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"Low-Frequency Sea Level Variability in the Northeastern Mediterranean"

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Low-Frequency Sea Level Variability in the Northeastern Mediterranean

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ABSTRACT

Analyses of time series of one year of sea level data from 11 stations in the northeastern Mediterranean (Adriatic, Ionian and Aegean seas) are presented in terms of local atmospheric pressure forcing. The study focuses on low-frequency oscillations with time scales ranging from one day to several weeks, but shorter than the seasonal scale. The summer and winter seasons are analyzed separately. An empirical orthogonal function analysis of both sea level and atmospheric pressure resulted in a separation of lower frequency oscillations of planetary-wave time scale (expressed by the first mode) from the higher frequency synoptic time scale variability (included in the second mode). The first mode is related to the in-phase sea level or atmospheric pressure variations of the entire area, while the second mode represents variations for which the Adriatic Sea is out of phase with both the Ionian and Aegean seas. Only those first two modes represent a regionally coherent signal subtracting more than 90% of the total variances of both sea level and atmospheric pressure. The sea level EOFs are closely related to respective atmospheric pressure modes both in space and time. Departures from the isostatic response, evidenced in the low frequency range of atmospheric planetary waves, are indicated not to be due to geostrophic control in straits. The second-mode time dependence is shown to be related to the surface pressure changes induced by the regional cyclonic activity. The location of the zero crossing of the atmospheric pressure second mode over Otranto Strait is explained in terms of the prevalent cyclone paths.

1. Introduction

Sea level variability in the low frequency range (periods from tidal to several weeks) represents an energetic part of the Mediterranean sea level spectrum. In the Adriatic and other parts of the Mediterranean, sea level variations at time scales from one to ten days, have been shown to be primarily due to surface pressure changes related to synoptic atmospheric disturbances (Kasumović 1958; Mosetti 1971; Papa 1978; Godin and Trotti 1975). On the other hand, sea level variations at time scales from ten days to several weeks have been explained as due to atmospheric planetary waves (Orlic 1983). Departures from isostatic response have been indicated to be due to either local winds (Palumbo and Mazzarella 1982) or to the restrictions at straits to water transport between basins (Garrett 1983; Garrett and Majaess 1984). Crepon (1975) showed that the response of a rotating fluid is never barometric. It may be quasi-barometric if the space scale of the atmospheric disturbance is smaller than the barotropic radius of deformation. He also showed that the larger the bottom friction is, the closer the response is to barometric. Coastlines which can support Kelvin waves ease barometric adjustment.

Lacombe (1961) pointed out that, by continuity, an isostatic response of the Mediterranean would require a strong fluctuating flow through the Strait of Gibraltar. Crepon (1965) concluded that the ratio of atmospheric pressure to sea level in the Western Mediterranean was consistent with an inverted barometric response. He also found a high correlation between cross-strait sea level differences and minus atmospheric pressure over the area, consistent with the geostrophic balance of the inflowing water.

In contradiction with the mass conservation requirement, Crepon (1965) and Lacombe et al. (1964) found, that in the Western Mediterranean, sea level rather than the rate of change of sea level is related to the inflow at Gibraltar. Garrett (1983) explained this with a simple model, using the barotropic response to eastward propagating cyclones and the exchange of water through the Strait of Sicily. He also predicted that the Eastern Mediterranean should react nonisostatically to moving atmospheric perturbations.

Commenting on his model subdivision of the Mediterranean into two large basins separated by a narrow channel, Garrett (1983) argues that "this does not allow

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adequately for the separate response of areas such as the Adriatic or the Aegean seas but, it is probably a good first approximation." He also stresses "the most pressing need for the further study of sea level response in the Eastern Mediterranean to atmospheric pressure." Garrett and Majaess (1984) showed that for one station in the Eastern Mediterranean (Katakolon, Greece), the sea level response to atmospheric pressure is nonbarometric at a time scale of about four days. At time scales larger than four days and smaller than three days, they showed a near-barometric response. Such a response at low frequencies occurs because there is enough time for sea level to adjust. On the other hand, high-frequency changes have space scales smaller than basin scales. Thus, internal adjustments occur and flow through straits is not required.

Garrett and Majaess (1984) also computed the cross spectrum between the atmospheric pressure variations at one station in the Eastern Mediterranean (Andravidha, Greece) and at another station in the Western Mediterranean (Cagliari, Italy). They showed that coherence was significant only for frequencies less than 0.005 cycles per hour. The lack of coherence between the Western Mediterranean and the Adriatic Sea was noted in the nontidal sea level variations by Rickards (1986) using a two-month time series. At the same time, she demonstrated that sea level variations in the Adriatic Sea were well correlated with the passage of synoptic atmospheric perturbations.

The two quoted Garrett (1983) comments and the results of Garrett and Majaess (1984) represent the starting point of our investigation.

This study focuses on time variability ranging from two days to several weeks but less than the seasonal time scale (i.e., scales at which the influence of atmospheric forcing should prevail). Our main objectives are 1) to determine the horizontal space scales of the subtidal sea level and the atmospheric pressure variability in the northeastern Mediterranean and 2) to examine the correspondence between space and time scales. The sea level response to the atmospheric pressure forcing in the subtidal frequency range is also studied.

2. Datasets

The sea level data are from five Adriatic stations (Koper, Rovinj, Split, Dubrovnik and Bar), three Ionian stations (Preveza, Katakolon and Kalamata) and three Aegean stations (Iraklion, Syros, and Kavala) for the period 1 November 1981–31 October 1982 (Fig. 1). Daily means were calculated from hourly sea level data (0000 to 2300 EMT inclusive). All sea level data are expressed in centimeters and are related to the local

FIG. 1. Study area. Open circles denote tide-gauge stations, while dots represent atmospheric pressure stations. Crosses denote locations where both tide gauge and atmospheric pressure stations coincide.

tide-gauge zero. Because of the low tidal amplitudes in the study area, daily averaging effectively eliminated tides from the sea level records.

The atmospheric pressure data were available from four Adriatic stations (Pula, Split, Dubrovnik and Ulcinj), three Ionian stations (Corfu, Katakolon and Methoni) and three Aegean stations (Iraklion, Naxos and Alexandroupolis) for the same period as the sea level data (Fig. 1). Daily means for the first four stations were computed from data taken at 0100, 0400, 0700, . . . EMT. The daily means for the remaining six stations were computed from 24 hourly values (0000 to 2300 EMT inclusive). All atmospheric pressure data are expressed in millibars and are corrected to sea level and zero degrees temperature.

Routine quality control of the data was carried out by the corresponding meteorological and hydrographic services.

3. Analysis and discussion

a. Sea level and atmospheric pressure time series

Time series of sea level and atmospheric pressure are presented in Figs. 2a and 2b. The similarity of the sea level records at all stations suggests a strong spatial coherence of sea level variability within the study area. The same comment can be made of the atmospheric pressure records.

Further examination of the figures reveals a possible seasonal signal in the sea level time series (also present but less energetic in atmospheric pressure). The records show that a sea level maximum occurred in late autumn and a minimum in spring. These extremes occur almost simultaneously in all of the station records. Part of this basic oscillation in the sea level can be attributed to barotropic phenomena (e.g., response to atmospheric pressure forcing), but most appear related to baroclinic phenomena such as steric effects (Palumbo and Mazzarella 1982).

