Long-term variations in the Mediterranean Sea level calculated by spectral analysis

Sea-level series
Meteorological series
Spectral analysis
Long-period climatic oscillations

Séries du niveau de la mer
Séries météorologiques
Analyse spectrale
Oscillations climatiques séculaires

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ABSTRACT

The aim of this paper is to investigate long-period climatic variations in the Mediterranean sea level, as well as some meteorological parameters and the influence of atmospheric forcing on sea-level fluctuations. Data for the annual mean sea level at seven stations (Trieste, Genoa, Marseilles, Alicante, Oran, La Goulette and Sfax), located in the Western Mediterranean, together with mean air pressure and temperature data for Zagreb, have been spectrally analysed.
Various peaks in the power, coherence and phase spectra have been detected. The period of about 5.1 years corresponds to the quasi-meridional fluctuation in the paths of Atlantic cyclones. The period of about 2.7 years may be excited by variations of currents and sea-surface temperature in the North Atlantic. Peaks at periods of 3.0 and 3.5 years show oscillations of secondary cyclones over the Gulf of Genoa bay and the Adriatic Sea. A quasi-biennial oscillation has been detected with a period of 2.15 to 2.25 years. Enlarged amounts of energies at 7.5 to 8 and 11.2 years may correspond to the polar tide and solar cycle oscillation, respectively.

RÉSUMÉ

Variations à long terme du niveau de la mer Méditerranée calculées par l'analyse spectrale.

Ce travail a pour objet les variations climatiques à longues périodes du niveau de la Mer Méditerrannée ; quelques paramètres météorologiques y sont également présentés, avec l'effet du forçage atmosphérique. L'analyse spectrale des données a porté sur le niveau annuel moyen de la Méditerrannée occidentale, en sept stations : Trieste, Gênes, Marseille, Alicante, Oran, La Goulette et Sfax, ainsi que sur la pression atmosphérique moyenne et la température de l'air à Zagreb.
Plusieurs pics sont observés dans les spectres d'énergie, de cohérence et de phase. La période de 5,1 années indique la fluctuation quasi-méridienne des trajectoires des cyclones atlantiques. La période de 2,7 années peut être liée aux variations des courants et de la température superficielle dans l'Atlantique nord. Les périodes de 3,0 et 3,5 années montrent l'oscillation des cyclones secondaires au-dessus du golfe de Gênes et de la mer Adriatique. Une oscillation biennale a été détectée avec une période 2,15 à 2,25 années. Des maxima de 7,5 à 8 et 11,2 années correspondraient respectivement à la marée polaire et à l'oscillation australe.

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INTRODUCTION

The response of the sea level to atmospheric forcing has been studied by many authors (*e.g.* Crisciani and Ferraro, 1989; Mosetti *et al.*, 1989; Gačić *et al.*, 1992; Currie *et al.*, 1993). One study of the global sea level, computed by a simple linear regression analysis, has shown that the level has risen by approximately 15 cm during the past century (Barnett, 1983); but Lambeck and Nakiboglu (1984) show that only half of this rise can be attributed to the continuing long-term response to glacial unloading. The rest of the increase is due to long-period climatic oscillations induced by atmospheric forcing.

A number of authors (Hamilton, 1983; Stravisi, 1987; Goy *et al.*, 1989; O'Brien and Currie, 1993; Fromentin and Ibanez, 1994; Currie, 1994) have reported discrete periods in meteorological, biological, hydrographic and other data. Even in the flora and fauna populations, long-period oscillations occur, for example in fish catches and wine harvests (Currie *et al.* 1993), tree-ring chronologies (Currie, 1992) and others. Long-period climatic oscillations of oceanographic parameters have also been analysed (Colebrook and Taylor, 1979; Sturges, 1987; Lanfredi *et al.*, 1988; El-Ghindy and Eid, 1990; Muller and Siedler, 1992).

