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Sea level changes along the turkish coasts of the Black Sea, the Aegean Sea and the Eastern Mediterranean

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Abstract

Short, tidal, subtidal, seasonal, secular sea-level variations, sea-level differences and interactions between the basins have been studied, based on the data collected at some permanent and temporary tide gauges located along the Turkish coasts, mostly along the Straits connecting the Marmara Sea to outer seas. Even though the deficiency of sufficient information prevented us to reach the desired results, many pre-existed studies have been improved.

Short-period oscillations were clearly identified along the Turkish Strait System and related to their natural periods. The tidal amplitudes are low along the Turkish coasts, except northern Aegean and eastern Mediterranean. The stability of harmonic constants of Samsun and Antalya were examined and most of the long period constituents were found to be unstable. Even the Marmara Sea is not affected from the tidal oscillations of Black and Aegean Seas, some interactions in low frequency band have been detected. Subtidal sea level fluctuations (3-14 day) have relations with the large-scale cyclic atmospheric patterns passing over the Turkish Straits System. Short-term effects of wind on sea level are evident.

Seasonal sea-level fluctuations along the Turkish Straits System are in accord with Black Sea's hydrological cycle. The differential range of the monthly mean sea levels between the Black Sea and the Marmara Sea is highly variable; high during spring and early summer and low during fall and winter.

On the average, there is a pronounced sea-level difference (55 cm) along the Turkish Straits System. However, the slope is nonlinear, being much steeper in the Strait of Istanbul. This barotrophic pressure difference is one of the most important factors causing the two-layer flow through the system. The topography and hydrodynamics of the straits, the dominant wind systems and their seasonal variations make this flow more complicated.

For secular sea level changes, a rise of 3.2 mm/a was computed for Karsiyaka (1935-71) and a steady trend (-0.4 mm /a) has been observed for annual sea levels at Antalya (1935-77). The decreasing trend (-6.9 mm/a) at Samsun is contrary to the secular rising trend of the Black Sea probably because of its rather short monitoring period (1963-77).

Keywords: Turkey, Black Sea, Marmara Sea, Aegean Sea, Mediterranean Sea, Sea level, Tide, Subtidal, Interaction.

Introduction

Turkey has a long coastline surrounded by three seas; the Black Sea, the Aegean Sea and the Levantine Sea (Mediterranean). In addition, the Marmara Sea is an inland sea connecting the Black Sea to the Aegean Sea through two narrow straits with two-layer flow; the Strait of Istanbul (Bosphorus) and Strait of Canakkale (Dardanelles). There is a net export of water from the Black Sea into the Aegean Sea. The physical characteristics of the sea-level variations along this long coastline and their dependability on the climatical and meteorological forces have been partly studied in the past.

The low pressure systems are generally west to east in direction. The cyclones move eastwards over the Aegean Sea towards the Levantine Sea. The life of cyclones is about 3 to 5 days, although they may last much longer. Occasionally they may slow down or stagnate completely for a period of few days (OZSOY, 1981).

In winter months, the weather is dominated by an almost continuous passage of cyclonic systems. Cyclones coming from the Aegean Sea to the Black Sea change the physical structures of the Marmara Sea.

During the summer, NE winds coming from the Black Sea, when they are a part of the seasonal N airstream, are dominant. When it does not blow from the NE direction, winds are most often from SW.

Material and data processing

Sea level measurements in Turkey are principally used in vertical datum determination for national mapping. The surveys of the network of vertical control points in Turkey (Fig. 1) were started by the establishment of the permanent tide gauges at Antalya (1935-1977), Karsiyaka (1936-1977) and Samsun (1961-1983). These gauges were destroyed in 1970's and replaced with new stations at Antalya, Bodrum, Mentes (Izmir) and Erdek in 1985 by the General Command of Mapping (1991). There are also many temporary stations such as Karadeniz Eregli (1996) in the Black Sea; Cubuklu (1965-1972), Vanikoy (1929-1976), Arnavutkoy (1934-1979), Ortakoy (1989-1989) and Uskudar (1966-1967) along the Strait of Istanbul; Marmara Eregli-Tekirdag (1997) in the Marmara Sea; Gelibolu (1966-1971) and Akbas (1969-1975) along the Strait of Canakkale and finally Bozcaada (1988-1992) in the Aegean Sea. The figures shown in parentheses are the time spans used in our analyses for the concerned data set.

Quality control ensures the scientific validity of the sea-level data. By using the software package developed by the TOGA Sea-level Centre (CALDWELL, 1991), data spikes, datum shifts and other spurious features in the data were inspected, timing errors in the observed data, due to shifts of exact increments of an hour, were corrected and short gaps in some sea level time series records were filled over the span of the gap using corresponding predicted data. The vertical datum for each tidal station was reduced to an arbitrary constant level covering the whole period of observations by correcting the datum shifts in the records.

Daily values are obtained from hourly sea-level data by using "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 is computed to daily values. Monthly averages were calculated by taking the simple arithmetic mean of daily averages, if seven or fewer values were missing. Finally, the annual mean sea levels were computed by taking averages of the monthly mean sea levels.

