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Subtidal Sea-level Variations in the Sea of Marmara, Their Interactions with Neighboring Seas and Relations to Wind Forcing

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ABSTRACT

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Subtidal sea level fluctuations in the Sea of Marmara, their interactions with neighbouring seas (Black Sea and Aegean) and relations to wind forcing were examined over a three-year (1992–1994) period. Although the dominant sea level fluctuations occurred at time scales greater than 10 days, there are shorter period fluctuations occurring between 3–8 days. Subtidal sea levels for Sea of Marmara are highly coherent for all subtidal frequencies. There is no cross coherency for periods greater than 2.5 days between Sea of Marmara and Black Sea, while there are some coherent fluctuations in subtidal band between Sea of Marmara and the Aegean Sea. Local wind forcing is important for the Sea of Marmara and most of the sea level change is driven by NE-SW wind for Erdek and Fenerbahce. However, at longer time scales, nonlocal contribution is important.

ADDITIONAL INDEX WORDS: *Sea of Marmara; sea level; tides; subtidal sea level variations; air-sea interaction; spectral analysis.*

INTRODUCTION

The Sea of Marmara (SOM) is a small inland sea connected to the Black Sea and Aegean Sea through two narrow, long and elongated straits of Istanbul (Bosphorus) and Canakkale (Dardanelles) (Figure 1). It was shown by recent studies that the SOM is completely isolated from the Black Sea for tidal oscillations while the tidal influence of the Aegean Sea is only limited to the Marmara exit of the Strait of Canakkale (SOC) (Yüce, 1986, 1991, 1993, 1994). Inverse water level variation between northern and southern parts of the SOM at daily and long term scales was argued (Yüce, 1994) but further investigations showed that the data for that period were erronously sampled. The characteristics of water level variations in the SOM and its interactions with the Northern Aegean Sea have been studied by Yüce and Alpar (1996). It was shown that southwestern SOM co-oscillates with the northeastern Aegean Sea. The present paper describes low frequency sea level fluctuations in the SOM, their interactions with neighboring seas and their relations with wind forcing. Coherent sea level variations between Fenerbahce and Erdek will be investigated.

DATA AND ANALYSIS

Sea levels are routinely monitored at Erdek with a mechanical R. Fuess stilling well type permanent tide gauge by the General Command of Mapping. A mechanical OTT float type temporary sea level station at Fenerbahce is operated by Department of Navigation, Hydrography and Oceanography (Figure 1). Sea level investigations are based on data collected between 1987–1994 for Erdek and 1992–1994 for Fenerbahce on the coast of SOM. The vertical datum planes for these tidal projections are arbitrary at each of the recording sites.

Original hourly-sampled data were low-pass filtered by using $A^2_{25}A_{24}/(25^2\times24)$ Godin (1970) tide-killing filter to remove diurnal, semi-diurnal and high-frequency fluctuations. Low-pass filtered records were then resampled to a 4-h interval (Figure 2). Subtidal sea level data were then adjusted by simply adding the air pressure.

Surface barometric pressure, wind speed and direction were obtained for Goztepe and Bandirma meteorological stations over the same period (Figure 1). Data were lowpass filtered and resampled to a 4-hr interval. Wind components and wind stress components, which were computed from the wind field from usual quadratic law using a drag coefficient of 2.5×10^{-3}, were then lowpass filtered and resampled to a 4-hr interval (Figure 2). This calculation provides a relative measure to quantify the effects of wind forcing.

Spectral estimates were computed for the sea level (Figure 3), barometric pressure and wind stress components (Figure 4) for the entire three-year observation period. To calculate the power spectral densities; 11 consecutive segments (50% overlapping) of each data set, of 1024 points each, were taken. Trend and mean were removed from each segment and Hamming window was applied. The tapered segments were then