In some parts of the Mediterranean Sea, recent investigations have resorted to spectral analysis for the determination of climatically-generated changes in the sea-level oscillations (Fais *et al.*, 1984; Stravisi, 1987; Mazzarella and Palumbo, 1988; Orlić and Pasarić, 1994), which are mostly the result of long-term air pressure forcing (Fais and Mosetti, 1983; Le Provost, 1991), but are also related to wind and air temperature (Reed *et al.*, 1961; Shah and Godson, 1966; Hamilton, 1983).

In the present paper, spectral analysis is applied to annual mean sea-level data at seven tide-gauge stations (Fig. 1), located mostly in the Western Mediterranean. Except for Sfax, the records are continuous for over 65 years. Power spectra were also computed for yearly mean values of air pressure and temperature at the Zagreb station, while coherence spectra between atmospheric parameters and sea level were computed to show frequency-dependent relationships.

DATA COLLECTION, SPECTRAL ANALYSIS

Annual mean sea-level values are available from Trieste, Genoa, Marseilles, Alicante, Oran, La Goulette and Sfax (see Fig. 1) with continuous data as indicated in Table 1. A time span of one hundred years (1890-1989) is used in the analysis. Some short gaps in the records have been interpolated from adjacent tide-gauge stations by Mosetti and Purga (1991). Meteorological data for air pressure and temperature are available at Zagreb (climatic data at Zagreb Observatory 1990), with continuous recording for 100 years.

Table 1

Periods of continuous for tide-gauge and meteorological stations.

Station	Period of continuous recording
Trieste	1890 - until now
Genoa	1884 - until now
Marseilles	1885 - until now
Alicante	1874 - until now
Oran	1890 - 1959
La Goulette	1889 - 1957
Sfax	1910 - 1959
Zagreb	1862 - until now

Spectral and cross-spectral analyses were applied to genuine time series of annual sea level, air pressure and air temperature records, using the Blackman-Tukey method with four degrees of freedom (Jenkins and Watts, 1968; Leder, 1992). The maximum lag and thus the number of spectral estimates amount to half the entered time series; for example, for Trieste with sea-level time series of 100 values, there are 50 spectral estimates. A coherence-squared value of 0.56 is statistically significant at a 95 % confidence level. Significant phase-difference intervals are plotted on figures with a 95 % confidence limit, depending on coherence-squared values with the same frequencies.

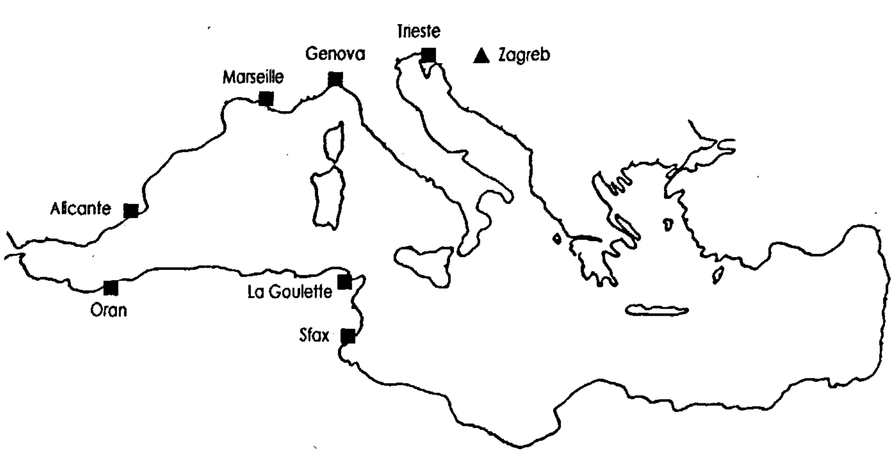

Figure 1

Position of tide-gauge stations (squares) and meteorological station (triangle) which are taken into account.