Spectral estimates were computed for the monthly, 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 was long enough. Trend and mean were removed from each segment. *Hamming* window was

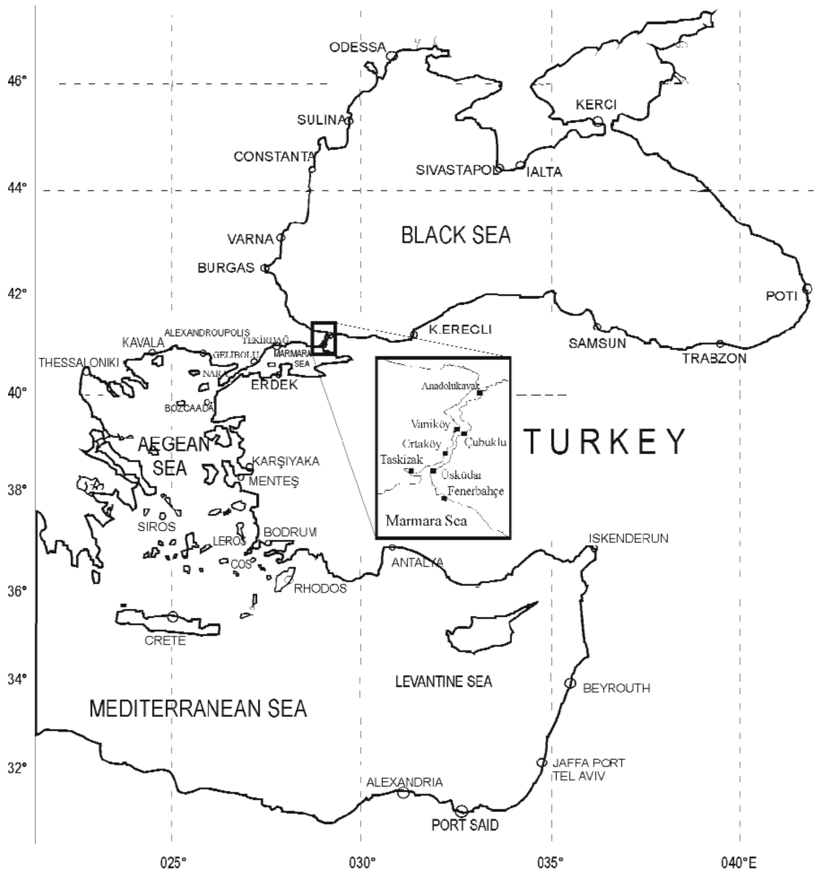

Fig. 1: The distribution of the permanent and temporary tide gauges in Turkey and its surroundings.

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, implementing the Seaspect Software (LASCARATOS *et al.*, 1990). A linear least squares tidal analysis Caldwell (1991) was also applied in order to calculate the tidal harmonic constituents.

Results

The energy spectra are almost red for the most of the sea-level stations along the Turkish coasts. They are dominated by long period energy inputs, with secondary contributions from semidiurnal and diurnal constituents. The only exception to this is the northeastern Aegean Sea (Gokceada and Bozcaada), the Aegean entrance of the Strait of Canakkale (Nara) and the eastern Levantine Sea (Iskenderun) where the tidal amplitudes are high and the semidiurnal constituents are dominant.

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 Burgas, respectively. These natural periods differ considerably from those of the tidal forces in the Black Sea and any influence from the Strait of Istanbul is hardly expected. On the other hand, the short-period oscillations with natural periods of one and three hours are known in the Strait of Istanbul and the Marmara Sea, respectively. The amplitude of seiches in the Strait of Istanbul is as high as 10 cm. In the Strait of Canakkale, the short-period oscillations with periodicities of 90 minutes and 11.0 hours are attributed to the natural periods of the seiches in the Strait of Canakkale and the Aegean Sea, respectively (YUCE, 1994).

Short-period oscillations with periods of 1.03, 2.15, 1.29, 1.18, 1.59 and 1.45 h were clearly identified in Anadolukavak, 90 and 32 minutes in Cubuklu, which is placed in the central part of the Strait of Istanbul. The main short period oscillations which were placed at periods of 1.55 and 1.34 h are shorter in magnitude at Ortakoy. The short-period oscillations with periods of 91.4, 53.3, 39.4, 32.4 and 24.4 minutes were identified in Tekirdag. The oscillations with 53.3-min periodicity may fit well with the NS theoretical model for the Marmara Sea, which gives 55.8 min for L=74 km and h=200 m. There are some periodicities around 3.1 hours in Erdek, Gelibolu and Nara corresponding to the southwestern part of the Marmara Sea and this agrees with the natural period of oscillation in the Marmara Sea, considering that this is a small rectangular closed basin. Some weak short periods of 2.14, 1.48 and 1.16 h were measured in Gelibolu. The value of 1.48 exactly fits with the theoretical model in the Strait of Canakkale, for L=62 km and h=55 m (ALPAR & YUCE, 1997).

In their studies concerning the northern Aegean Sea, WILDING *et al*. (1980) reported rather weak tides and short-period fluctuations. Subsequently, YUCE (1991), using the data sets used herein this study, calculated short-period fluctuations with 2.68 and 2.40 h periods. In our analyses, we calculated short period oscillations with periods of 2.12, 2.71, 3.50-4.19 and 5.18 h in the Izmir Bay. These mainly depend on E-W wind

Table 1
Tidal harmonic constituents along the Turkish coasts (amplitudes and ranges are in cm.).