Variations at the time scale of a month are also present in both sea level and atmospheric pressure time series. Their amplitudes are of comparable magnitude to the amplitude of the seasonal signal. Higher frequency oscillations at time scales of several days (synoptic variability), appear in both time series at all stations. Amplitudes of these variations are at a minimum in summer and a maximum in winter. Both high and low frequency sea level variations are approximately opposite in phase to the respective atmospheric pressure variations.

Figures 2a and 2b show that the sea level and atmospheric pressure variance differs seasonally. In order to separately study the winter and summer periods, each dataset was split into two 160-day subsets: "winter" (the high variance period) is the interval from 1 November 1981 to 9 April 1982 (day 1 to 160) and "summer" (the low variance period) is the interval from 1 May to 7 October 1982 (day 182 to 341).

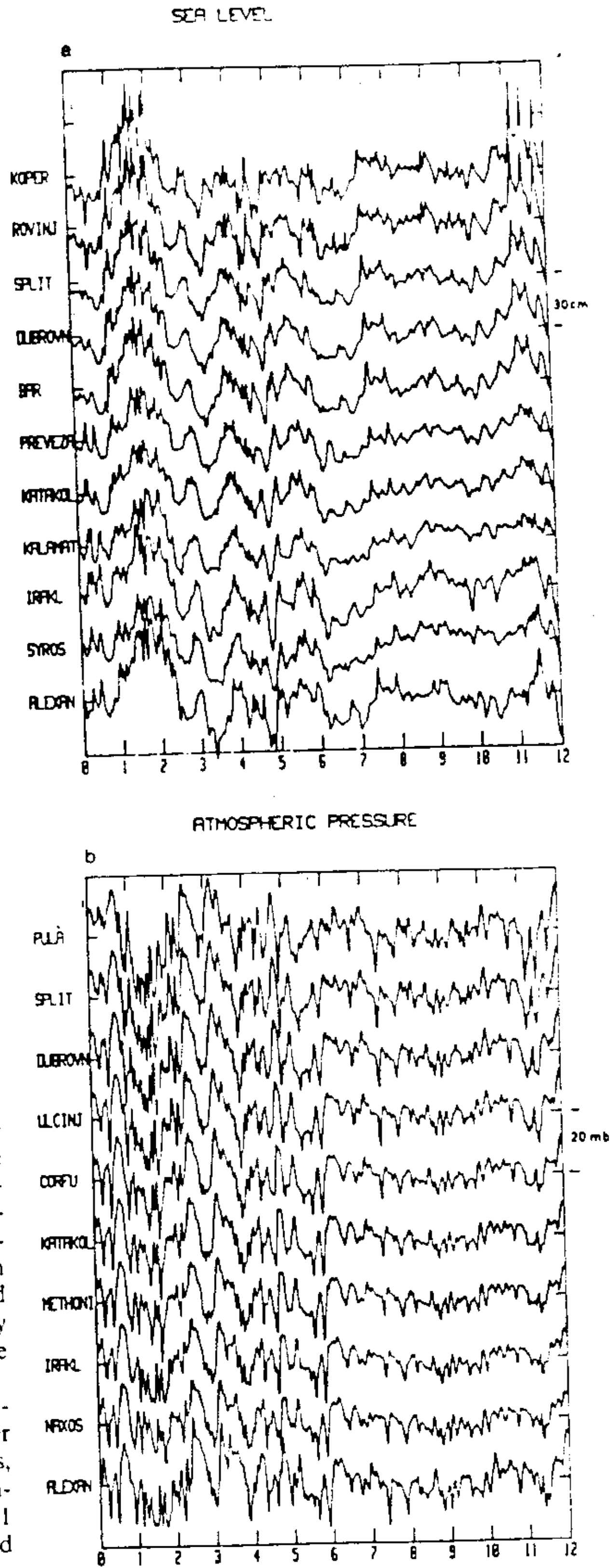

FIG. 2. Time series of (a) sea level and (b) atmospheric pressure.

b. Spatial coherence of sea level atmospheric pressure variability (EOF analysis)

In order to investigate the space scales involved in sea level and atmospheric pressure variability, we used an empirical orthogonal function (EOF) analysis. This method was developed for meteorological forecasting purposes (Kosambi 1943), and its summary can be found in Wallace and Dickinson (1972), Kundu and Allen (1976) and Weare (1977). Recently, it has been widely used in analyses of the sea level data (Enfield and Allen 1983; Halliwell and Allen 1984; Rickards 1985; Pugh and Thompson 1986; Barnett 1983, 1984). Sollow (1987) applied EOF analysis to simple models of tide gauge records. He argues, however, that this method may introduce errors if used to study long-term climatological trends.

The EOF analysis was applied separately to the summer and winter datasets after mean and trend removal. The first two modes are shown in Figs. 3 and 4. The remaining higher modes contribute less than 10% to the total variance. They are assumed to be associated with local effects with no regional significance and have not been taken into further consideration.

1) FIRST MODE

The first mode represents a simultaneous rise and fall of sea level or atmospheric pressure inside the study area. In winter, it accounts for about 88% of the total variance in both sea level and atmospheric pressure. In summer, the percentage of the explained variance by the first mode is larger in atmospheric pressure than in the sea level (about 83% in atmospheric pressure and 73% in sea level). The high percentage of variance explained by the first mode in all datasets is in accordance with the good spatial coherence of the time series evident in Figs. 2a and 2b.

The shape similarity of the first EOFs of the sea level and atmospheric pressure (Figs. 3a and 3b) indicates the uniform distribution of amplitudes over the entire area. The figures show only slight amplification of sea level and atmospheric pressure variations in the areas of the northern coasts of the Adriatic and the Aegean (Koper, Rovinj and Alexandroupolis). Note the slight increase of the sea level eigenfunction at Iraklion (we will return to this point in the next paragraph). The shape of the first-mode EOF and the high percentage of the total variance explained by it shows that most of the sea level and atmospheric pressure variabilities have length scales greater than that of the study area.