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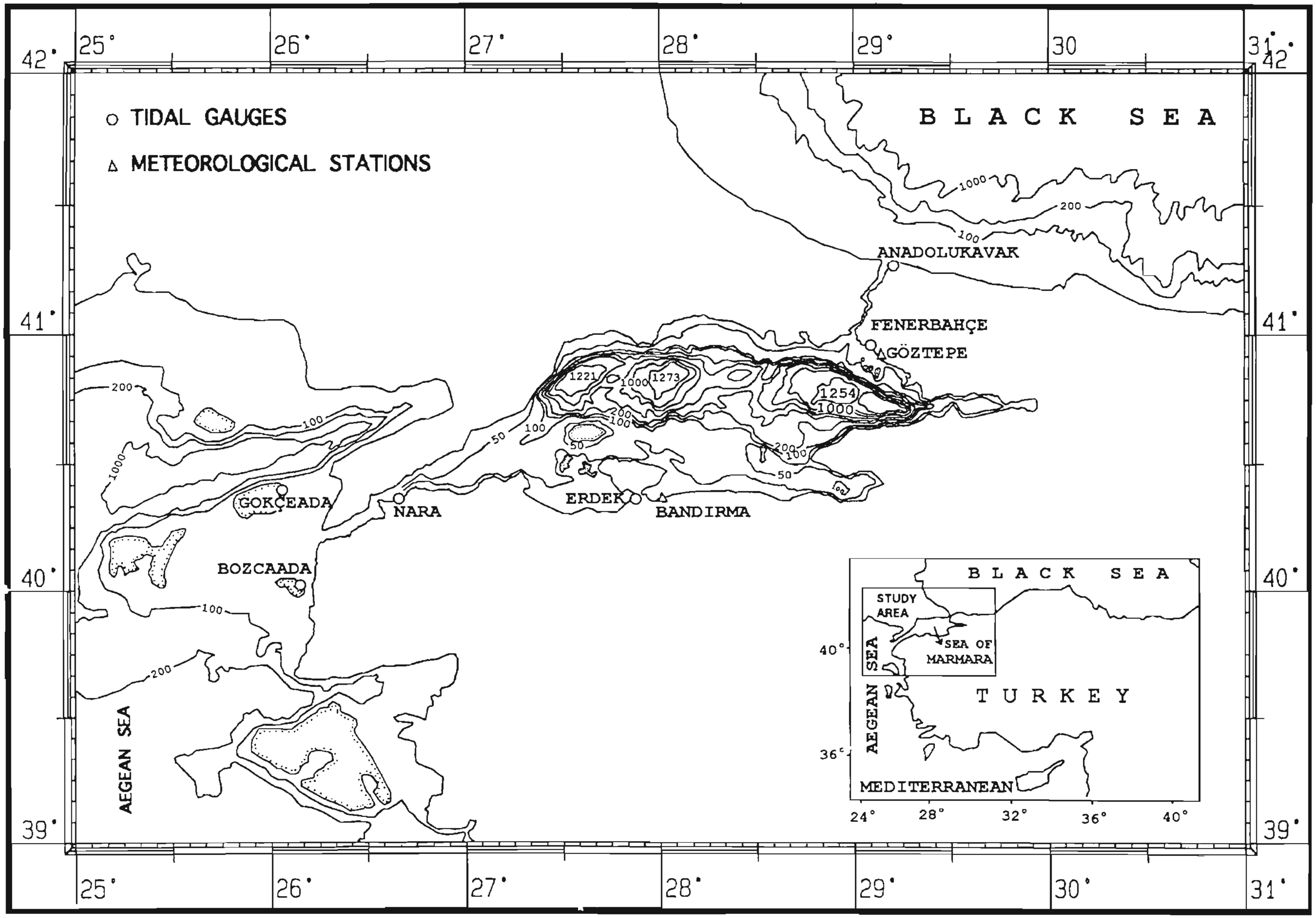

Figure 1. Location and bathymetric map of the study area.

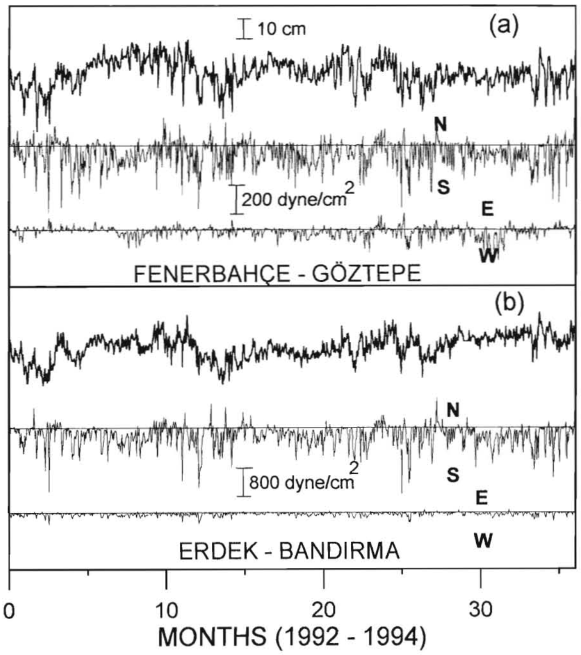

Figure 2. Daily averages (Godin's lowpass filter) of the adjusted sea level variations and the NS and WE components of the wind stress at (a) Fenerbahce/Goztepe and (b) Erdek/Bandirma between 1992 and 1994.