Station name	M_2	S_2	K_1	O_1	Mean Spring Range	Neap Spring Range	Form Number
Trabzon	2.24	1.48	1.31	1.68	7.4	1.5	0.804
Samsun	1.13	0.53	0.39	0.26	3.3	1.2	0.390
K.Eregli	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
Cubuklu	1.01	0.58	0.69	0.73	3.2	0.9	0.893
Vanikoy	0.74	0.46	0.85	0.50	2.4	0.6	1.125
Arnavutkoy	0.60	0.38	0.56	0.49	2.0	0.4	1.071
Ortakoy	0.65	0.44	0.93	0.75	3.4	2.2	1.541
Uskudar	0.57	0.54	1.18	0.68	3.7	2.2	1.676
Fenerbahce	0.84	0.51	0.96	0.74	3.4	2.7	1.259
K.Cekmece	1.61	0.82	0.51	0.79	4.9	1.6	0.535
Erdek	0.43	0.32	1.19	0.79	4.0	0.8	2.640
Tekirdag	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
Akbas	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
Gokceada	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
Karsiyaka	5.1	3.7	2.5	1.3	17.4	2.8	0.441
Mentes	5.2	3.7	2.4	1.3	17.8	3.0	0.416
Nemrut Bay	5.1	4.4	1.6	1.6	18.9	1.3	0.334
Bodrum	3.3	2.4	2.1	1.1	11.4	1.8	0.560
Antalya	7.4	4.5	2.3	1.5	23.8	5.8	0.319
Iskenderun	12.5	7.9	2.7	1.9	40.8	9.2	0.225

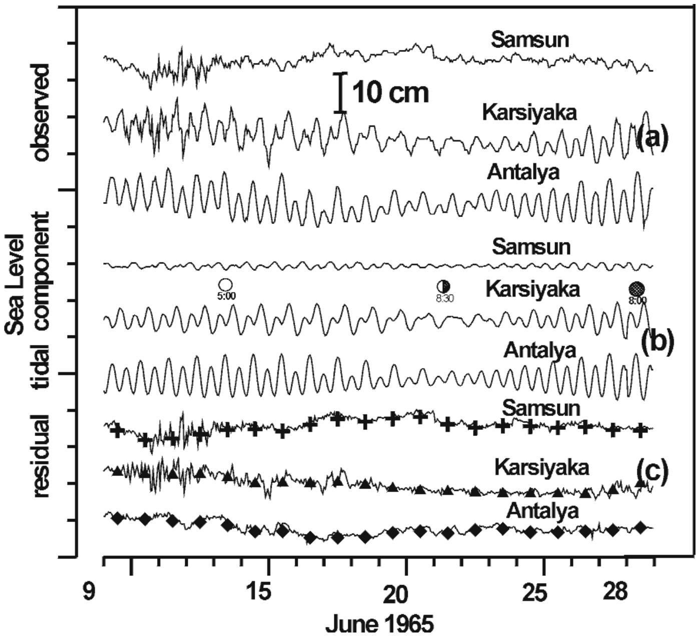

Fig. 2a: Sample historic records of (a) observed, (b) predicted tides and (c) tidal free residuals from the Black Sea (Samsun), the Aegean Sea (Karsiyaka) and the Levantine Sea (Antalya). The daily averages were superimposed on the residuals.

stress component which shows variations due to the diurnal sea breezes. The short-period oscillations, with periodicity between 3.5 to 4.2 h, were in agreement with the calculated theoretical natural periods in the Izmir Bay (L=70 km and h=35-50 m), and attributed to seiche-like motions.

Tidal oscillations

The amplitudes of the M_2, S_2, K_1 and O_1 principal components, form numbers, mean spring ranges and mean neap ranges (DEFANT, 1961, AMIN, 1986) along the Turkish coasts have been calculated (Table 1). The amplitudes were calculated by applying the nodal corrections to the output from the linear least squares tidal analysis.

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 semidiurnal tides. Tidal amplitudes are very small (3-9 cm) and there is not any influence from the Strait of Istanbul on them (DEFANT, 1961).

The Marmara Sea, 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. Semidiurnal tidal pattern of the Black Sea is only effective in the northern part of the Strait of Istanbul where tides are mixed but mainly semidiurnal. The semidiurnal tides of the Black Sea mainly dissipate along the Strait of Istanbul and at its south end, they become mainly diurnal with a spring range of 2.5 cm. (YUCE, 1986; YUCE & 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.

Sample historic records of observed, predicted tides and tidal free residuals from the Black Sea (Samsun), the Aegean Sea (Karsiyaka) and the Mediterranean (Antalya) have low tidal amplitudes (Fig. 2a).

Tidal amplitudes are small and vary along the Marmara Sea and its Straits (Turkish

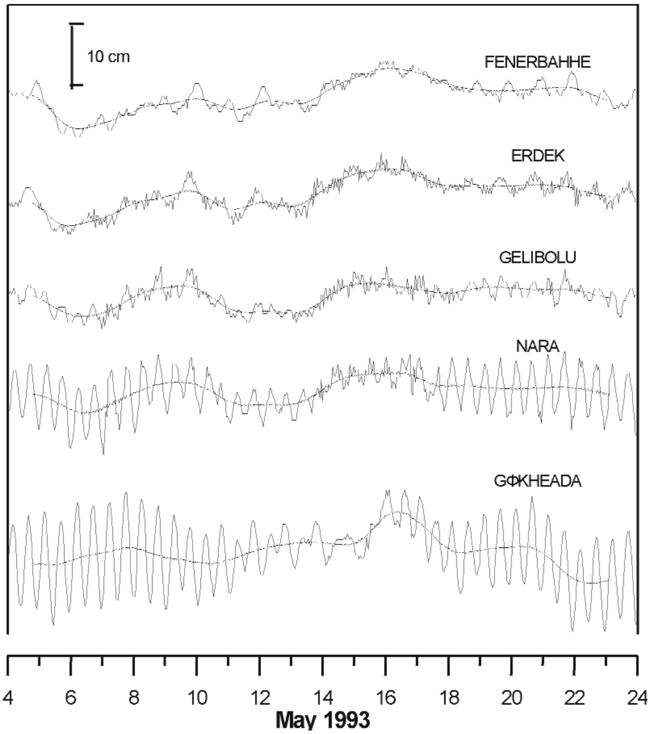

Fig. 2b: Tidal amplitudes along the Turkish Strait System. Tidal influences are masked by fluctuations caused by wind stress and the magnitude of surface water flow from the Black Sea to the Aegean Sea.