2) SECOND MODE

The second mode represents the out-of-phase oscillations in the area with one zero crossing for both sea level and atmospheric pressure (Figs. 4a and 4b). In winter, the percentage of the total variance explained

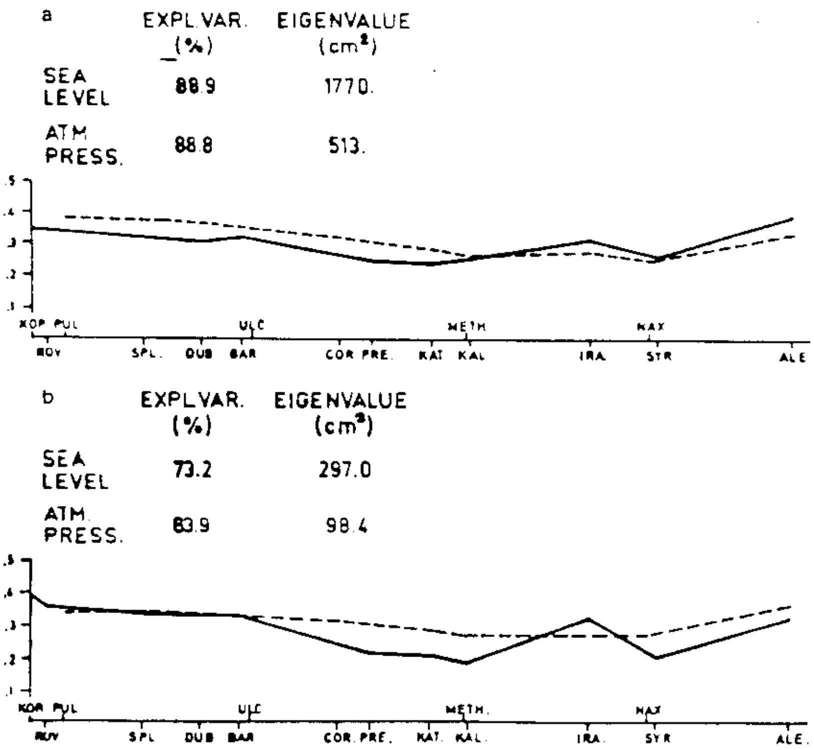

FIG. 3. Eigenfunctions of the first atmospheric pressure (dashed line) and sea level mode (continuous line) for (a) winter and (b) summer.

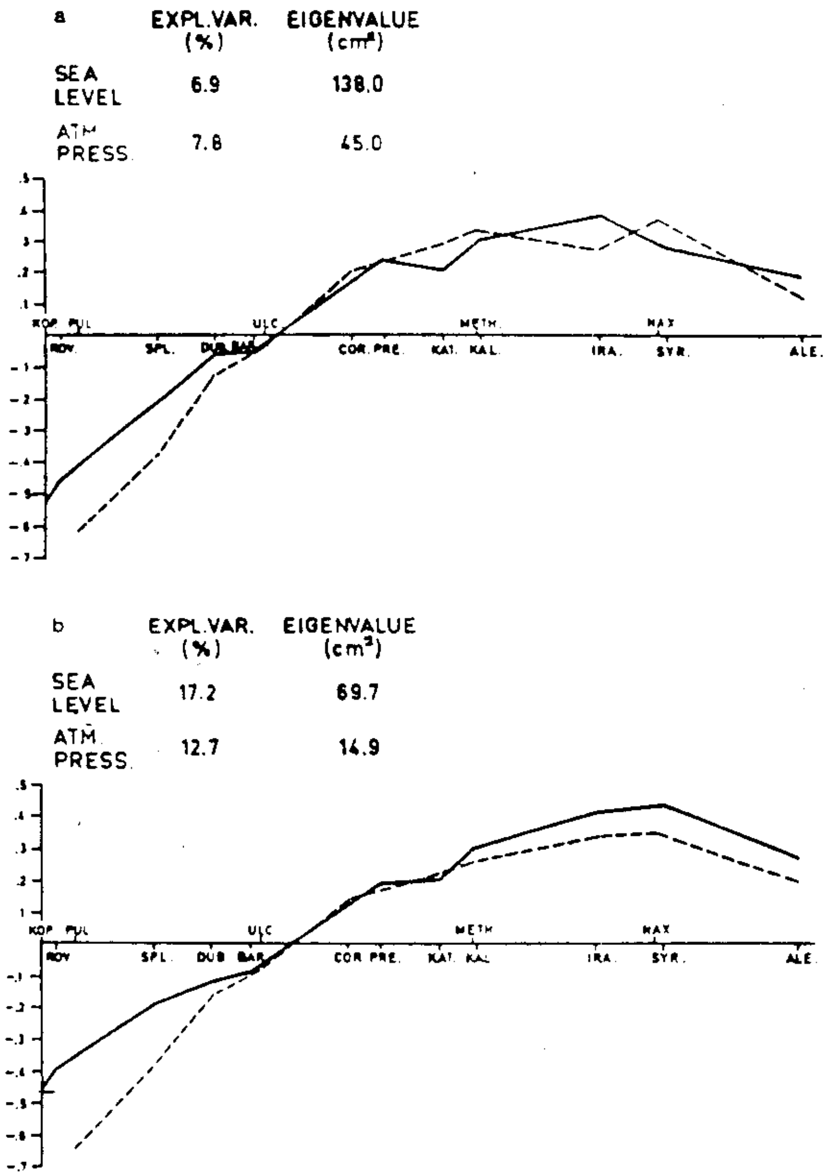

FIG. 4. Eigenfunctions of the second atmospheric pressure (dashed line) and sea level mode (continuous line) for (a) winter and (b) summer.

by this mode is for both sea level and atmospheric pressure smaller than 10%, while in summer it amounts to about 15%.

The atmospheric pressure node and the sea level node are located somewhere between the southernmost Adriatic station (Ulcinj for atmospheric pressure and Bar for sea level) and the northernmost Ionian station (Corfu for atmospheric pressure and Preveza for sea level). Consequently, sea level or atmospheric pressure variations (represented by the second mode) are out-of-phase in the Adriatic with respect to both the Ionian and Aegean seas.

In absolute terms, the summer and winter sea level variances in the first two modes are about three times larger than that of atmospheric pressure. This indicates that isostatic response is not the only mechanism generating the low-frequency sea level variations. Almost 30% of the sea level regionally coherent signal could be explained in terms of atmospheric pressure forcing. The residual variance in sea level can be attributed to low-frequency steric effects (which should still be present in our six-month time series) and to wind influence at higher frequencies. The existence of a half-annual sea level cycle poorly correlated with the atmospheric pressure was documented in the Adriatic Sea by Mosetti (1969). Nonisostatic response with a barometric factor larger than one at very low frequencies (i.e., periods larger than approximately 40 days) was also evidenced in the Western Mediterranean by Palumbo and Mazzarella (1982), who attributed it to steric effects.

3) LOCATION OF THE SECOND MODE ZERO CROSSINGS

As mentioned earlier, the nodes of atmospheric pressure and sea level almost coincide near the southernmost part of the Adriatic. A more accurate determination of their locations would need closer station spacing. Therefore, any smaller shift of the sea level node (eventually imposed by the bathymetry at the Otranto Strait) with respect to the atmospheric pressure zero crossing cannot be detected.

The climate of the Mediterranean is characterized by strong cyclonic activity especially in winter. The majority of these cyclones are formed in the Genoa and, to a lesser extent, in the Atlas cyclogenesis regions (Ozsoy 1981). Only one-third of cyclones formed in the Genoa area traverse the longitudinal axis of the Adriatic to affect the Otranto Strait area. Another third move to the northeast towards Central Europe. The remaining cyclones move to the southeast staying west of the Italian peninsula; south of Italy they meet the semi-permanent Mediterranean front and then continue eastward without influencing the southernmost part of the Adriatic Sea and Otranto Strait. Cyclones formed in the Atlas region also move eastward passing mostly south of Italy and Otranto Strait (Kendrew 1937; Ozsoy 1981).

