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LONG PERIOD (SUBTIDAL) SEA LEVEL VARIATIONS AND THEIR RELATIONS TO ATMOSPHERIC FORCING IN THE GULF OF ANTALYA

ANTALYA KÖRFEZİNDE UZUN PERYOTLU (GELGİT DIŞI) SU SEVİYESİ DEĞİŞİMLERİ VE ATMOSFERİK GÜDÜMLEME İLE OLAN İLİŞKİLERİ

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Abstract

Long period (subtidal) sea level fluctuations in the Gulf of Antalya and their relations to atmospheric forcing were examined over one-year period. Main study tools were the power spectra of time series and the cross spectral analyses of sea level on local atmospheric pressure and two orthogonal wind stress components. The results shown an inverted barometer response to atmospheric pressure and a frequency dependent response to wind that can be tentatively interpreted in terms of wind setup or barometric setup of semi-enclosed regions.

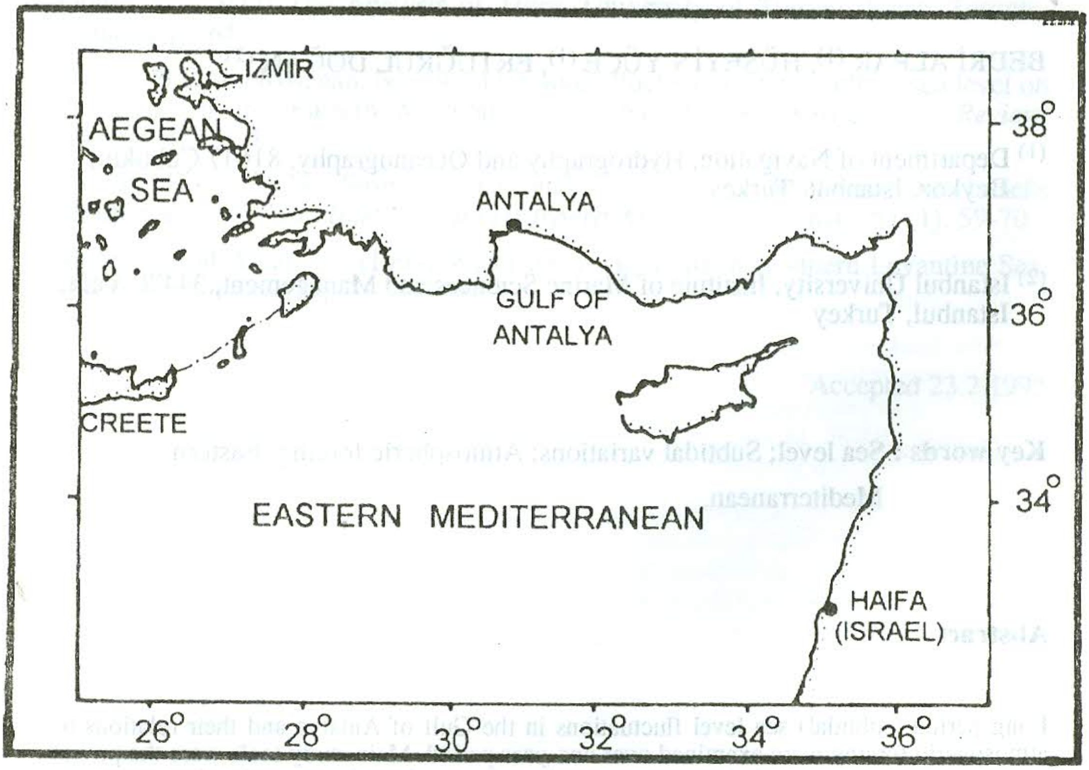
The seasonal fluctuation of the monthly mean sea level is in accord with hydrologic cycle of the Eastern Mediterranean. The dominant coastal sea level fluctuations occurred at a time scale of 2-4 weeks.

The variance of barotropic fluctuaton is higher in the winter (November - April) than in the summer (May - October), due to the increased cyclone activities. Local wind forcing as important and most of the coastal sea level change as driven by the cross-shore wind in the Gulf of Antalya.

Introduction

The Levantine Sea is one of the four major basins of the Eastern Mediterranean. It is connected to the Ionian and Aegean Seas by means of the Creete-Africa passage and two straits to the east of Creete (Figure 1).

Figure 1. Location of the study area.