Strait System) (Fig. 2b). 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 Black Sea to the Aegean Sea. The Marmara Sea is also almost entirely isolated from the Black Sea tides and it is not large enough to generate its own tides.

The semidiurnal tidal pattern of the Black Sea is only effective in the northern part of the Strait of Istanbul where tides are mixed, but mainly semidiurnal. The semidiurnal 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. (YUCE, 1986; YUCE & 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. Towards the north along Strait of Canakkale, 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 (YUCE, 1994).

The Aegean Sea has low tidal amplitudes. In all cases, the most important constituent is M_2. The S_2 tidal input from the sun is typical Mediterranean. Tides are generally mixed, but mainly semidiurnal in nature in the Eastern Aegean Sea. The amplitudes of the principal tidal constituents decrease southwards in the Aegean Sea, so that the mean spring tidal range becomes as small as 11.3 cm at Bodrum, from 20.3 cm at Bozcaada. Low tidal amplitude at Bodrum may due to the presence of a nodal line to the south, located between Bodrum and Antalya.

Tides in Eastern Mediterranean are characterised by semidiurnal tides in the east;

mixed but mainly semidiurnal tides in the west (DEFANT, 1961). The semidiurnal tidal patterns with a spring ranges of 52 cm largest, 42.8 cm average and 35 cm smallest on the Israeli coast were reported by STRIEM (1974) based on 6-year data set. These amplitudes decrease westwards with a mean Spring range of 36.6 cm at the east coast of Cyprus. In the Gulf of Antalya, the mean Spring range is 20.8 cm and the tidal regime is mixed, but mainly semidiurnal in nature (YUCE & ALPAR 1994). The semidiurnal lunar (M_2) constituent is the major tidal component and secondary contribution comes from solar (S_2) component, being typical Mediterranean.

Stability of the harmonic constants

Tidal constituents computed from Samsun (1963-1978) and Antalya (1935-1995) were examined for the stability of the harmonic constants of constituents. The result of these analyses, with a one-year shift, indicated that diurnal (K_1, O_1), semidiurnal (M_2, S_2, K_2, N_2) and some long period constituents were worthy of consideration (Fig. 3 a,b). Long-term changes of the physical characteristics of the water masses and also geophysical medium may cause some slow rate changes on the sea level systems. On the other hand, the determination of the constituents Sa and Ssa, which are known as

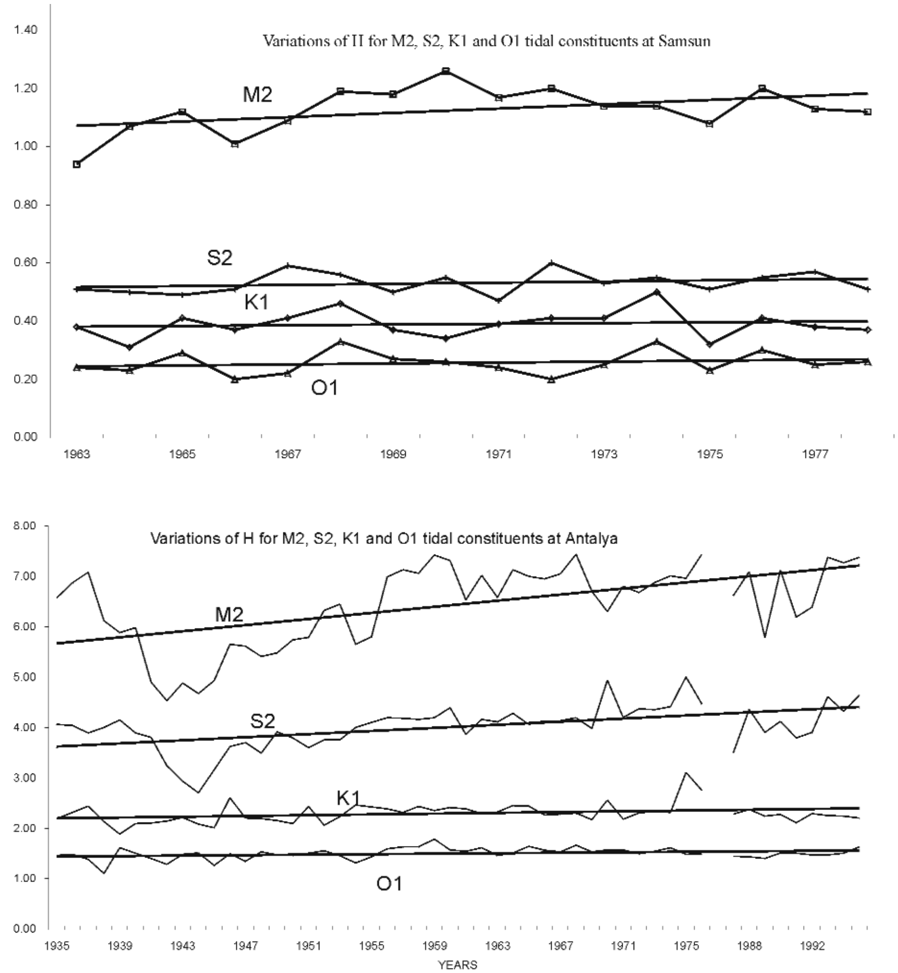

Fig. 3: Variations of H for M2, S2, K1 and O1 tidal constituents at Samsun and Antalya.