Therefore, it can be concluded that most of the cyclones pass either to the north or to the south of Otranto Strait. This in turn could explain the location of the atmospheric pressure node in that area.

c. *Time variability and relation of the sea level to atmospheric pressure forcing*

1) TIME SCALES INVOLVED IN REGIONALLY COHERENT SIGNALS

We have shown that the shape of the two regionally coherent sea level modes are very similar to those of atmospheric pressure, i.e., the spatial structure of sea level variability is very close to that of atmospheric pressure. A further point to investigate is the time scale related to these spatially coherent modes and the relationship between the sea level and atmospheric pressure in different modes.

Time series of amplitudes of the first two modes of atmospheric pressure and sea level are displayed for winter in Figs. 5a and 5b. One can see that sea level variations in both modes are approximately 180 degrees out of phase with respect to that of atmospheric pressure. It is also evident that the first modes contain lower frequency variability than the second modes.

To examine the prevalent time scales in the two modes, spectral analysis via a Fast Fourier Transform method (Bendat and Piersol 1971) was applied to the summer and winter series. Nine consecutive 50% overlapping segments, of 32 points each, were taken. Trend and mean were removed from each segment prior to spectral analysis. The resulting number of degrees of freedom was 18 (Hunt 1984). A Hanning window was also applied to each 32 point segment.

Normalized spectra of the time-series, presented in Figs. 5a and 5b, are displayed in Fig. 6. The first modes have most of their variance at time scales longer than 10 days, while the second-mode spectra peaks at a period of approximately 10 days. The first atmospheric pressure mode displays variations at planetary time scales (several weeks), while the second mode displays variations at the synoptic time scale. Accordingly, the first sea level mode mainly contains low frequency oscillations generated by atmospheric planetary waves (Orlić 1983). The second mode represents the sea level response to atmospheric pressure and wind forcing at the synoptic time scale. Therefore, our EOF analysis of sea level and atmospheric pressure has resulted in separating their variability at different space and time scales. Length scales corresponding to the first mode, i.e. the scales of atmospheric planetary waves, are much larger than the study area. On the other hand, the second mode represents shorter length scales since the typical dimension of midlatitude cyclones in the Mediterranean is of the order of 1000 km.

Synoptic maps for the study period confirm that the large positive value of the amplitude of the second mode always coincided with the presence of a cyclone in the area. For example, Figure 7 represents November–December 1981 synoptic situations for all days with a maximum of the second-mode amplitude. The figure indicates that the maximum values of the second mode amplitude usually coincided with the presence of a cyclonic disturbance over the Ionian or Aegean Sea. In these situations, the Adriatic sea level decreased due to the increased atmospheric pressure behind the cyclones. At the same time, the sea level in the Aegean and Ionian rose due to decreased atmospheric pressure in the area of cyclonic activity. It is evident from Fig. 7, that a typical length scale of these cyclones is of the order of the longitudinal dimension of the Adriatic Sea. It also appears that the first mode is weakly correlated with the cyclonic activity in the region.

2) FORCING-RESPONSE RELATIONSHIP

To relate regionally coherent signals in sea level and atmospheric pressure, we summed up the first two modes and calculated the cross spectra (using the method described earlier) between the resultant time-series. The summation of the first two sea level or atmospheric pressure modes results in an unique time series which is representative for the entire area and accounts for almost 95% of the total variance.

The coherence (squared), phase and gain spectra (Bendat and Piersol 1971; Hunt 1984) for both winter and summer are shown in Fig. 8. The coherence be-

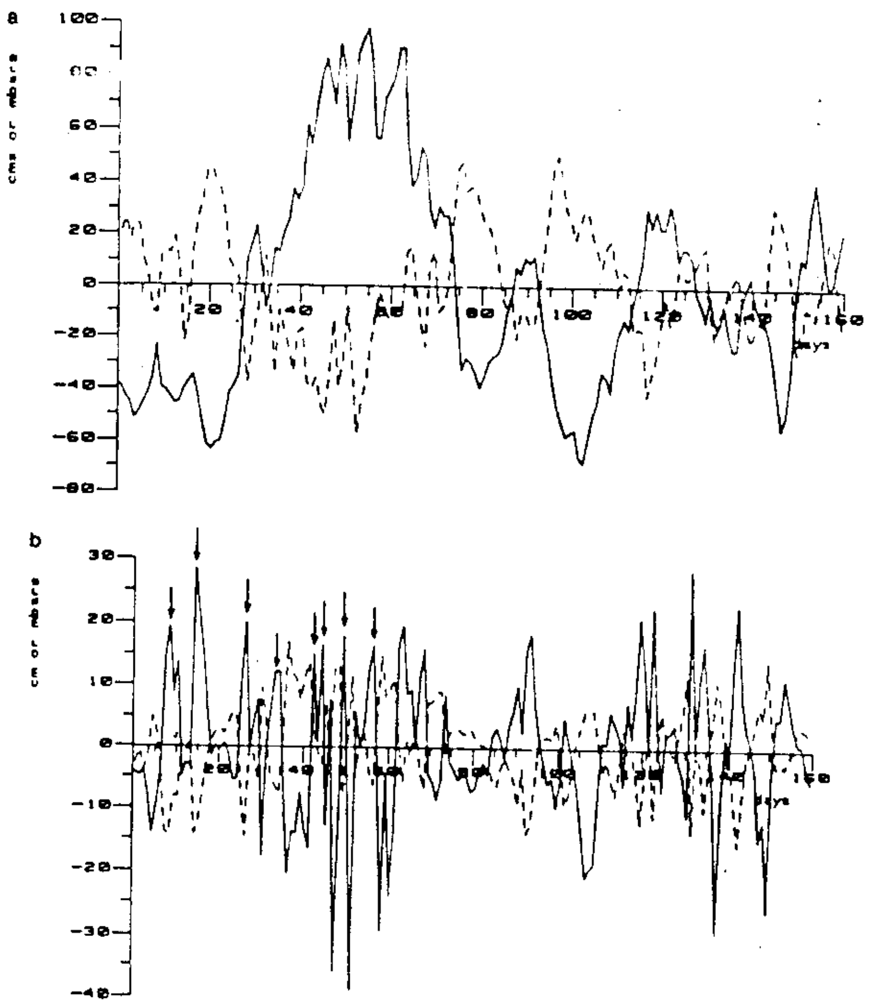

FIG. 5. (a) Time-varying amplitudes of the first atmospheric pressure (dashed line) and sea level EOF (continuous line) for winter. (b) As in Fig. (5a) but of the second EOFs. Vertical arrows correspond to events in Fig. 7 (see text).

tween atmospheric pressure and sea level in winter is above the 95% significance level at all frequencies. Nevertheless, there is a coherence decrease at time scales longer than ten days. In the same part of the spectrum (8–16 days), the atmospheric pressure was found to lead sea level by a few tens of degrees less than 180 degrees. This is equivalent to saying that the atmospheric pressure leads the minus sea level by a few tens of degrees (i.e., an approximately one day phase lag). Similar time lags between sea level and atmospheric pressure at low frequencies has been documented elsewhere (Garrett and Toulany 1982). Because of this phase lag, we cannot say that the sea responds barometrically to atmospheric pressure at low frequencies in winter although the gain is close to one. This is also true in summer when the decrease of coherence and gain at frequencies lower than 0.1 cpd, is very pronounced decreasing to almost zero values.