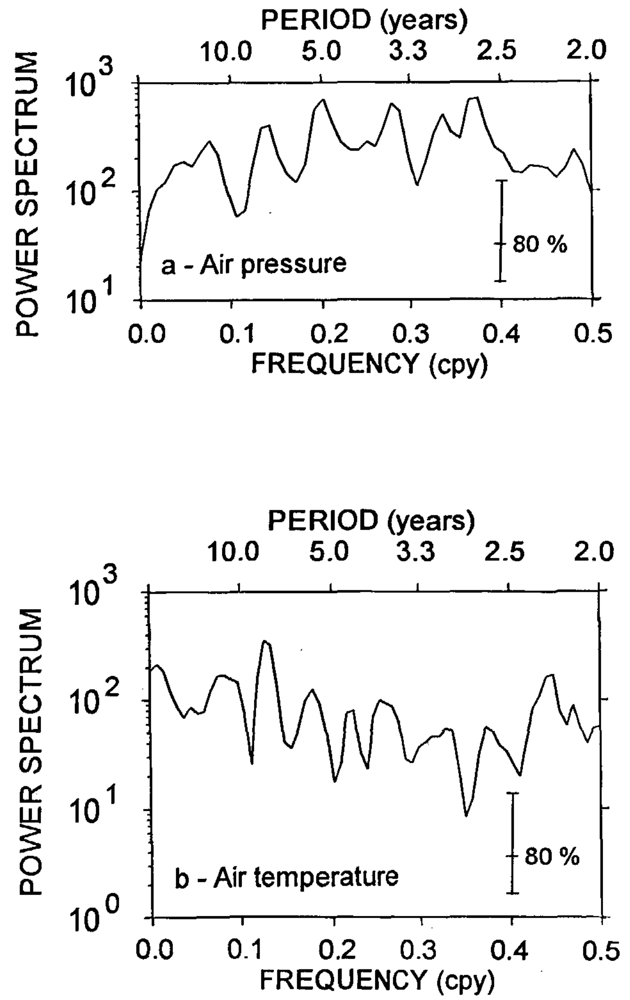

Figure 2

Power spectra of annual mean air pressure (in $(10^{-1}\ hPa)^2/cpy$) and annual mean air temperature (in $(10^{-1}\ °C)^2/cpy$) at Zagreb.

RESULTS

Power spectra of air pressure and temperature at Zagreb are presented in Figures 2*a* and 2*b*. The strongest occurrence of energy peaks in the air pressure spectrum can be observed at periods of about 2.7, 5.1, 3.5, 3.0, 7.5 and approximately 15 years. The strongest peak, close to 2.7 years, has been reported at various places in Europe (Stravisi, 1987; Fromentin and Ibanez, 1994), and is related to fluctuations of currents in the North Atlantic. These currents, together with processes of upwelling and downwelling, cause fluctuations in the sea-surface temperature, determining the fluctuations of surface heat transfer and cyclonic activity in the North Atlantic (Colebrook and Taylor, 1984).

The period around 15 years is caused by secular oscillations (Fais and Mosetti, 1983). The period of around 7.5 years reflects the influence of the polar tide (Gray and Christie, 1983). Meanwhile, the air temperature power spectrum has a maximum around 8 years. This spectrum (Fig. 2*b*) also shows major peaks at periods around 11 and 2.25 years. The 8-year period is related to El-Niño fluctuations (Quinn *et al.*, 1978); the peak at 11.2 years reflects the period of sun-spot activities (Mazzarella and Palumbo, 1988); and that at 2.25 years is related to the changes in the upper atmosphere shifted from the air pressure peak (2.15 years), also found before (Stravisi, 1987). This means that within the periods of around 2.2 years, – the so called quasi-biennial oscillation – two separated oscillations occur with periods of 2.15 and 2.25 years, as shown by careful analysis of Figures 2*a* and 2*b* (on both power spectra two separate peaks can be observed), and by further analysis of the sea-level spectra.

In addition to these periods, long-term climatic oscillations of the air temperature at Zagreb can be found in periods of around 5.7, 3.9 and 4.7 years, as also determined in previous works (Stravisi, 1987; Mosetti *et al.*, 1989; Fromentin and Ibanez, 1994).