generated mainly by meteorological forces and steric effects, according to one year data, is far from being perfect. Based on the 10-year data sets between 1935 and 1976, the amplitudes of the tidal constituents S_a and S_{sa} were found to be 8.1±0.3 and 5.2±0.5 cm, respectively. Most of the remaining long period constituents were found unstable.

Long-period (subtidal) variations

Subtidal sea-level fluctuations in the Strait of Istanbul, which indicates significant variability in a 3-14 day period range, have been reported by GUNNERSON & OZTURGUT (1974), DE FILIPPI *et al.* (1986), UNLUATA *et al.* (1990) and YUCE & ALPAR (1994, 1997). Cyclonic passages produce synoptic fluctuations in subtidal sea level. Multivariate regression analyses of sea-level and meteorological data along the Turkish Strait System have shown that the long-period oscillations are mainly induced by the meteorological forces. The long-period fluctuations of subtidal sea-level data have significant variability in a 3-14 day period range, corresponding to the cyclone frequency in the region. High frequency subtidal sea-level fluctuations in the Marmara Sea were generally driven by the wind.

In the Izmir Bay, the sea-level fluctuations indicate significant variability in a 5.6-12 days period. These long-period oscillations are related inversely to barometric pressure, which in turn, are generally associated with large-scale meteorological patterns. The low frequency (<12 day) sea level variability is mainly due to wind forcing. There is a significant coherence with the northward winds at very low frequency band, while there is no significant sea-level response to the eastward winds in low frequency band. Higher frequency (diurnal and semidiurnal) sea-level fluctuations are mainly caused by E-W wind stress variations due to sea breezes.

Interactions

Small basins such as the Marmara Sea, generally co-oscillate with neighbouring seas. However, recent studies show that the Marmara Sea is not affected by the tidal oscillations of the neighbouring seas and does not co-oscillate with them in short tidal period ranges, because the straits are long, narrow, shallow and intricately configured. Similarly, the semidiurnal tides of the Aegean Sea are reflected off the narrow entrance of the Strait of Canakkale (YUCE, 1993, 1994).

However, there are some interactions in low frequency band. The dominant sea-level fluctuations are coherent all over the Marmara Sea and their periods are greater than 6.5 days. The subtidal sea level fluctuations are generally driven by the wind in the Marmara Sea. Coastal sea level response to wind forcing in the Marmara Sea shows variations depending on their time scales and also on the wind direction. For time scales shorter than 5 days, sea levels were driven by the local wind. The sea levels are not coherent between northern and southern part of the Marmara Sea. For longer time scales greater than 15 days, however, the non-local contribution is important. 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 N-S winds. The NS wind sets up a large surface slope between the northern and southern parts. There is no coherency between the Black Sea and the Marmara Sea in the subtidal frequency band. On the other hand, the subtidal sea level variations are partly coherent between the Marmara and Aegean Seas.

The Aegean basin co-oscillates with the eastern Mediterranean (DEFANT, 1961). The natural period of oscillations of the Aegean Basin is such a one, that it may be considered to co-oscillate with the lunar semidiurnal (M_2) tide of the eastern Mediterranean (11.4 h) (STERNEC (1914) in DEFANT (1961)) with a nodal line at the opening, somewhere in the north of Rhodes. Subsequent studies of the semidiurnal tidal constituents (TENANI (1930) in DEFANT, (1961)) suggested that a nodal line was situated in the north of Leros island.

Seasonal variations

The seasonal fluctuation of the monthly mean sea levels, time of seasonal highs and lows as well as the differences between the highest and lowest monthly mean-sea-levels (in cm relative to the local annual mean sea levels) are given in Tables 2 and 3.

In the Black Sea, the range of seasonal fluctuation increases to a maximum in spring and early summer and decreases to a minimum in late fall. There is a regular fluctuation of sea level along the Turkish Strait System throughout the year. The seasonal sea-level variations for northern end of the Strait of Istanbul also reflects the general pattern of the Black Sea, with a maximum in June and a minimum in November.

The differential range of the monthly mean sea levels between the two ends of the Strait of Istanbul is highly variable. It is high during 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 during late fall, 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 normal position. Even when the wind persists, a new equilibrium state may be established, so that the surface water may again flow towards the Marmara Sea. The major reason for the varying difference is that the response of the sea level to the wind varies along the Strait of Istanbul, due to its intricate configuration and its exposure to the wind. Winds from north, occurring 50% of the time, are not only dominant from May to October, but

Table 2
The range of highest and lowest monthly mean-sea-levels.