However, at periods shorter than five days in winter, the phase lag between atmospheric pressure and sea level is practically 180 degrees. In this frequency range the coherence is high, and the gain increases from 0.8 to 1.2. Therefore, for these shorter periods, the sea level response to atmospheric pressure is close to barometric. In summer, an important decrease of coherence is observed at periods centered around 3.6 days, whereas at shorter periods, the coherence increases and the gain becomes close to one. Such a decrease of coherence at the period of about four days was also observed by Garrett and Majaess (1984) at one station in the Ionian (Katakolon, Greece).

The shape of both gain and phase spectra observed in winter corresponds very well with the prediction for the Eastern Mediterranean obtained from a model by Garrett and Majaess (1984, see their Fig. 10b). It seems, however, that cyclone dimensions in the area are closer to 1000 km as demonstrated in Fig. 7 of this paper than to the 2000 km they obtained.

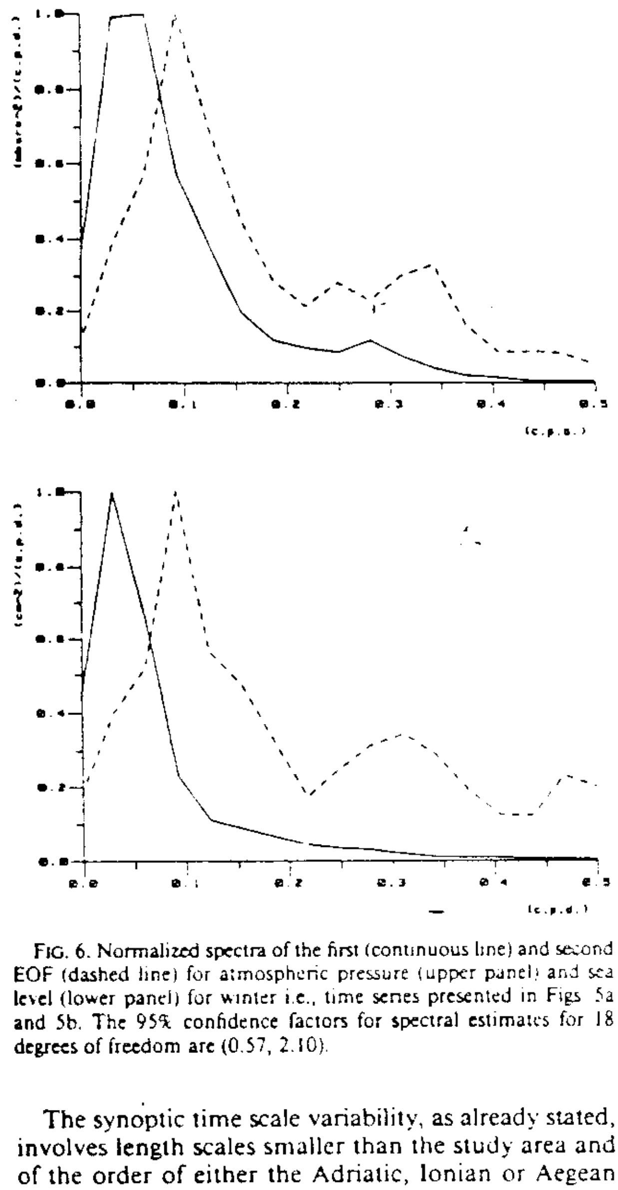

FIG. 6. Normalized spectra of the first (continuous line) and second EOF (dashed line) for atmospheric pressure (upper panel) and sea level (lower panel) for winter i.e., time series presented in Figs. 5a and 5b. The 95% confidence factors for spectral estimates for 18 degrees of freedom are (0.57, 2.10).

The synoptic time scale variability, as already stated, involves length scales smaller than the study area and of the order of either the Adriatic, Ionian or Aegean Sea. If the straits connecting these seas do seriously constraint the interchange of water, then no barometric response through internal adjustment is possible. Inside the study area, the only strait that might impose such a restriction at the synoptic time scale is the Otranto Strait.

Garrett (1983) defined a critical dimensionless parameter ϵ, which shows whether or not the geostrophic control represents constriction to water flow through the straits. From the expression for ϵ we have defined the time scale which is an estimate of the upper limit above which geostrophic control does not impose flow constriction. In that case, the flow is sufficient to permit an isostatic response of the basin. This time scale is expressed by the following relationship:

$$T = \frac{Af}{gH}$$

where H is the depth of the strait separating a basin of area A from an ocean and f and g represent Coriolis parameter (10^{-4} s^{-1}) and acceleration due to gravity.

Taking 700 m as the appropriate value for the depth of the Otranto Strait and 1.39×10^{11} m^2 as the area of the Adriatic Sea, this time scale has a value of one hour. Therefore, the flow through the Strait of Otranto is not geostrophically controlled and the strait does not prevent the Adriatic Sea from having barometric response at the time scales considered here.

The response at time scales of atmospheric planetary waves (first mode) involves at least the entire Eastern Mediterranean and in that case the limiting time scale should be calculated for the Strait of Sicily. The ap-

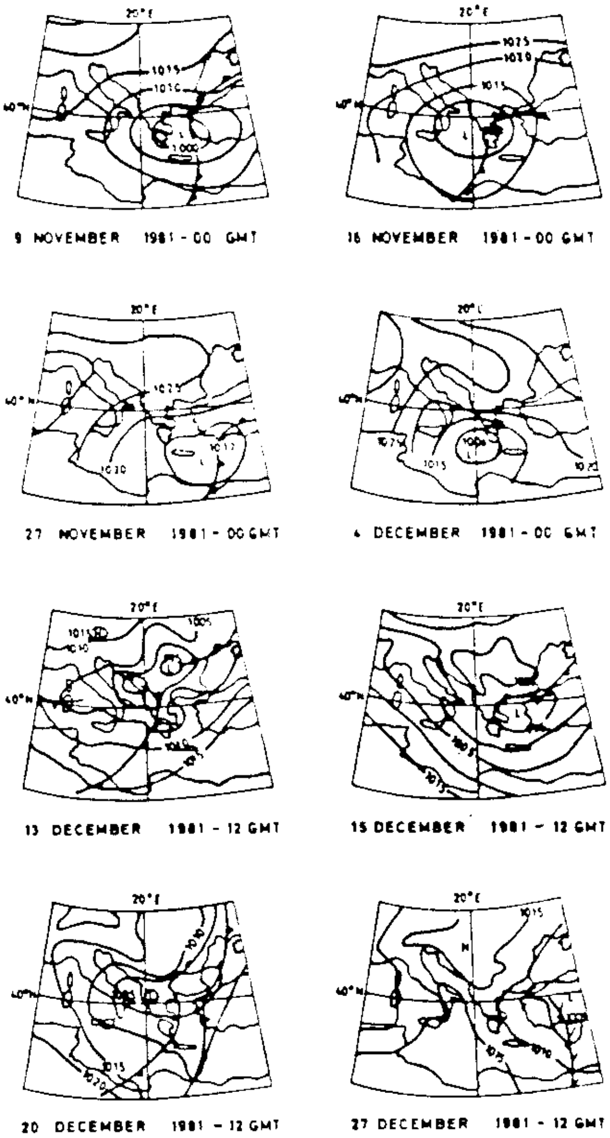

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FIG. 7. Surface synoptic charts from the period November–December 1981 for days when maximum of the time-varying amplitude of the second sea level EOF occurs (peaks denoted by arrows in the Fig. 5b).