Striem and Rosenan (1972) and Striem (1974) studied seasonal fluctuations, storm surges and unusual sea level changes on Israel's coasts and reported semi-diurnal tidal patterns with a mean spring range (Defant, 1961) of 52 cm. They also reported, based upon 10 - year averages of monthly mean sea levels, a major minimum in April and a major maximum in July/August with a range of 21 cm between extremes.

The tidal characteristics of water level variations in the Gulf of Antalya have been studied by Yüce and Alpar (1994). Their numerical analysis for coastal sea level energy distribution indicates that the water level variations are mainly governed by the energy inputs (56 %) in low frequency band and semi-diurnal variations (39 %). That means low frequency subtidal energy input is dominant in the Gulf of Antalya. Tides, on the other hand, are characterised by the semi-diurnal components. The amplitude and phase values of the 4 main constituents (semidiurnal lunar M_2, semi-diurnal solar S_2, soli-lunar diurnal K_1 and the main lunar diurnal 0_1) were calculated by using the software package developed by Caldwell (1991) and presented in Table 1. The amplitudes and phases were calculated as applying the nodal corrections to the outputs from the linear least squares tidal analysis. The results indicate that the tidal regime at Antalya are mixed, predominantly semi-diurnal. The tidal components are not pure astronomical but also linked with the solar radiation (daily temperature evolution). The gravitational efect, although in a small quantity, may also contribute.

Table 1. Tidal harmonic constituents. Amplitude values (H) in cm; phase lags (g) in degrees, relative to the Eastern European time (30 E).

M_2		***S_2***		***K_1***		***O_1***		***MEAN RANGES***	
H	**g**	**H**	**g**	**H**	**g**	**H**	**g**	**SPRING**	**NEAP**
6.2	**304**	**4.2**	**308**	**2.4**	**281**	**1.5**	**296**	**20.8**	**4.0**

Despite the previous studies, subtidal sea level changes and their relations to atmospheric forcing has not yet received much attention for the region. To have a better understanding of the nature of barotropic response in the Gulf of Antalya, we took into account coastal sea level and meteorological data for one-year period. The subtidal sea level variability, its relation to atmospheric forcing and its seasonal variation are investigated, and the driving mechanism is discussed.

Sea Level and Meteorological Data

Sea levels are routinely monitored at Antalya with a mechanical R. Fuess stilling well type permanent tide guage that is operated by the General Command of Mapping (1991). Since the records have been found to be dependable in quality and without any gaps, the tidal projections are based on data collected between

0100 EET January 1st 1971 and 2400 EET December 31st, 1971 (Figure 2). The datum levels for these tidal projections are directly related to the tide staff zeroes.

In order to obtain subtidal variations, tidal and high frequency oscillations should be eliminated. So hourly sea level records were lowpass filtered using the tide-killing numerical filter, $A^{2}25^{A}24$ / (25^{2}x24) (Godin 1970). These tidal free data were adjusted for inverse barometric effect and then decimated to a 4-h interval (Figure 3).

Surface barometric pressure and wind (speed and direction) data were obtained over the same period (1971) from Antalya Meteorological Station. All barometric pressure data are expressed in millibars and corrected to the sea level and zero degrees temperature (Figure 2, 3). Wind stress components were computed from usual quadratic stress formulation using a constant drag coefficient of 2.5×10^{-3} and then lowpass filtered and decimated to a 4-h interval (Figure 4). This computation provides a relative measure for wind stress which quantify the effect of the wind forcing.

Figure 2. The hourly sea level and barometric pressure at Antalya for the year of 1971.