Region	Seasonal high	Seasonal low	Difference (cm)
Black Sea	May-June	October-November	19
South of Istanbul Strait	June-July	February-March	23
Southern Marmara Sea	October	January-February	18
Northeastern Aegean	October	January	12
Izmir Bay	July-August	February-March	8
Antalya	July-August	March-April	17.3

Table 3
The seasonal fluctuation (in cm) of the monthly mean sea levels (relative to their annual means).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Samsun	-0.5	1.1	0.4	3.4	6.8	8.5	6.6	2.2	-4.4	-9.2	-10.1	-4.9
K.Eregli	-4	-4	1	3	7	9	5	0	-3	-7	-8	-1
Erdek	-11.1	-11.6	-9.1	-2.4	0.8	6.1	5.9	5.5	2.9	6.4	3.4	3.3
Bozcaada	-5.5	-3.8	-1.2	4.6	3.0	0.3	0.6	-1.9	0.8	6.4	0.1	-3.3
Mentes	-4.5	-1.6	-5.9	-1.9	-1.2	2.1	3.2	3.1	3.0	4.0	0.4	-0.6
Karsiyaka	-3.3	-3.9	-3.9	-3.3	-1.6	4.7	3.0	3.5	1.1	0.7	-0.4	3.4
Bodrum	3.1	2.9	-0.4	-9.2	-12.6	-9.1	-5.0	-1.9	0.7	0.9	2.7	6.2
Antalya	-2.0	-4.6	-7.2	-6.7	-5.5	1.5	9.3	10.1	5.4	-0.8	-0.8	1.3

also are the strongest. The northerly winds blowing along the Strait of Istanbul with a duration of 6 days may cause a southward mean-sea-level slope along the strait, which may be as high as 60 cm. Southerly winds, occurring 20% of the time, predominate during winter months. The persistent southerly winds generally raise the sea level at the northern coasts of the Marmara Sea, 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 Marmara Sea and the northeastern Aegean, on the other 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 Black Sea river runoff effect and hydrologic regime of the Marmara Sea.

The seasonal variation in Karsiyaka shows a major minimum in February and March, and a major maximum in June. In Antalya, a major minimum occurs in March and April followed by a major maximum in July and August.

Spectral analyses of the monthly mean barometric pressures explain most of the seasonal sea level oscillations occurring at 12, 6 and 4 month periods in the Mediterranean Sea, but not those in the Aegean Sea where the steric effect has an important contribution (TSIMPLIS & VLAHAKIS, 1994).

Sea-level differences

MOLLER (1928) estimated mean-sea-level differences of 6 and 7 cm, respectively, between the two ends of the Strait of Istanbul and the Strait of Canakkale. 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 a maximum value of 57 cm in June between Ialta (northern Black Sea) and Antalya (southern coast of Turkey), by BOGDANOVA (1965).

Other estimates are related only to the sea-level measurements in the Strait of Istanbul (GUNNERSON & OZTURGUT, 1974; DE FILIPPI *et al.*, 1986; BUYUKAY, 1989). The average sea-level differences between Anadolukavak and Uskudar (Fig. 1) 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 & OZTURGUT, 1974, CECEN *et al.,* 1981). An average sea-level difference of 37 cm was determined for the April-August 1984 period (DE FILIPPI *et al.* 1986).

While the average sea-level difference between the ends of Strait of Istanbul is typically of the order of 30-40 cm, the slope of free surface is found to be nonlinear (GUNNERSON & OZTURGUT, 1974; DE FILIPPI *et al.,* 1986). The surface slope in the southern half (2.9 cm per km between Uskudar and Cubuklu) was much steeper than that one in the northern half (1.4 cm per km between Cubuklu and Anadolukavak). Strong southwesterly winds have notable effects in diminishing, even reversing, the sea surface slope. BUYUKAY (1986) found the seasonal mean sea-level

Table 4
Seasonal mean-sea-level differences and their standard deviations (in parentheses) between Anadolukavak and Ortakoy (BUYUKAY, 1986).

Season	1985	1986
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)

Table 5
Mean-sea-level differences between the two ends of the Marmara Sea.

Station Name	Mean Sea Level	Standard Deviation	Mean-sea-level differences (All units are in cm)	
Anadolukavak	59.9	6.5		
Fenerbahce	29.5	6.9	Anadolukavak-Fenerbahce	30.4
Erdek	16.8	15.0	Fenerbahce-Erdek	12.7
Gelibolu	13.2	6.6	Erdek-Gelibolu	3.6
Nara	5.1	8.3	Gelibolu-Nara	8.3

differences between Anadolukavak and Ortakoy for 1985 and 1986 (Table 4).

The historic data which was gathered between 1985-1987 along the Strait of Istanbul was reviewed and the average sea-level difference between the two ends of the Strait of Istanbul 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, Fenerbahce, Erdek, Nara and Gelibolu, the mean sea levels relative to a common datum, standard deviation and the elevation differences between successive stations are calculated (Table 5).

Consequently, the mean-sea-level at the Black Sea entrance of the Strait of Istanbul was 55cm higher than that one at the Aegean entrance of the Strait of Canakkale, assuming that the two sites have been correctly geodeticaly levelled (Fig. 4).

Secular sea level variations

The characteristics of the secular sea-level changes may be extracted from historic sea level records by careful analyses. The secular changes may show linear or higher degree polynomial variations reflecting the integrated effect of long-period tidal variations (longest 18.6 years), variations in ocean circulation due to climatic changes, eustatic changes and land/ocean plate

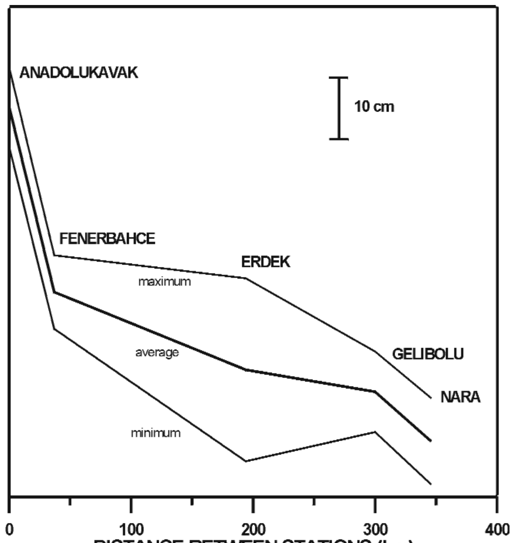

Fig.4: Mean sea level differences along the Turkish Strait System. Averaged data sets; 4-23 May 1993 and 5 April - 3 July 1994.