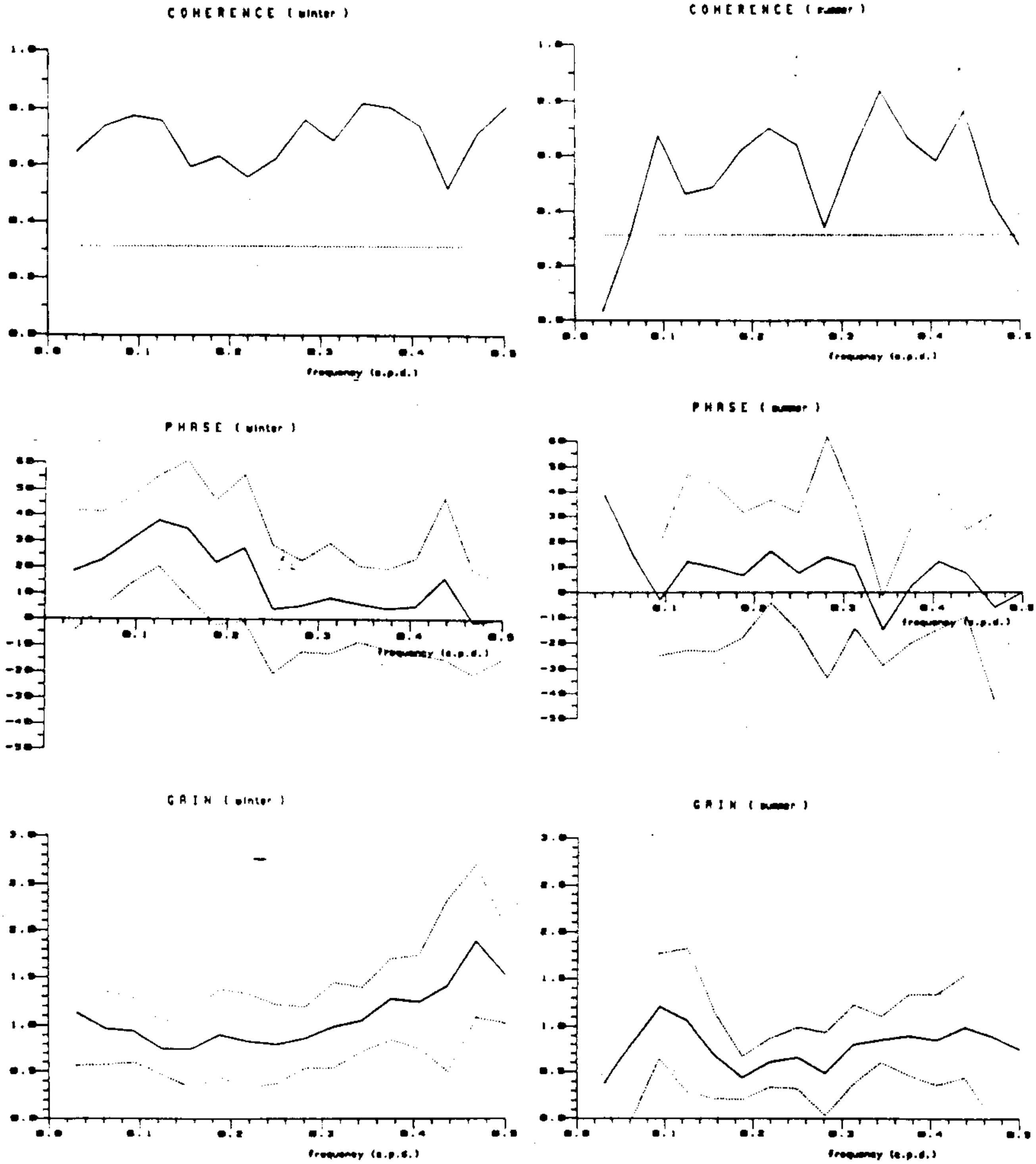

FIG. 8. Coherence (squared), phase and gain spectra between the sum of the first two EOFs of atmospheric pressure and sea level for winter (left) and summer (right). The 95% confidence limits are denoted by dotted lines.

propriate values for the area of the Eastern Mediterranean and for the depth of Strait of Sicily are 1.7×10^{12} m^2 and 250 m. Results show that the limiting time scale is of the order of one day. Therefore, for time scales of 3 to 4 days (synoptic time scale), the Strait of Sicily can be a significant restriction, through geostrophic control, to the water flow necessary for a barometric response. However, departures from the barometric response at the planetary wave time scales evidenced earlier in this paper cannot be explained in terms of the geostrophic control. In fact, Wright (1987) in commenting on the geostrophic control of low frequency flow through straits, showed that in a number of cases the flow is controlled by friction rather than geostrophy.

3) SPATIAL STRUCTURE OF THE RESPONSE

More detailed spatial structure of the atmospheric pressure–sea level relationship can be obtained from cross spectra at individual stations. In Figs. 9a and 9b coherence and gain have been contoured as a function of horizontal distance and frequency for summer and winter season (for tide gauge stations that did not coincide with an atmospheric pressure station, the closest one has been chosen for cross-spectral calculations, the distance between stations being at most 100 km, which is smaller than the typical cyclone scales).

High coherence between atmospheric pressure and sea level at the frequency interval 0.04 to 0.09 cpd is evident throughout the study area. This is the frequency range containing most of the first-mode energy of atmospheric pressure and sea level.

In the southern Aegean (Iraklion) and even more at the southern coast of Greece (Kalamata) there is evidence of generally lower coherence between sea level and atmospheric pressure. In both summer and winter, in the southern part of the study area, the low frequency part of sea level variability (especially for time scales of about 30 days) has a low coherence with the atmospheric pressure.

Over most of the frequencies, gain is slightly smaller than the barometric one especially in the Adriatic Sea (Fig. 9b). Values of the gain larger than the barometric in the Adriatic occur at the high frequency part of spectrum at periods smaller than three days which is probably due to the wind set-up (Gačić 1980). The same is evident in the Central and Northern Aegean (stations Syros and Alexandroupolis respectively), i.e., locations which are next to the wide shelf and sea level is subject to stronger wind setup. Figure 9b shows also that an isolated low frequency area of high gain is present in Iraklion having values as high as 1.5. This area comprises periods within the range 8 to 30 days. High values of gain at the same frequency in Iraklion occur also in summer (Fig. 9b). This could be the consequence of wind setup coherent with the atmospheric pressure and/or resonance at the shelf wave cutoff frequency at the Cretan shelf. This feature, also evident in sea level EOFs, needs more detailed study.

