difference between the two ends of the SOI was found to be 33·5 cm. Its standard deviation was found to be 10·0 cm, taking into account individual 36 months (or 7·2 cm, taking into account 3 years monthly averages, that is 12 months).

According to the long-term simultaneous sea-level measurements at Anadolukavak, Fenerbahçe, Erdek, Nara and Gelibolu, the MSLs relative to a common datum, standard deviation and the elevation differences between successive stations are calculated and given in Table 5. Consequently, the MSL at the BS entrance of SOI was slightly higher (55 cm) than at the Aegean entrance of the SOC (assuming that the two sites have been correctly geodetically levelled (Figure 10).

On the other hand, by analysing the simultaneous sea-level data between 5 April and 3 July 1994, the mean sea-level differences from April to July between Anadolukavak and other stations are given in Table 6. These figures fit well with the findings presented in Table 5 which are calculated from longer, but non-simultaneous data sets. For example, the MSL differences from Anadolukavak for Erdek and Nara stations are within 4 cm range between alternative computations. The differences in July, which only span the first 3 days of July, are a bit larger than normal, however, this may be due to wind conditions at the northern part of SOI during that short period of time.

Conclusions

The TSS, 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 h were clearly identified for the northern entrance of the SOI; they are shorter in magnitude and placed at periods of 1·3–1·6 h for the southern entrance of the SOI. Short-period oscillations with periods of 90 and 32 min were clearly identified in the central part of the SOI. There is some periodicity around 3·1 h for the south-western part of the SOM. In the SOC the short-period oscillations have periods between 1·1 and 2·2 h. These fluctuations are related to the natural period of the respective straits and the SOM.

Tidal oscillations are small in amplitude and vary along the TSS; they are diurnal in the SOI, mixed but mainly diurnal at the sound end of the SOI and in the SOM, and semi-diurnal in the SOC. The SOM is not affected by the tidal oscillations of the Black Sea and the Aegean Sea, but there are some interactions in low-frequency band. The dominant sea-level

TABLE 5. The elevation differences between the mean sea levels calculated along the TSS

Station name	Mean sea level	Standard deviation	Average elevation difference	
Anadolukavak	59·9	6·5		
Fenerbahçe	29·5	6·9	Anadolukavak–Fenerbahçe	30·4
Erdek	16·8	15·0	Fenerbahçe–Erdek	12·7
Gelibolu	13·2	6·6	Erdek–Gelibolu	3·6
Nara	5·1	8·3	Gelibolu–Nara	8·3

All units are in cm.

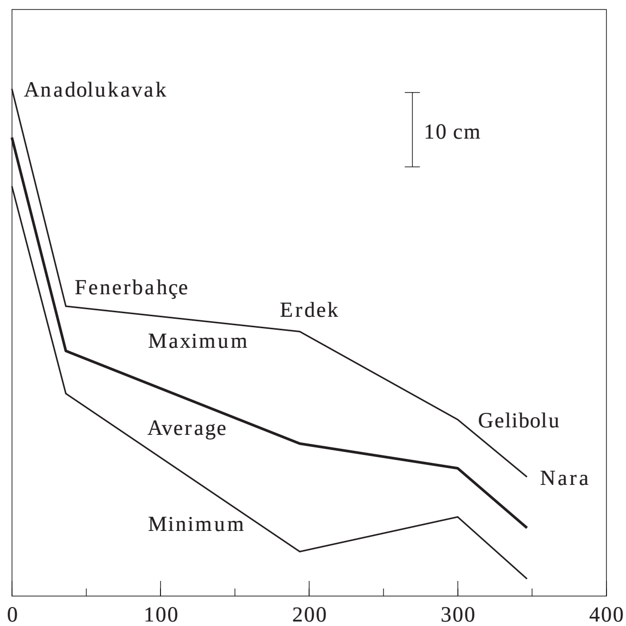

FIGURE 10. Mean sea-level differences between the tide gauges placed on the Turkish Strait System which were obtained by taking simple averages from the two simultaneous data sets: 4–23 May 1993 and 5 April–3 July 1994.

TABLE 6. Seasonal mean sea-level differences and their standard deviations (the latter ones are shown in parentheses) between Anadolukavak and other tide gauges

	Fenerbahce	Erdek	Nara
April	31·1 (7·3)	35·0 (6·7)	51·5 (7·4)
May	39·9 (8·1)	43·5 (7·9)	63·2 (7·3)
June	33·4 (10·3)	34·8 (7·6)	56·5 (7·1)
July	45·8 (2·1)	43·3 (3·7)	64·8 (3·3)
Average	37·5	39·2	59·0

fluctuations occurred at time scales greater than 6·5 days and are coherent all over the SOM basin.

Subtidal sea-level fluctuations indicate significant variability in the 3–14 day period range, but the dominant coherent sea-level fluctuations occur at time scales greater than 6·5 days. On the other hand at shorter time-scales sea levels were not coherent between the northern and the southern part of the SOM. These fluctuations were mainly related to the meteorological forcing. Strong southerly winds cause a rapid rise in sea level in the southern part of the SOI, while northerlies result in high levels.

The sea-level variations in the TSS display seasonal variability as well as short-term fluctuations in response to atmospheric forcing. Winds have the most pronounced effect on sea level in the SOI. The differential range of the monthly MSL between BS and SOM is highly variable. It is high during spring and early summer and low during fall and winter, corresponding to the varying difference of the response of the sea level to the wind, and to the freshwater inflow changes in the Black Sea.

There is a pronounced MSL difference along the TSS. The MSL at the BS entrance of SOI is about 55 cm higher than at the Aegean entrance of SOC, but its slope is non-linear. The sea-surface slope is much steeper in the SOI than that in the SOM and the SOC.

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