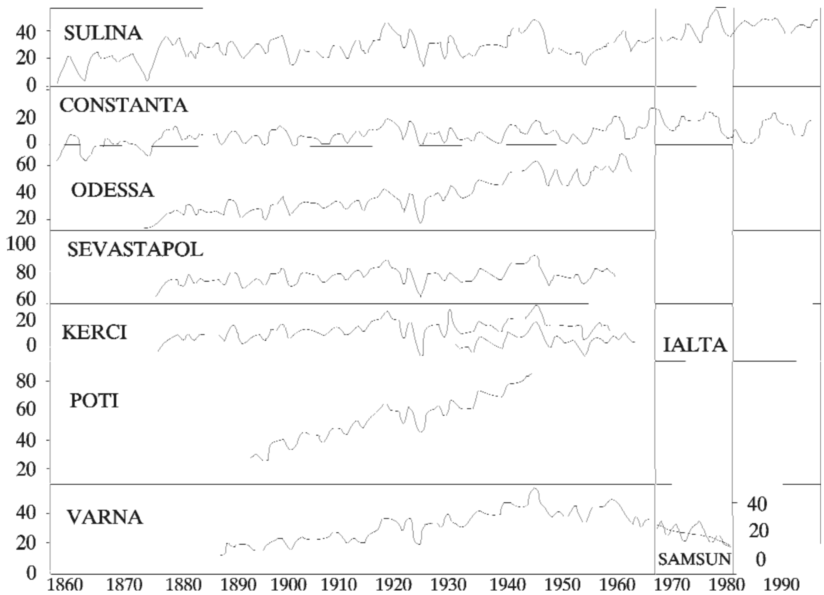

Fig. 5: The chronological graph of the mean annual sea levels along the Black Sea coast points out a continual rising trend. The annual averages calculated from Samsun tidal data were added on the variations of the Black Sea annual levels given by Bondar, 1989. Level units are in cms.

deformations.

The chronological graph of the mean annual sea levels in the Black Sea points out the long-range mean sea level variations (Fig. 5). A continual rising trend can be seen in all observational points. The quantitative analysis of these trends indicated the rise of the Black Sea mean level varies from one point to another along the coast. For instance, in Varna, Constanta, Sulina, Odessa and Sevastopol the rise is of 3.3, 2.7, 3.7, 7.1 and 3 mm/year, respectively. The greatest rise in the Black Sea mean level is recorded in Poti (8.2 mm/year) and the lowest one in Kerci (1.3 mm/year) (BONDAR, 1989). These secular changes (rise) are due to the joint action of eustatic movements and land subsidence. The mean subsidence speeds of the Black Sea coasts are about 5.2, 1.1 and 6.5 mm/year at Odessa, Ialta (Sevastopol) and Poti, respectively (LISITZIN, 1974; BONDAR, 1989) and eaustatism is assessed at about 1.1 mm/year. On the other hand, the rise of the Mediterranean Sea mean level is about 5.3 mm/year (LISITZIN, 1974).

The quantitative analyses of the trends in the Aegean and the Eastern Mediterranean indicate mean sea level rises in Thessalonika (2.1 mm/year), Karsiyaka (0.2 mm/year), Leros (3.7 mm/year), Antalya (0.1 mm/year), Beirut (0.1 mm/year) and Port Said (6.6 mm/year). The greatest rise in mean sea level is recorded in Kios (7.3 mm/year) between 1969-1976. Decreasing slopes were reported in Alexandroupolis (-0.2 mm/year), Kavala (-3.6 mm/year), Rhodos (-1.0 mm/year) and Jaffa Port (-0.8 mm/year) (MOSETTI & PURGA, 1991). The average eustatic sea level rise in the Mediterranean Sea is given to be 1.1-1.6 mm per year.

The quantitative analyses of the annual mean sea levels in Samsun, Karsiyaka and Antalya indicate some distinct minimum and maximum values fluctuating around their third order polynomial fits (Fig. 6). A linear fit is made to the time series and the sea level rises in annual means are computed to be -6.6, 4.2 and -0.5 mm per year at

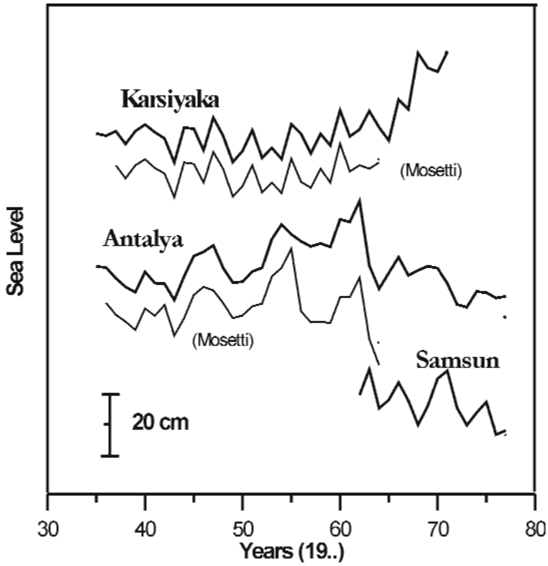

Fig. 6: Variations of the mean annual levels at Samsun, Karsiyaka and Antalya. The shorter data sets are the ones used in MOSETTI & PURGA'S (1991) calculations. The quantitative analyses of the annual mean sea levels in Samsun, Karsiyaka and Antalya indicate some distinct minimum and maximum values fluctuating around their third order polynomial fits.