It is obvious from Figs. 8 and 9a that the coherence between sea-level and atmospheric pressure oscillations is greatest in winter, especially in the Adriatic and Ionian seas. We find this experimental result quite interesting and try to give it an explanation.

Let us assume that sea-level (sl) oscillations are related to atmospheric pressure (p) and wind (w) oscillations through the relation:

$$\text{sl}' = f(p') + g(w') \qquad (1)$$

where $f(p')$ and $g(w')$ are arbitrary functions of p' and w' (primes stand for departures from the mean).

Recently it was shown both theoretically and experimentally (e.g., Sandstrom 1980; Hickey 1981; Garrett and Toulany 1982; Garrett et al. 1984) that a linear relation of the sea elevation to the alongshore wind velocity component is as good an approximation as the one between sea elevation and wind stress. Therefore, in a first-order approximation relation (1) can be equivalently written as

$$\text{sl}' = f(p') + kw'. \qquad (2)$$

If w' is a linear function of p' ($w' = mp'$), Eq. (2) becomes

$$\text{sl}' = f(p') + kmp'. \qquad (3)$$

Therefore an eventual linear relation of wind to atmospheric pressure would obviously increase the linearity (and coherence) of sea elevation to atmospheric pressure.

For $w' = mp'$ to hold, it can easily be demonstrated (from the geostrophic wind equation) that the spatial distribution of pressure must be (close to) exponential. The pressure distribution inside cyclones frequently crossing the Eastern Mediterranean during winter could, in fact, be approximated by such double exponential (or bell shape) function. Therefore the frequent passage of winter cyclones might be the reason of the observed seasonal increase of coherence between sea level and atmospheric pressure.

In contrast, during summer the frequency of easterly propagating cyclones is reduced and the region is dominated by larger stable systems whose centers are far from the area.

4. Conclusion

Our analyses indicate that the subtidal sea level fluctuations are highly coherent over the entire northeastern Mediterranean (Adriatic, Ionian and Aegean seas). An EOF analysis shows that the regionally coherent signal represents more than 90% of the total variance in both sea level and atmospheric pressure. In-phase sea level oscillations in the area have time scales longer than a week and are coherent with atmospheric pressure variations. Their length scales are larger than the study area reaching up to 8000 km. Departures from the barometric response at these very low frequencies are not due to the geostrophic control in the Strait of Sicily.

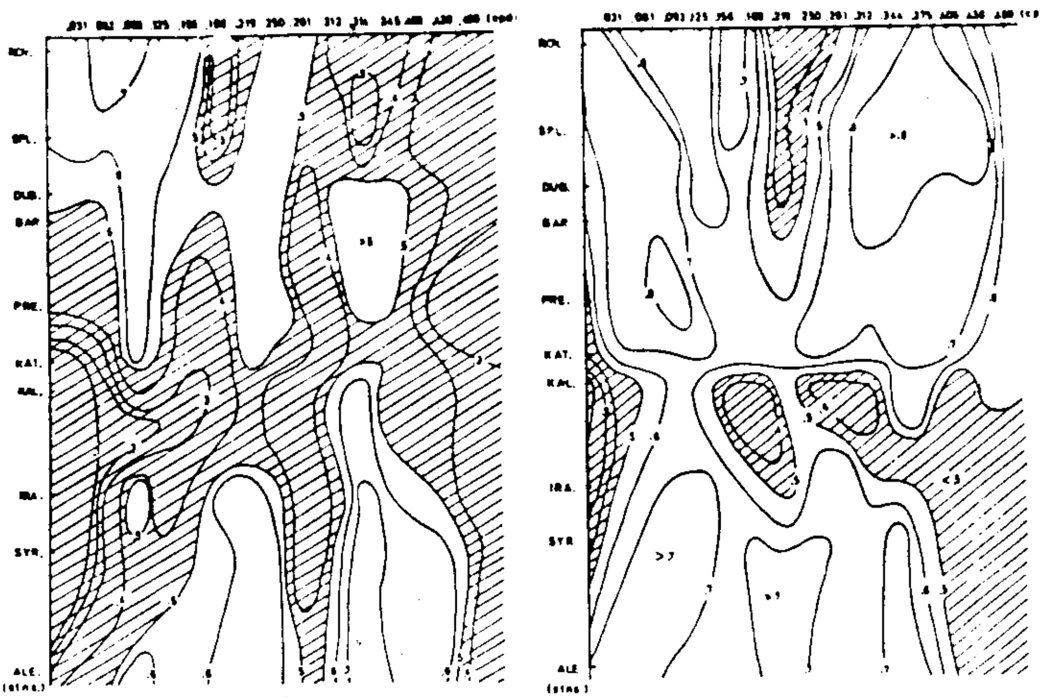

FIG. 9a. Coherence squared between the sea level and local atmospheric pressure contoured as a function of frequency and horizontal distance for summer (left) and winter (right). Dashed areas represent coherence lower than 0.5. The 95% confidence level for the coherence is 0.312.

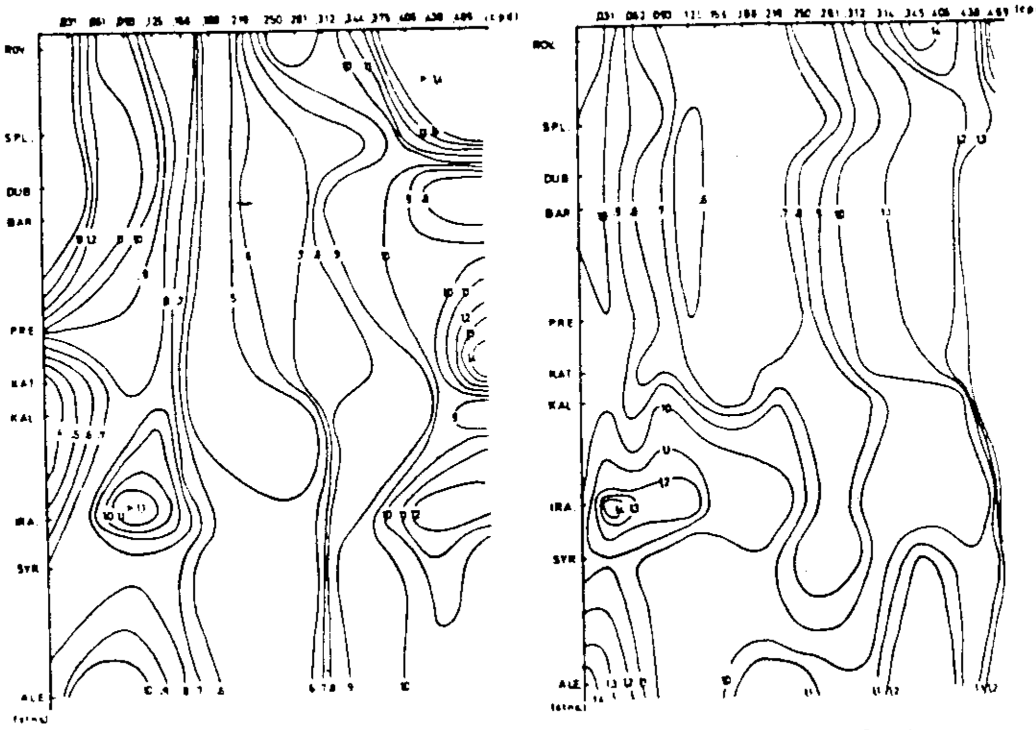

FIG. 9b. Gain of the sea level over the local atmospheric pressure contoured as a function of frequency and horizontal distance for summer (left) and winter (right).