Figures 3*a* to 3*g* illustrate the power spectra of the annual mean sea level along the Mediterranean coast, Figures 4*a* to 4*n* show the coherence-squared spectra and phase-difference spectra between the tide-gauge stations, and Figures 5*a* to 5*d* represent the coherence-squared spectra and phase-difference spectra between air pressure and temperature at Zagreb, and sea level along the Mediterranean coast. Plotted significant phase-difference intervals are related to the coherence-squared values on the same frequencies (linear interpolation can be used to calculate the intervals for all significant coherence-squared values).

At Trieste (Fig. 3*a*), the station closest to Zagreb, the strongest peak in the sea-level spectrum occurs in the period around 5.1 years, the same period as in the air pressure oscillations at Zagreb. Well marked peaks are also found in the periods 3.5 and 3.0 years. The relationship between air pressure and sea level, known as the "inverted barometer" (Karabeg and Orlić, 1982), can be obtained from an analysis of Figure 5*a*, with high coherence-squared values in these periods. At the period of 5.1 years, peaks can be also detected at Genoa (Fig. 3*b*), Marseilles (Fig. 3*c*) and Sfax (Fig. 3*g*); they are less marked at Alicante (Fig. 3*d*), poorly marked at La Goulette (Fig. 3*f*), and do not occur at Oran (Fig. 3*e*). Coherence-squared values between all stations except Oran show significant peaks, more developed between Genoa and Alicante (Fig. 4*f*, 0.95), Trieste and Genoa (Fig. 4*a*, 0.85), Trieste and Alicante (Fig. 4*b*, 0.8) and Trieste and Sfax (Fig. 4*e*, 0.8). Phase difference shows that between Trieste, Genoa, Marseilles and Alicante, a slight shift in phase occurs (between –30° and 40°). At the same time, the stations on the south coast of the Mediterranean are almost opposite the north stations (Marseilles - La Goulette 170°, Genoa - Sfax 110°, Trieste - La Goulette 140°). Therefore, it can be concluded that this oscillation belongs to the oscillation of the Atlantic cyclone paths, moving eastward and southeastward over Europe. Their paths move to lower latitudes every five years, causing secondary cyclones over the Adriatic shelf and the Gulf of Genoa. This explains a slight phase difference between the stations on the north coast. The quasi-opposite phase difference from the stations on the south coast can be related to general circulation in the atmosphere, connected with cyclonic activity. In other words, winds from the north and northwest to the rear of cyclones pile