Samsun, Karsiyaka and Antalya, respectively. Since the data sets used in this study are 7-13 years longer than those ones used by MOSETTI & PURGA (1991), the slopes at Karsiyaka and Antalya are somehow different from the ones given by MOSETTI & PURGA (1991). To get more confident results, any individual monthly mean value more than 4.5 standard deviations from the fitted line was dismissed. Then, a second linear fit was made to the remaining time series to calculate linear trends. Hence, the secular changes in annual means were computed to be -6.9, 3.2 and -0.4 mm/yr at Samsun, Karsiyaka and Antalya, respectively. The annual averages from the Samsun tide station, from 1963 to 1977, were also added in Figure 6, together with its third order polynomial fit. Its trend, as if a continuation of the secular trend given in Varna, seems to be coherent with the secular trend of Constanta. The linear decreasing trend of Samsun annual means has a conflict with that one located at Sulina about the same period of time, although the fluctuations around the trends have similar characteristics. This may indicate vertical land movements in reverse directions at these two distinct places. For tide stations placed where the tectonic movements were not expected, the secular trends of the records less than 30 years are 2-5 times steeper than those of the longer data sets more than 40 years, which are about +4 mm per year (HEKIMOGLU, 1990; HEKIMOGLU & SANLI, 1993). So it would be unsafe to calculate vertical crustal movements from absolute sea-level variations (ZERBINI *et al.*, 1996) or even to calculate long-term trends from relatively short data sets, such as at Samsun.

The power spectra of the monthly sea-level data for Karsiyaka and Antalya, which are sufficiently long-time series for such an analysis, were calculated (Fig. 7). The spectral computations were made using one segment over the simultaneous data. There are periodicities around 42.6, 10.6, 7.1, 4.2, 2.7 and 1.7 years at Karsiyaka, while 42.6, 7.1, 3.8, 2.5 and 1.8 years variations are dominant at Antalya besides annual and semiannual fluctuations (4, 6, 12, 21.3 months).

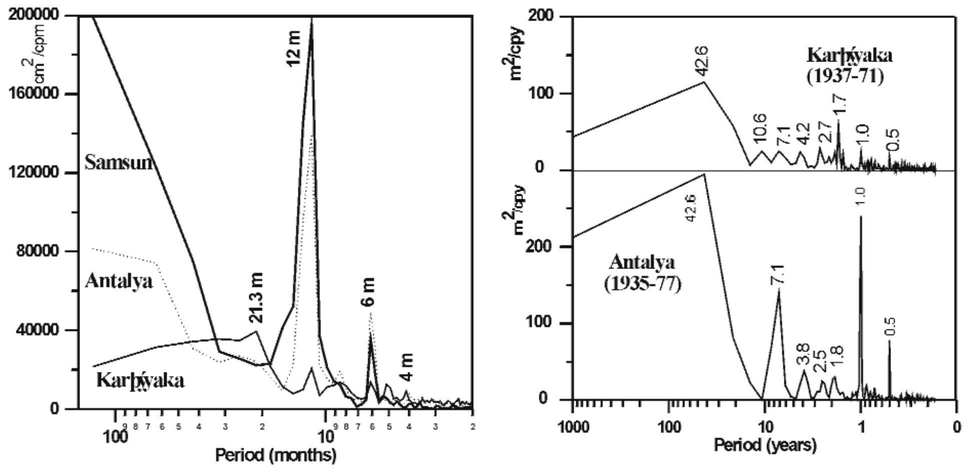

Fig. 7: 4, 6, 12 and 21.3 month periodicities are evident from the power density spectra of the monthly averages of the sea-level data for Samsun, Karsiyaka and Antalya (d.o.f are 6, 10 and 14, respectively). Longer periodicities are placed around 42.6, 10.6, 7.1, 4.2, 2.7 and 1.7 years for Karsiyaka, 42.6, 7.1, 3.8, 2.5 and 1.8 years for Antalya.

Conclusions

Studying eustatic changes needs high-quality continuous data. Only sea level records of the tide stations which are regularly checked out for precise levelling are trustful. Therefore, for precise calculations such as local land subsidence, the network of vertical control points should be checked out regularly. This will make possible the replacing of the tide staff at the same elevation during the progress of the observations, should it become destroyed or should its elevation be changed by accident? The procedures for the establishment of a tide staff and the associated network of vertical control points are described, and common reference level problems and correction techniques are discussed in IOC (1985).

Since some deficiencies occurred due to the distribution of the responsibilities among different institutions, lost geodetic points, mistakes in choosing and establishing the tide gauge stations, only the sea-level stations and records that were found reliable enough were used in this study. Some previous works have been improved based on the analyses of improved data. However, the lack of sufficient information prevented us archiving the desired results. An urgent necessity to the scientific community is the establishment of an everlasting archive that contains quality-controlled data suitable for exchange and analysis.

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