Synoptic time scale variations of sea level are shown to be related to cyclonic activity in the area and have spatial scales equal to those of midlatitude weather systems (~1000 km). The Otranto strait has been indicated to be the node of these oscillations in both sea level and atmospheric pressure. The sea level response to the atmospheric pressure forcing at these time scales is close to barometric probably through internal adjustment processes between different basins of the area. It has been shown that the Strait of Otranto does not impose any geostrophic control constriction to the subtidal water flow between the Adriatic and Ionian Seas.

The continuation of this study should include the effect of the regionally coherent wind, especially at the synoptic time scale. The residual variance could then be related to local winds and resonance phenomena. Indications exist that resonance might play an important role at the Cretan shelf in the southern Aegean.

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REFERENCES

Barnett, T. P., 1983. Recent changes in sea level and their possible causes. *Climatic Change*, **5**, 15–38.

——, 1984: The estimation of "Global" sea level change: A problem of uniqueness. *J. Geophys. Res.*, **89**, 7980–7988.

Bendat, J. S., and A. G. Piersol, 1971: *Random Data. Analysis and Measurement Procedures.* Wiley-Interscience, 407 p.

Crepon, M., 1965: Influence de la pression atmospherique atmospherique sur le niveau marin de la Mediterranee occidentale et sur le flux a travers le detroit de Gibraltar. *Cah. Oceanogr.*, **17**, 15–32.

——, 1976: Sea level, bottom pressure and geostrophic adjustment. *Mem. Soc. R. Sci. Liege*, **6**(10), 43–60.

Enfield, D. B., and J. S. Allen, 1983. The generation and propagation of sea level variability along the Pacific coast of Mexico. *J. Phys. Oceanogr.*, **13**, 1012–1033.

Gačić, M., 1980. Some characteristics of the response of the Adriatic Sea coastal region to the atmospheric forcing. *Acta Adriatica*, **21**(2), 239–254.

Garrett, C. J. R., 1983: Variable sea level and strait flow in the Mediterranean: A theoretical study of the response to meteorological forcing. *Oceanol. Acta*, **6**, 79–87.

——, and F. Majaess, 1984: Nonisostatic response of sea level to atmospheric pressure in the Eastern Mediterranean. *J. Phys. Oceanogr.*, **14**, 656–665.

——, —— and B. Toulany, 1985: Sea-level response at Nain, Labrador, to atmospheric pressure and wind. *Atmos.-Ocean*, **23**(2), 95–117.

——, and B. Toulany, 1982: Sea level variability due to meteorological forcing in the northeast Gulf of St. Lawrence. *J. Geophys. Res.*, **87**(C3), 1968–1978.

Godin, G., and L. Trotti, 1975: Trieste-water levels 1952–1971: A study of the tide, mean level and seiche activity. Environment Canada, Fisheries and Marine Services, Miscellaneous Special Publication 28, 23 p.

Halliwell, G. R., and J. S. Allen, 1984: Large-scale sea level response to atmospheric forcing along the west coast of North America, Summer 1973. *J. Phys. Oceanogr.*, **14**, 864–886.

Hickey, B. M., 1981: Alongshore coherence on the Pacific Northwest continental shelf (January–April, 1975). *J. Phys. Oceanogr.*, **11**(6), 822–835.

Hunt, M. M., 1984: PROSPECT: A software package for spectral analysis. Woods Hole Oceanographic Institution, 89 p.

Kasumović, M., 1958: On the influence of air pressure and wind upon the Adriatic sea level changes (in Croatian). Hidrografski godišnjak 1956/57, 107–121.

Kendrew, 1937: *The Climates of the Continents*, third edition. Oxford University Press.

Kosambi, D. D., 1943: Statistics in function space. *J. Indian Math. Soc.*, **7**, 76–88.

Kundu, P. K., J. S. Allen and R. L. Smith, 1975: Modal decomposition of the velocity field near the Oregon coast. *J. Phys. Oceanogr.*, **5**, 683–704.

Lacombe, H., 1961: Contribution a l'etude du regime du detroit de Gibraltar. I Etude dynamique. *Cah. Oceanogr.*, **13**(2), 73–107.

Lacombe, H., P. Tchernia, C. Richez and L. Gamberoni, 1964. Deuxieme contribution a l'etude du regime du detroit de Gibraltar (travaux de 1960). *Cah. Oceanogr.*, **16**, 283–314.

Mosetti, F., 1969: Oscillazioni del livello marino in rapporto con le oscillazioni di pressione atmosferica. *Boll. Geofis. Teor. Appl.*, **11**(43–44), 264–278.

——, 1971: Considerazioni sulle cause dell' acqua alta a Venezia. *Boll. Geofis. Teor. Appl.*, **13**, 169–184.

Orlić, M., 1983: On the frictionless influence of planetary atmospheric waves on the Adriatic sea level. *J. Phys. Oceanogr.*, **13**, 1301–1306.

Oszoy, E., 1981: On the atmospheric factors affecting the Levantine Sea. European Centre for Medium Range Weather Forecasts, Tech. Rep. No. 25, 29 p.

Palumbo, A., and A. Mazzarella, 1982: Mean sea level variations and their practical applications. *J. Geophys. Res.*, **87**, 4249–4256.

Papa, L., 1978: A statistical investigation of low-frequency sea level variations at Genoa. Istituto Idrografico della Marina, Universita' degli Studi di Genova, F. C. 1087, Grog. 6, 13 p.

Pugh, D. T., and K. R. Thompson, 1986: The subtidal behaviour of the Celtic Sea-I. Sea level and bottom pressures. *Contin. Shelf Res.*, **5**(3), 293–319.

Rickards, L. J., 1985: Report on sea level data collected during the MEDALPEX experiment from September 1981–September 1982. Institute of Oceanographic Sciences Rep. No. 209, 170 p.

Sandstrom, H., 1980: On the wind-induced sea level changes on the Scotian shelf. *J. Geophys. Res.*, **85**, 461–468.

Sollow, A. R., 1986: The application of eigenanalysis to tide-gauge records of relative sea level. *Contin. Shelf Res.*, **7**(6), 629–641.

Wallace, J. M., and R. E. Dickinson, 1972: Empirical orthogonal representation of time series in the frequency domain Part I. Theoretical considerations. *J. Appl. Meteor.*, **11**, 887–892.

Weare, B. C., 1977: Empirical orthogonal analysis of Atlantic Ocean surface temperature. *Quart. J. Roy. Meteor. Soc.*, **103**, 467–478.

Wright, D. G., 1987: Comments on "Geostrophic Control of Fluctuating Barotropic Flow through Straits." *J. Phys. Oceanogr.*, **17**(12), 2375–2377.