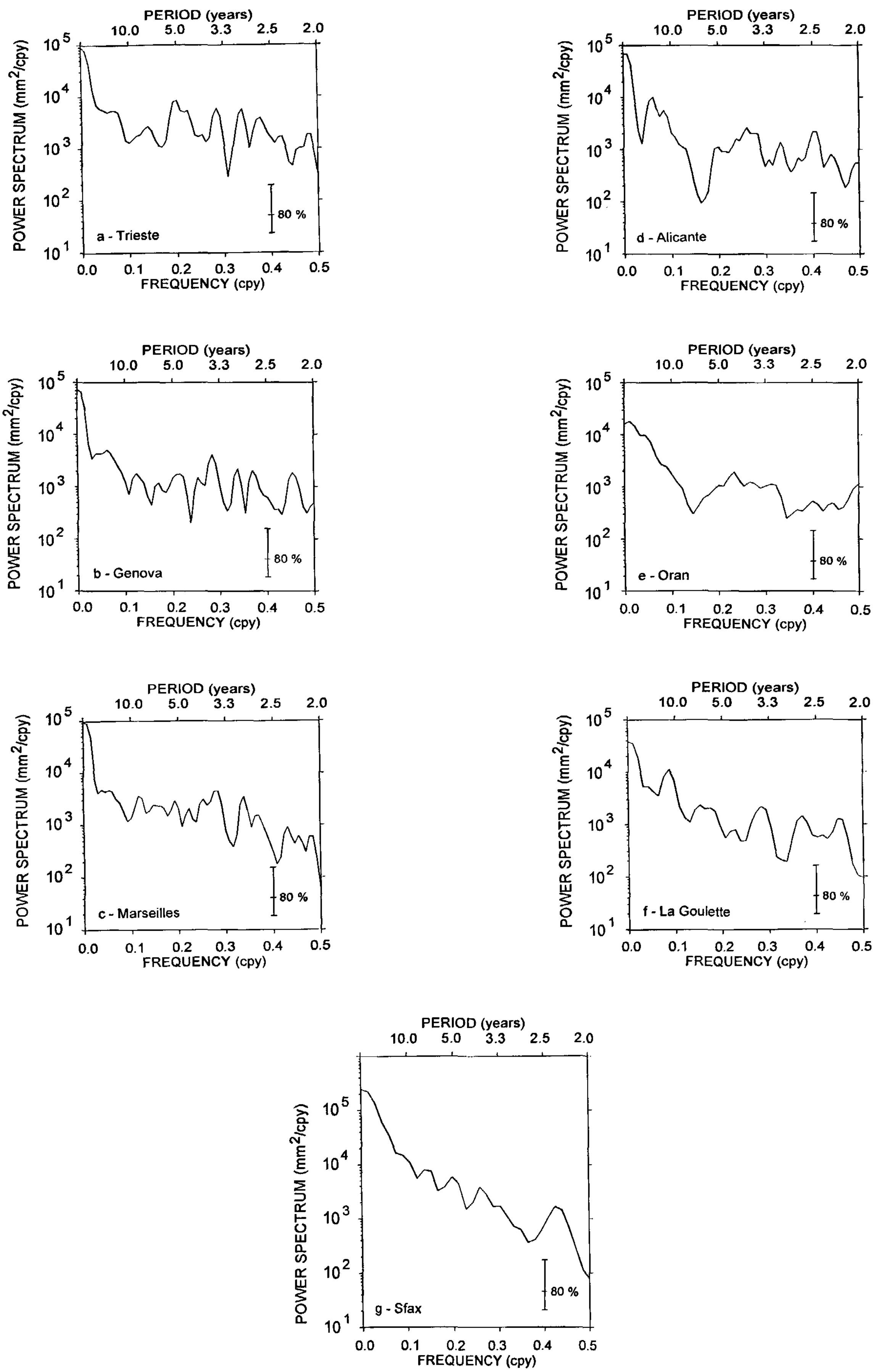

Figure 3

Power spectra of annual mean sea level.