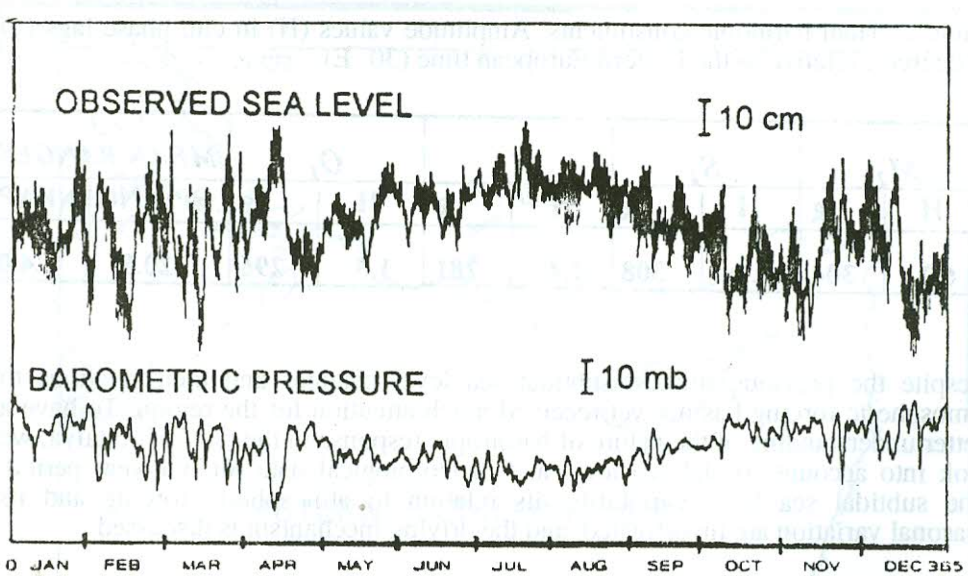


Figure 3. The original, tidal free (Godin's lowpass filter) and pressure adjusted sea levels at Antalya (1971).

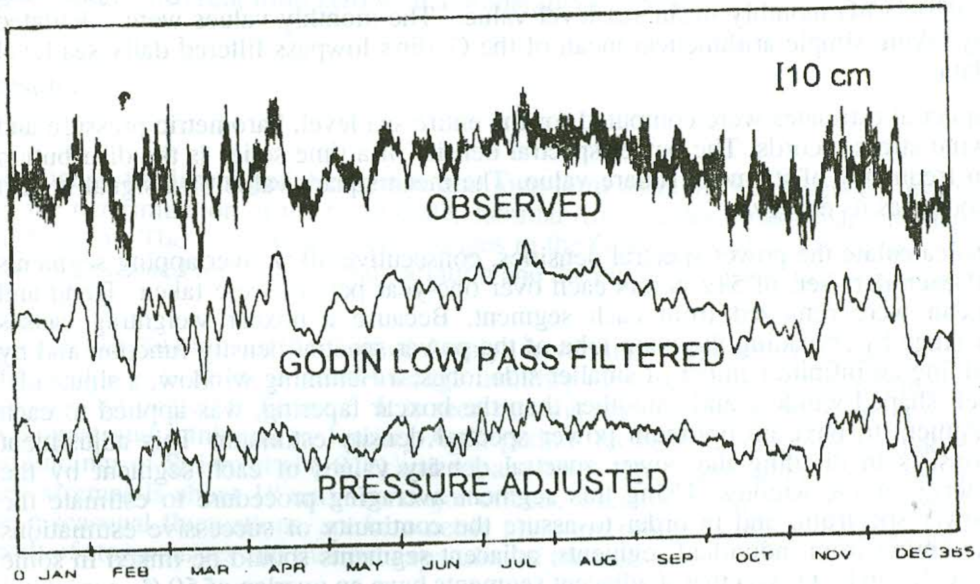
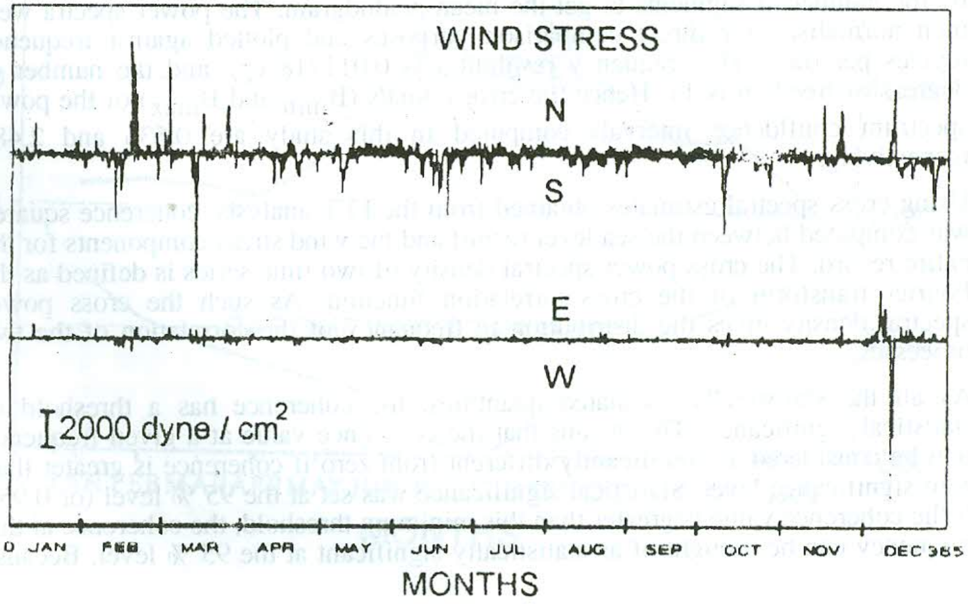


Figure 4. The NS and WE components of the wind stress at Antalya (1971).