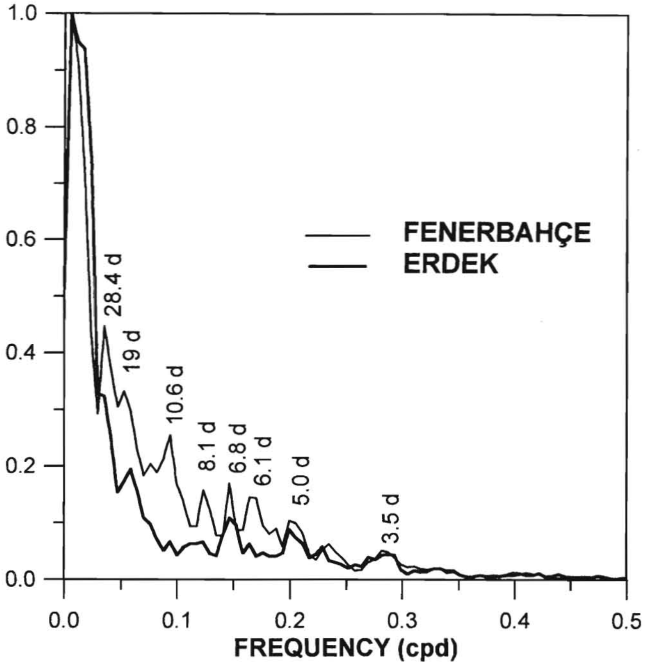

Figure 3. The normalised power spectra of the adjusted sea level variations at Fenerbahce and Erdek. Spectrum normalisation factors are 0.3502E + 7 and 0.2781E + 7, respectively (d.o.f. 22).

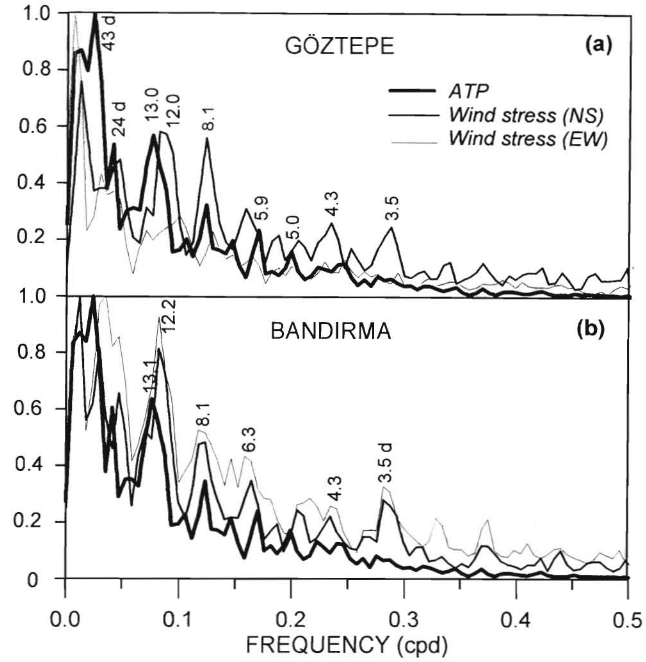

Figure 4. The normalised power spectra of the barometric pressure and the wind stress components (north-south and east-west) at (a) Goztepe and (b) Bandirma. Spectrum normalisation factors are 0.1341E + 7 and 0.1114E + 7 for barometric pressures, 0.1093E + 10 and 0.1089E + 11 for NS components and 0.3094E + 9 and 0.2039E + 9 for EW components, respectively.

subjected to fast Fourier transform (FFT) analysis (JENKINS *et al.*, 1968) to calculate the power spectra, utilizing the Seaspect Software (LASCARATOS *et al.*, 1990). The power spectra were then normalized for direct comparison purposes and plotted against frequency [cycles per day]. All of the power spectra in this study were computed with a frequency resolution of 0.005859 cpd. For 95% confidence, minimum and maximum error bounds of the power spectrum, for 22 degrees of freedom, are (0.598 and 2.003).