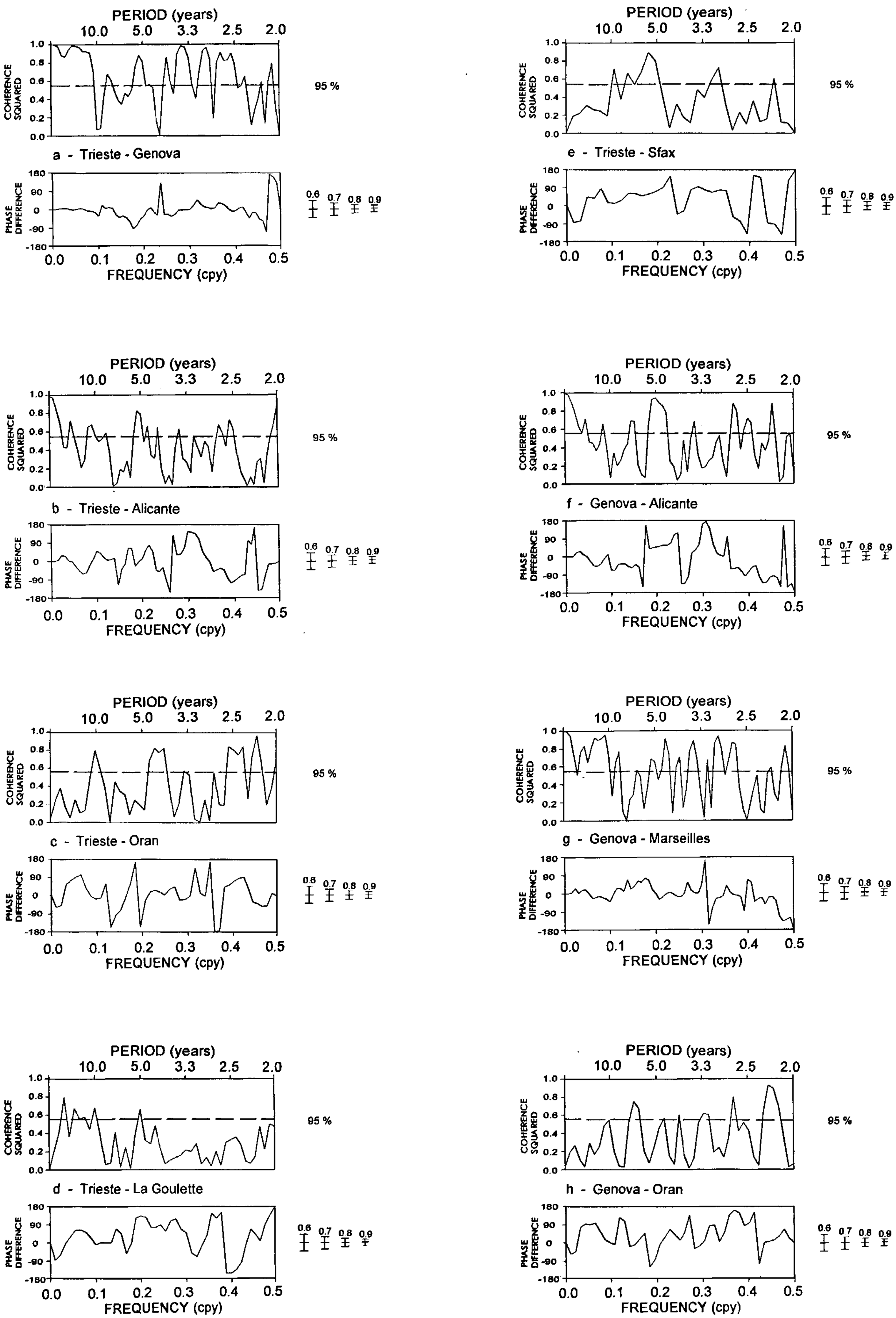

Figure 4

Coherence-squared spectra and phase-difference spectra of annual mean sea level.