Data Analysis

The average monthly mean sea levels were calculated using 5 year-long (1970-1974) monthly mean sea level values. The monthly values were calculated by taking simple arithmetical mean of the Godin's lowpass filtered daily sea level data.

Spectral estimates were computed for the entire sea level, barometric pressure and wind stress records. The power spectral density of a time series is the distribution in frequency of its mean square value. The mean square value of a signal is also known as its energy.

To calculate the power spectral densities, consecutive 50 % overlapping segments of each data set, of 512 points each over one-year period, were taken. Trend and mean were removed from each segment. Because a boxcar weighting causes leakage by spreading the main lobe of the power spectral density function and by adding an infinite number of smaller side lobes; a Hamming window, a sinusoidal bell-shaped window and smoother than the boxcar tapering, was applied to each segment to have an optimum power spectral density estimator. This adjustment consists in dividing the power spectral density values of each segment by the energy of the window. Using this segment averaging procedure to estimate the power spectrum, and in order to assure the continuity of successive estimations stemming from individual segments, adjacent segments should be linked in some way. It can be proven that if adjacent segments have an overlap of 50 %, a minimal distortion of the final power spectrum estimation is obtained. The tapered segments were then subjected to Fast Fourier Transform (FFT) analysis (Jenkins and Watts, 1968) to calculate the power spectra, utilising the Seaspect Software (Lascaratos *et al.*, 1990). The FFT's of the two adjacent sequences were extracted and divided by the energy of the window to compensate for its effects. The squared values were added to a running sum power spectral density and this process was repeated until no more segments. When the process is over the power spectral density is divided by the number of segments to get the mean peidodgram. The power spectra were then normalised for direct comparison purposes and plotted against frequency (cycles per day). The frequency resolution is 0.011718 cpd and the number of degress of freedom is 14. Hence the error bounds (B_{min} and B_{max}) of the power spectrum confidence intervals computed in this study are 0.536 and 2.487 respectively.

Using cross spectral estimates obtained from the FFT analysis, coherence squared was computed between the sea level record and the wind stress components for the entire record. The cross power spectral density of two time series is defined as the Fourier transform of the cross-correlation function. As such the cross power spectral density gives the distribution in frequency of the correlation of the two processes.

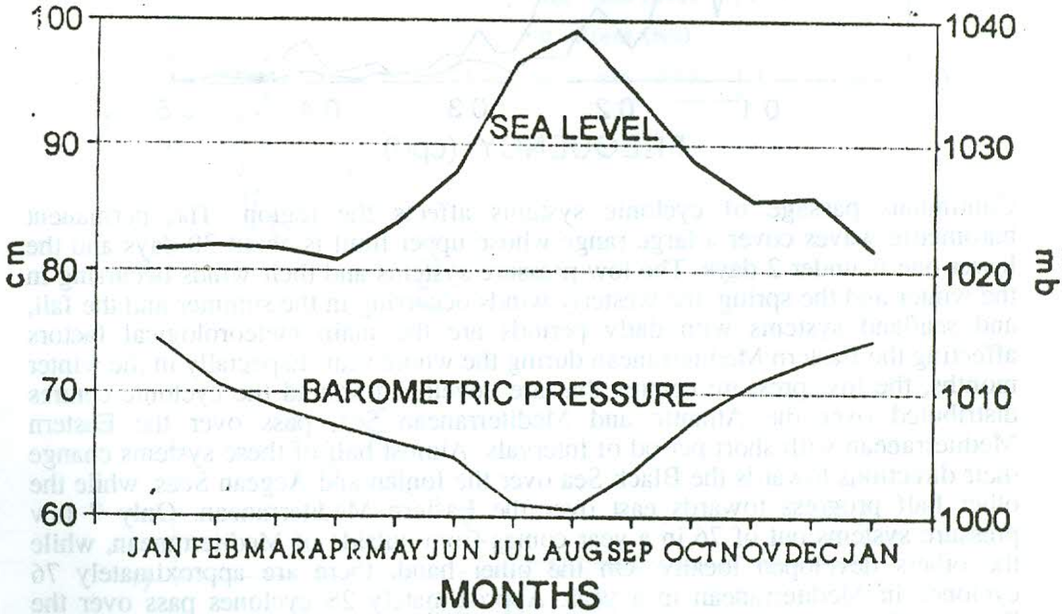
As all the statistically estimated quantities, the coherence has a threshold of statistical significance. This means that the coherence value at a given frequency will be considered as significantly different from zero if coherence is greater than zero significance level. Statistical significance was set at the 95 % level (or 0.95). If the coherence value is greater than this minimum threshold, the coherence at this frequency can be thought of as statistically significant at the 95 % level. Because the number of segments on which the estimation has been based is 16, the zero significance level (or 95 % confidence interval) is 0.181 in this study. Consequently only value of coherence greater than 0.181 can be thought of as significantly different from zero with a probability of 95 %.