Using cross spectral estimates obtained from the FFT analysis, coherence squared was computed between the sea level records and the wind stress components for Fenerbahce and Erdek (three years record) and also for the straits (short data sets). For short data sets, the hourly input data for each station (6 Jan–23 March 1993 for Anadolukavak and Fenerbahce and 14 July–31 December 1994 for Erdek and Bozcaada) were mean and trend removed, processed by Hamming window and then band-pass filtered for subtidal band (0–0.8 cpd). The 95% confidence intervals for consistency with zero coherence are 0.059 and 0.393 for long and short data sets, respectively. Consequently only values of coherence greater than these values can be thought of as significantly different from zero with a probability of 95%.

RESULTS AND DISCUSSION

Low Frequency Sea Level Variations

The energy spectra of the adjusted subtidal sea level are almost red (Figure 3). There are distinct peaks greater than 10 days and also between 3.5 and 8.1 days. Surface atmospheric data (from land stations only) indicated a similar, large-scale feature; the dominant periods were 43, 24, 12–13, 8.1, 6, 4.3 and 3.5 days (Figure 4a, b).

Sea level variability in the SOM in winter months is about 2.9 times larger than that in summer. For barometric pressure, it is about 3.1 times. For summer, sea level variations are 4.1 and 3.3 times larger than that of barometric pressure for FEN and ERD respectively; 3.9 and 3.0 for winter. This means barometric pressure is not the only mechanism generating low frequency (greater than 2 days) sea level variations. The residual variance in sea level can be due to wind influence and other factors such as low frequency steric effects.

Sea-Level Interactions in the Subtidal Band

The adjusted subtidal sea levels for FEN and ERD are coherent for all subtidal frequencies, but marked especially at 21, 4.7, 3.3 and 2.4 days. The coherence squared is as high as 0.6 for all time scales greater than 3 days and also high (about 0.5) for shorter time scales (Figure 5a). Around 10 days periodicities the coherence become smaller. There is no significant phase difference from zero in the high-coherence bands. In other words, the sea level fluctuations between Fenerbahce and Erdek are simple oscillations in these bands.

The hourly subtidal input data sets (with lengths 77 and 171 days for Strait of Istanbul and for Strait of Canakkale, respectively) were used to investigate the cross coherency between the subtidal variations between the SOM and neighboring seas (Black Sea and Aegean). The results were given in Figure 5b, c. There is no cross coherency greater than 2.5 days between SOM and Black Sea. On the other hand, there are some coherent fluctuations with periodicities of 2.8, 3.9, 6.1–8.5 and 14 days between SOM and the Aegean Sea. The long-period subtidal fluctuations are simple oscillations, but SOM waters follows the Aegean waters by a time lag (between 7 and 10 hours) for periods shorter than 3 days.

Wind Forcing

During the winter, continuous passage of cyclonic systems affects the region for periods between 3 to 12 days. They follow three main tracks; eastward over the Aegean towards the eastern Mediterranean, from Balkans towards the Black Sea, and from the Aegean Sea towards the Black Sea. During the summer, northerly winds from the Black Sea affect the region (OZSOY, 1981).

The coastal wind fluctuations were mainly in the SW-NE direction over Fenerbahce and Erdek. In contrast, the NW-SE component of the wind has a minor effect on the total wind fluctuation in the SOM. The average wind speeds at Goztepe and Bandirma meteorological stations were calculated as 2.1 and 2.6 m/s, respectively, for 1992–1994 period. The wind direction is mainly from the NE for both stations. The dominant wind direction for Goztepe is from NE with a percentage of 32.6 and 61.7% of them having a wind speed varying between 2–5 m/s, with an average of 3.2 m/s. The dominant wind direction for Bandirma, on the other hand, is from NE with a percentage of 55.6 and 36.1% of them having a wind speed varying between 5–8 m/s, and an average of 5.3 m/s. The total energy of the wind stress at Bandirma is almost 7 times greater than that of Goztepe.

The data were consistent with the fact that the cyclones affect Erdek during their early stage, and the Fenerbahce when they develop. Consequently, wind over the western SOM was not coherent with the wind further east, despite both being dominated by cyclones. Wind stress spectra for Goztepe and Bandirma were given in Figure 4. They have distinct peaks with periods longer than one week such as 8.1, 12, 24 and 43 days, which may be correlated with the sea level spectrum. The energy spectra of the wind stress components have also distinct peaks between 3 and 6 days (especially at 3.5, 4.3 and 5.9 days). The east-west wind stress shows the additional effect of the diurnal sea breeze.