Results

Because of the large spatial coverage and long-term duration, sea levels are useful for the determination of the large scale, subtidal (time scales longer than one day) fluctuations. The subtidal sea level changes in the Gulf of Antalya, Levantine Sea, will be examined for the seasonal variation and the evidence of wind-driven coastal circulation.

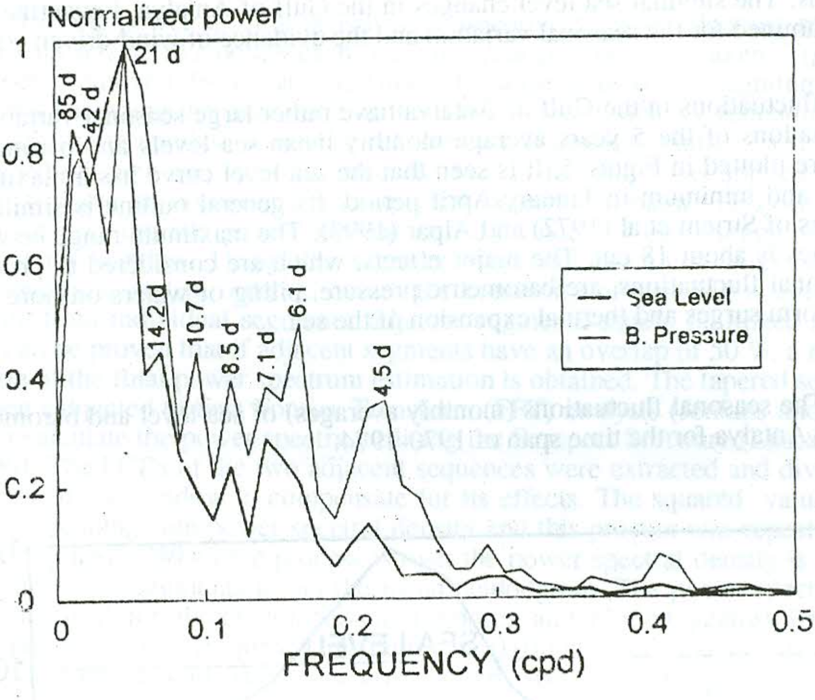
Sea level fluctuations in the Gulf of Antalya have rather large seasonal variability. The fluctuations of the 5 years average monthly mean sea levels and barometric pressure are plotted in Figure 5. It is seen that the sea level curve has a maximum in August and minimum in January-April period. Its general outline is similar to the findings of Striem et al (1972) and Alpar (1993). The maximum range between the extremes is about 18 cm. The major effects, which are considered to produce these seasonal fluctuations, are barometric pressure, piling of waters onshore as a result of storm surges and thermal expansion of the sea.

Figure 5. The seasonal fluctuations (monthly averages) of sea level and barometric pressure at Antalya for the time span of 1970-1974.



Spectral analysis of the observed sea level data reveals long period oscillations with pronounced periods around 14, 21 days and 3 months. On the other hand, barometric data indicated similar, large-scale features with dominant time scales of 6.1, 10.7, 21 and 42 days (Figure 6). Therefore most of the low frequency part (> 14 days) of the sea level variations can be attributed to the long period fluctuations in barometric pressure.

Figure 6. Normalized power spectra of the sea level variations and barometric pressure data at Antalya. Spectrum normalization factors are 0.12092E+07 and 0.1992E+06 respectively.

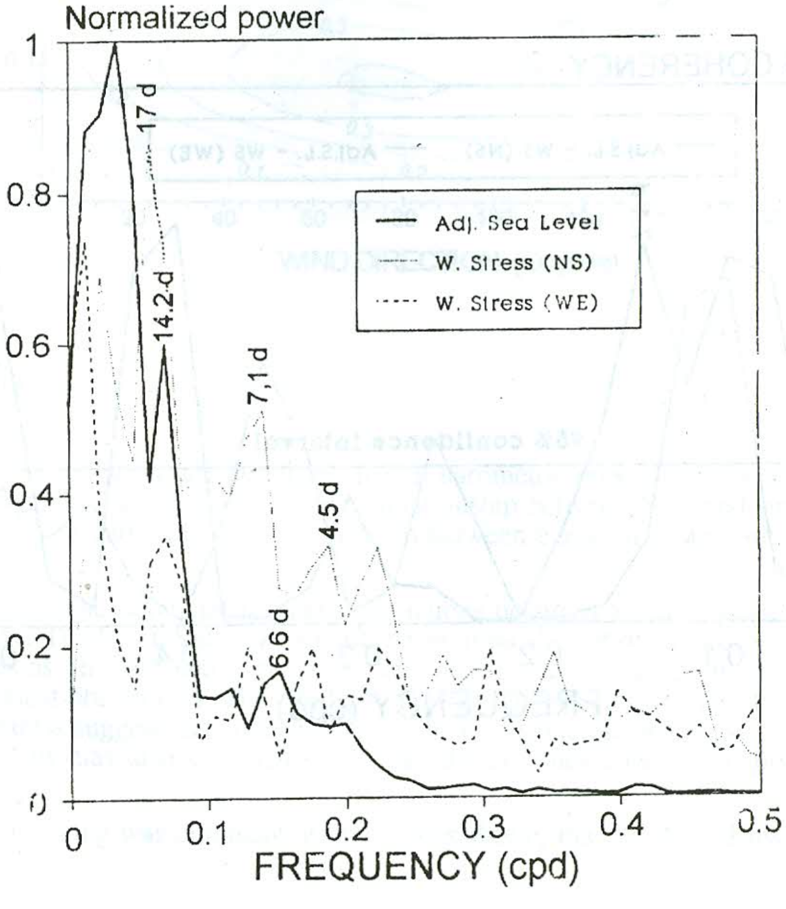


Continuous passage of cyclonic systems affects the region. The permanent barometric waves cover a large range whose upper limit is about 30 days and the lower one is under 2 days. The low pressure systems and their winds occurring in the winter and the spring, the westerly winds occurring in the summer and the fall, and sea/land systems with daily periods are the main meteorological factors affecting the Eastern Mediterranean during the whole year. Especially in the winter months, the low pressure centres that are developed around the cyclonic centres distributed over the Atlantic and Mediterranean Sea, pass over the Eastern Mediterranean with short period of intervals. Almost half of these systems change their directions towards the Black Sea over the Ionian and Aegean Seas, while the other half progress towards east over the Eastern Mediterranean. Only 7 low pressure systems out of 76 in a year comes from outside of Mediterranean, while the others developed locally. On the other hand, there are approximately 76 cyclones in Mediterranean in a year. Approximately 28 cyclones pass over the Eastern Mediterranean and affect the region about 4-6 days. Offshore wind fluctuations is mainly in the E-W (along-shore) direction outside the Gulf of Antalya. But during the passage of low pressure systems in the winter and spring, some strong northerly winds develop on the valleys (Antalya, Göksu and İskenderun) along the Taurus Mountains. The land-originated air masses coming from the main land of Europe causes dry and cold north-easterly winds on these passages (Özsoy, 1981).

On the other hand, the annual (1971) averages of wind directions at Antalya were south-westward and north-eastward. Wind blows predominantly from the NE (frequency of occurrence 38.1 %) and SW (frequency of occurrence 18.7 %), mainly in the winter time. The magnitude of mean wind is rather small (3.5 m/s) compared to the wind fluctuations which occurred mainly at time scales of 7-17 days, corresponding to the interval between two successive passages of the cyclone.