The cross coherency functions between adjusted subtidal sea level and wind stress components were computed (not given here individually) as a function of the wind direction. Coherence squared of adjusted sea level against NS wind stress component is above the 95% confidence interval (> 0.122) for time scales of 2–5 days for Erdek (with distinct peaks at 2.3, 2.9, 3.5 and 4.3 days) and greater than 3 days (with distinct peaks at 3.7, 7.7, 10.7 and 83 days) for Fenerbahce. On the other hand, coherence squared of adjusted sea level against EW wind stress component is above the 95% confidence interval for time scales of 2.5–6.7 days (with two distinct peaks at 3.2 and 4.3 days) for Erdek and about 2.9–28.2 (with a distinct peak at 7.7 days) days for Fenerbahce.

To examine the relations between wind and adjusted subtidal 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 6. Sea levels were highly coherent with NE-SW wind (*i.e.,* wind direction 45 in Figure 6). For time scales 2.2 and 4.5 days, the sea level in Erdek was highly coherent with easterly winds (060–090°). In other words, water was driven out by easterly winds, and an inflow was induced by winds blowing eastward. On the other hand, the sea level in Fenerbahce was highly coherent with northeasterly winds (020–060°) for time scales between 4.5 and 20 days; water was driven out by northerly winds, and an inflow was induced by southerly winds.

The phase difference between adjusted subtidal sea level and NS component of the wind stress for Fenerbahce and Erdek have nearly linear trends against frequency (Figure 7). This implies time lags (adjustment time) of about 2.3 and 5.7 hr, for the dominant sea level fluctuations occurred between the 8.1 and 3.5 day time scales (Figure 3), which corresponds to the observed peaks of NS wind stress at Fenerbahce and Erdek (Figure 4). The latter is responsible for 5.7 hr time lag between two stations.

CONCLUSIONS

Sea level, barometric pressure and winds show a high spatial correlation over the SOM. The subtidal sea level variations are coherent all over the SOM and partly between the SOM and the Aegean Sea. But it is not coherent between Black Sea and SOM for periods longer than 2.5 days.

The correspondance between the spectra of the winds and adjusted sea level suggests that the subtidal sea level fluc-