The power spectra of subtidal sea level and comparative wind stress components (NS and WE) are given in Figure 7. The spectrum of subtidal sea level is red,

Figure 7. Normalized power spectra of the subtidal variations and wind stress components [north-south and east-west] at Antalya. Spectrum normalisation factors are 0.5725+06, 0.3159E+10 and 0.8051E+08 respectively.



indicating long-term change (time scale > 14). The spectrum has distinct peaks at 6.6, 14.2 and 28 days. These oscillations are mainly due to the long period tidal and meteorological influences. The meteorologically induced long period oscillations may be related to large scale cyclic atmospheric patterns. Wind stress spectra (NS and WE) have peaks around 4.2, 7.1 and 17 days. At longer time scales than 10 days, non local wind forcing becomes important.

The cross coherency functions between adjusted sea level and wind stress components are given in Figure 8 as a function of the wind direction. Coherence squared of adjusted sea level against wind is above the 95 % confidence interval (> 0.181) for time scales longer than 7.1 days. To examine the relations between wind and adjusted sea level, its cross power spectral density was computed and the coherence squared as function of the frequency and wind direction is shown in Figure 9. For time scales between 7 and 25 days, the sea level in the Gulf of Antalya was highly coherent with the south-wesward wind. In other words, water was driven out of the Bay by south-westward winds, and an inflow was induced by north-westward winds.

Figure 8. Cross coherency functions between subtidal variations and wind stress components [north-south and east-west] at Antalya.

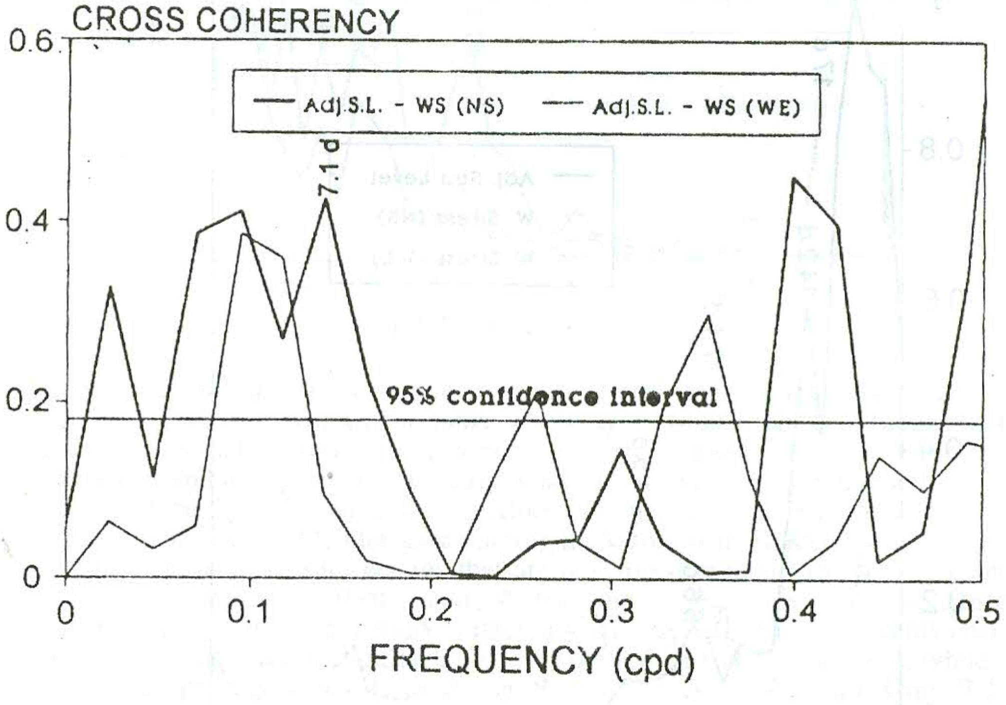
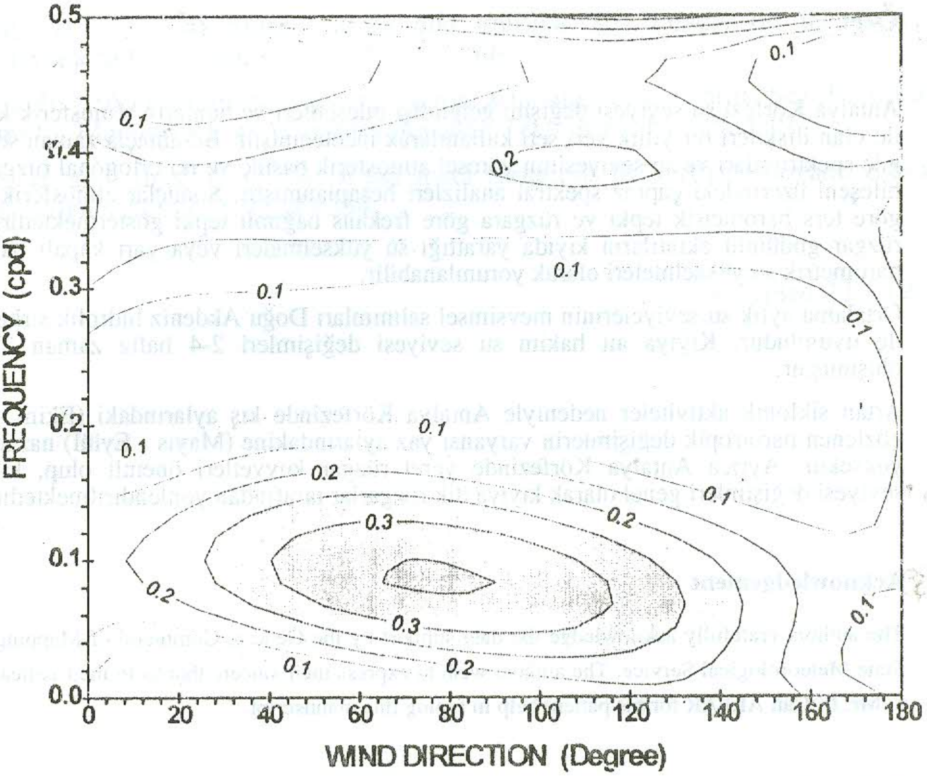


Figure 9. Coherence squared as a function of the wind direction for subtidal sea level and wind. The 90 direction is along the north-south axis.



Conclusion

Long period oscillations are dominant in both barometric pressure and wind stress. In low frequency band, there is a direct relationship between NS wind stress and coastal sea level and an inverse relationship between barometric pressure and sea level.

On the region, the dominant subtidal fluctuations occurred at time scales of 14.2 and 28 days. The low frequency band of the subtidal oscillations corresponds with the variations in barometric pressure and can be associated with mesoscale meteorological phenomena. The similarity between the spectra of coastal sea level and wind stress suggests that the subtidal sea level fluctuations were also driven by the wind. This may also support the fact that the cyclones affect the region when they develop.

Local wind forcing was dominant at time scales shorter than 10 days. However, at longer time scales, non local contribution was important. Coastal sea level response to wind forcing may have some variations changing with seasons, which may deserve further studies. The NS wind may also set up a surface slope.

Özet

Antalya Körfezi su seviyesi değişim gelgitdışı bileşenleri ve bunların atmosferik kuvvetler ile olan ilişkileri bir yıllık veri seti kullanılarak incelenmiştir. Bu amaçla zaman serilerinin güç spektrumları ve su seviyesinin yöresel atmosferik basınç ve iki ortogonal rüzgar şiddet bileşeni üzerindeki çapraz spektral analizleri hesaplanmıştır. Sonuçlar atmosferik basınca göre ters barometrik tepki ve rüzgara göre frekans bağımlı tepki göstermektedir. Bunlar rüzgar güdümlü akıntıların kıyıda yarattığı su yükselmeleri veya yarı kapalı havzalarda barometrik su yükselmeleri olarak yorumlanabilir.

Ortalama aylık su seviyelerinin mevsimsel salınımları Doğu Akdeniz hidrolik sirkülasyonu ile uyumludur. Kıyıya ait hakim su seviyesi değişimleri 2-4 hafta zaman ölçeğinde oluşmuştur.

Artan siklonik aktiviteler nedeniyle Antalya Körfezinde kış aylarındaki (Ekim - Nisan) gözlenen barotropik değişimlerin varyansı yaz aylarındakine (Mayıs - Eylül) nazaran daha yüksektir. Ayrıca Antalya Körfezinde yerel rüzgar kuvvetleri önemli olup, kıyısal su seviyesi değişimleri genel olarak kıyıya dik rüzgarlar tarafından yönlendirilmektedir.

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