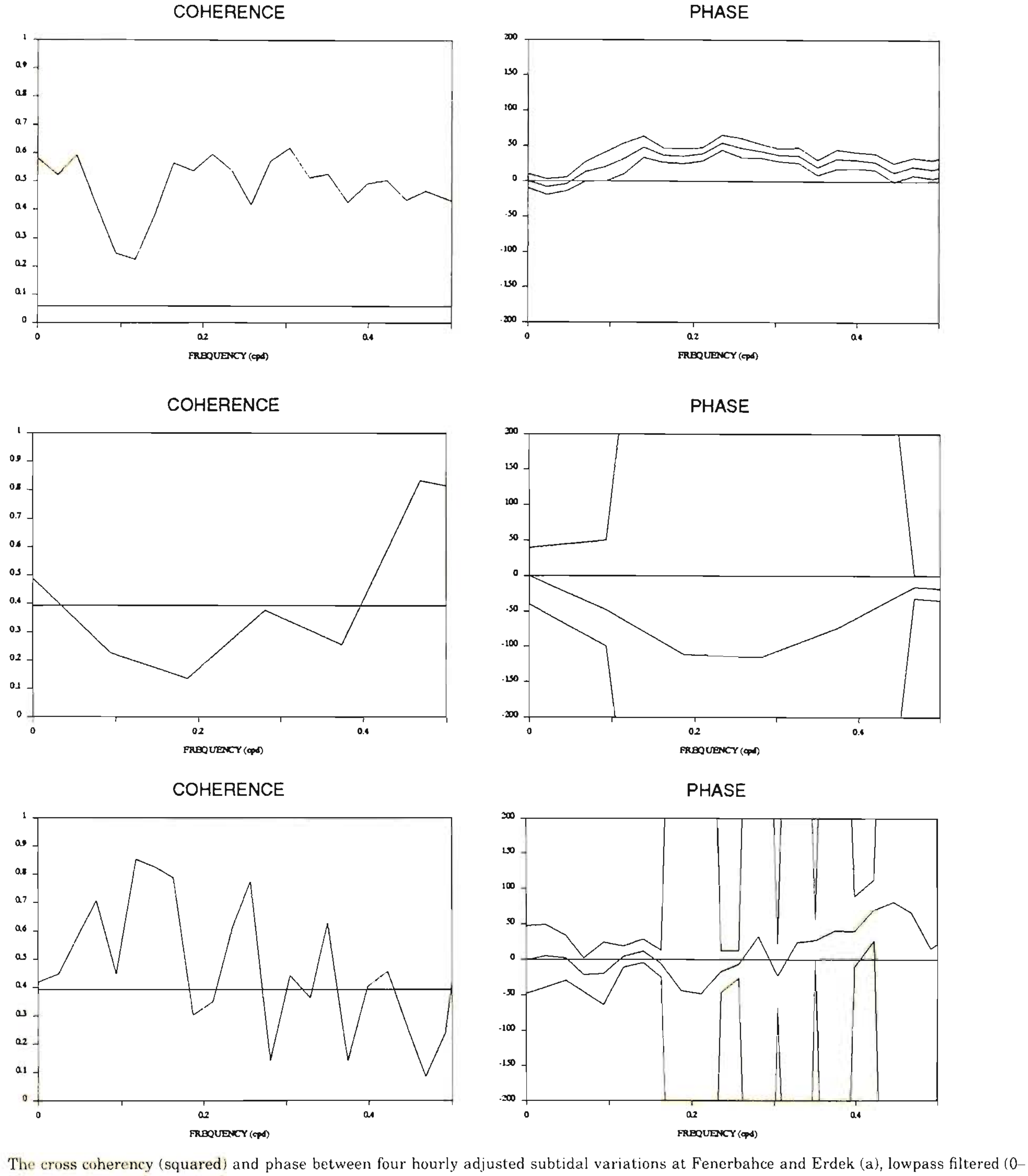

Figure 5. The cross coherency (squared) and phase between four hourly adjusted subtidal variations at Fenerbahce and Erdek (a), lowpass filtered (0–0.8 cpd) hourly variations at the two ends of SOI (b), and SOC (c). The 95% significance levels are marked.

tuations are generally driven by the wind in the SOM. Coastal sea level response to wind forcing in the SOM 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. Coherence squared of the adjusted sea level against NS wind stress component is important for time scales of 2–5 days for Erdek and greater than 3 days for Fenerbahce. Against EW wind stress component, it is significant for time scales of 2.2–4.5 days for Erdek and about 3 and 4 days for Fenerbahce. In other words, the sea level in Erdek was highly coherent with easterly winds for time

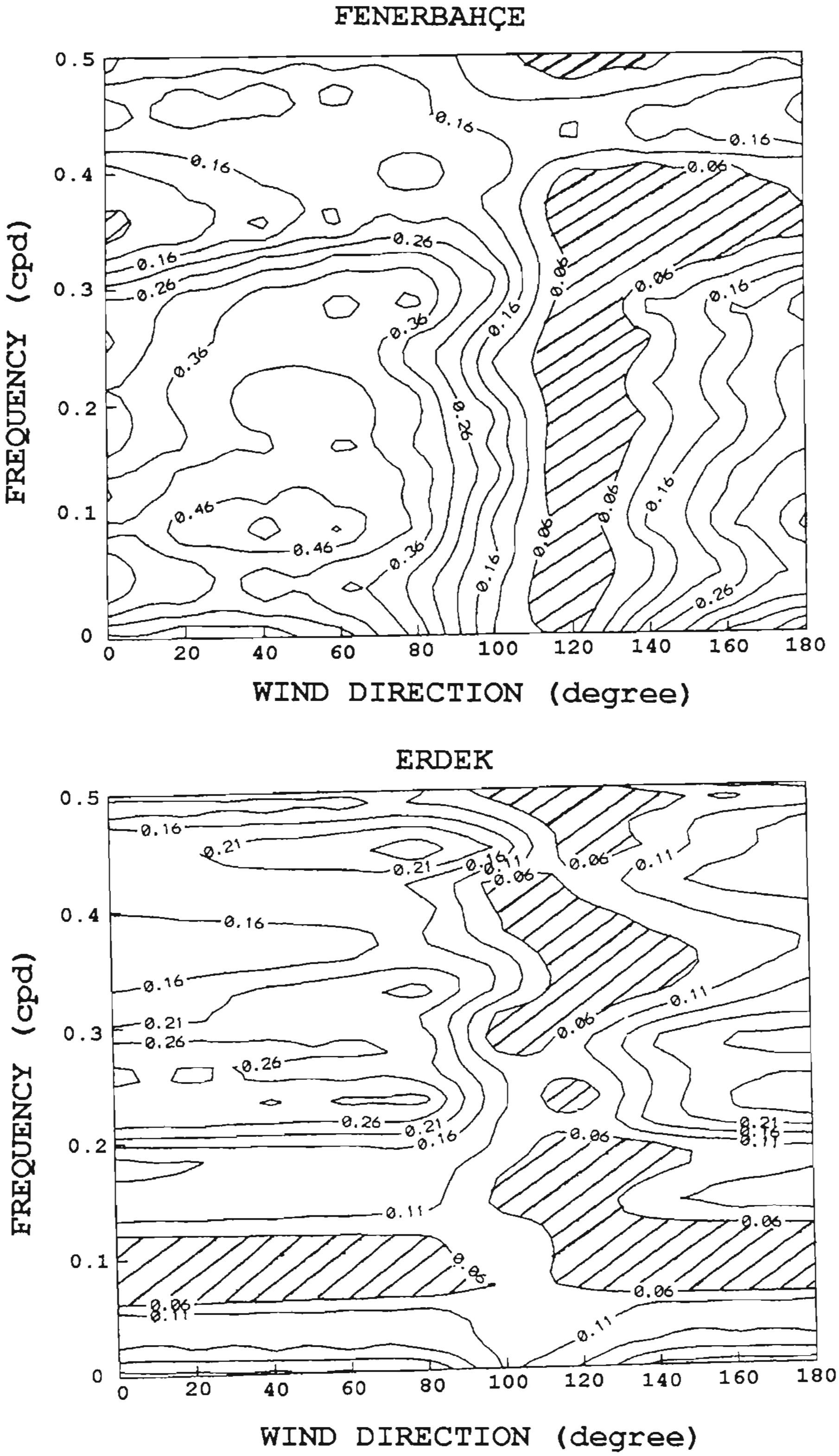

Figure 6. The coherence squared as a function of the wind direction for subtidal sea level and wind at (a) Fenerbahce and (b) Erdek. The shaded area represents that the coherence is lower than the 95% confidence interval.

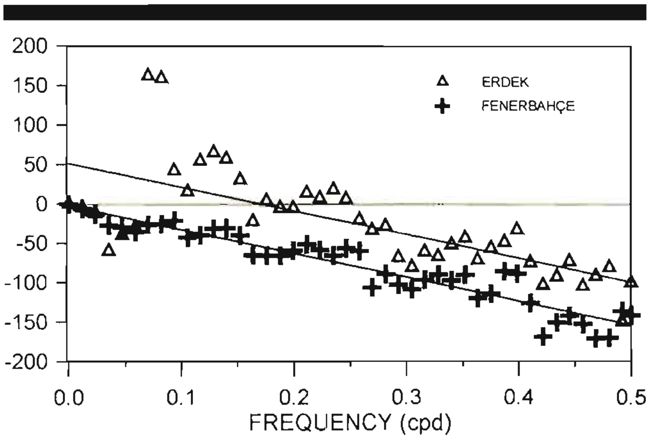

Figure 7. The phase differences between NS wind stress and sea level at Fenerbahce and Erdek. Solid lines corresponds to 4–2 hr time lags for dominant periods of subtidal sea level fluctuations between 5–10 days.

scales between 2.2–4.5 days, and it was highly coherent with northeastrly winds for time scales between 3–5 days for Fenerbahce.

For longer time scales greater than 15 days, however, the nonlocal contribution was important as evidenced by the lack of local wind coherence and the northeastward phase propagation of sea levels from Erdek and Fenerbahce. Between 5 and 15 days in which most of the cyclone forcing occured, the response of the local and nonlocal forces was coupled, and mainly driven by N-S winds. The NS wind setups a large surface slope between the northern and southern parts.

The phase difference between sea level and NS wind for northern and southern parts of the SOM have nearly linear trends against frequency, implying constant time lags of about 2.3 and 5.7 hours for the dominant sea level fluctuations.

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