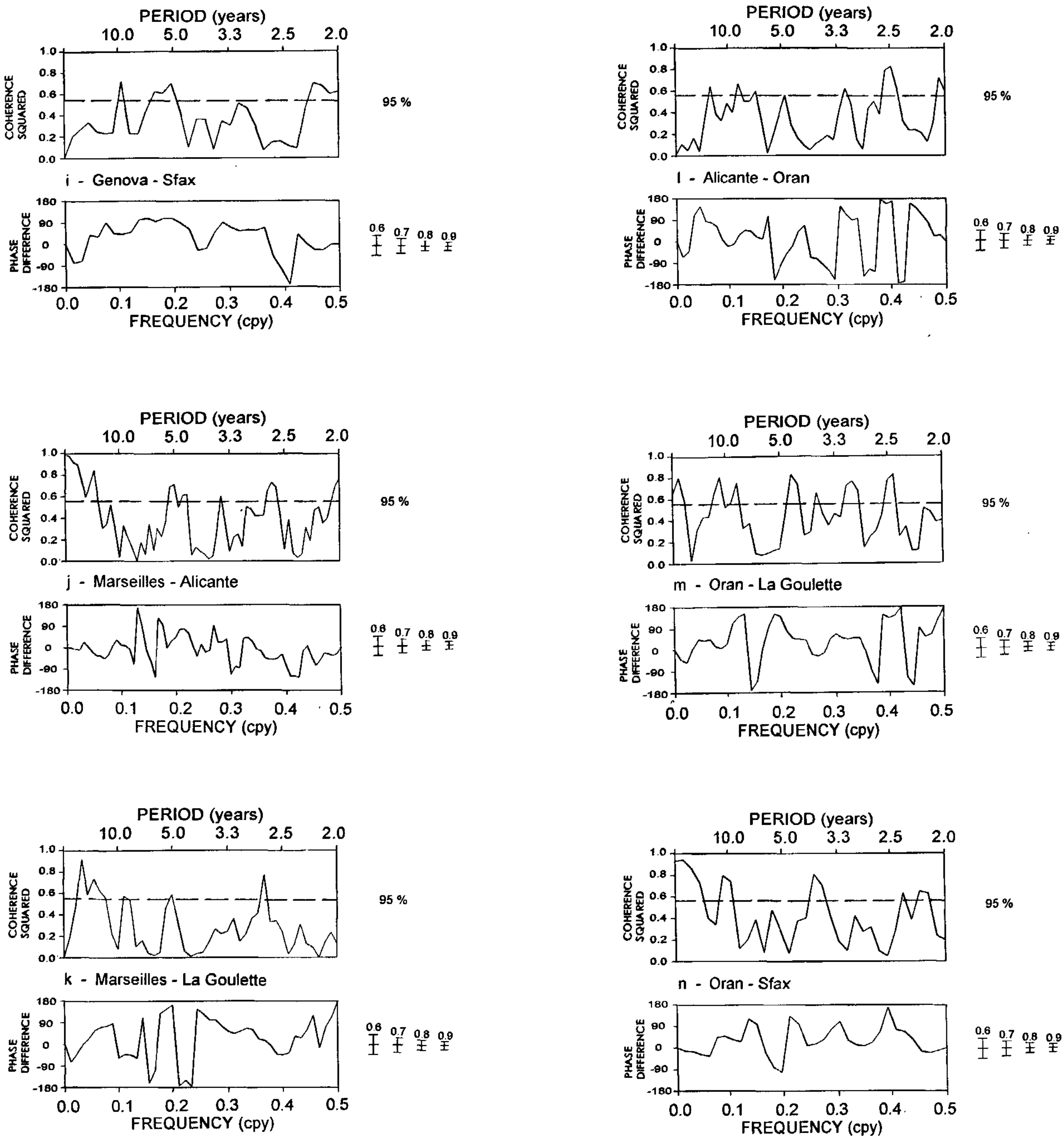

Figure 4 (continued)

up the water on the southern coast, causing higher waters at the same time as low water occurs on the north coast. The Oran station is not under this influence because of its position (at the entrance to the basin), and because the proximity of the Sahara desert affects the climate of this area (very high amount of sunshine, low precipitation and cloudiness, etc.), which means that the Atlantic cyclones path oscillations have no significant impact.

At the period around 3.5 years, a well marked peak occurs on power spectra at all stations, including the air pressure at Zagreb. But coherence-squared values are significant only between the stations on the north Mediterranean coast, and – to some extend – at Oran. The highest values are between Trieste and Genoa (Fig. 4*a*, 0.98) and Genoa and Marseilles (Fig. 4*g*, 0.9); they are lower between Genoa and Alicante (Fig. 4*f*, 0.7) and Marseilles and Alicante (Fig. 4*j*, 0.7). Phase difference has values of around 0°, except for Alicante, whose phase is shifted by 30°. This oscillation can be related to the occurrence of secondary cyclones in the Gulf of Genoa and partly in the Western Mediterranean, showing the highest coherence in that area (Genoa, Trieste and Marseilles), and lower coherence with Alicante, located at the edge of this synoptic disturbance.

At the period of 2.7 years, strong oscillations can be noticed in the air pressure at Zagreb (Fig. 2*a*), and in the sea level at Trieste (Fig. 3*a*). From Genoa (Fig. 3*b*) this oscillation shows a decrease in power towards Marseilles (Fig. 3*c*), where it has low energies, and Alicante (Fig. 3*d*), where it can scarcely be observed. At Oran (Fig. 3*e*), it has greater values again. Coherence-squared values are high between Trieste, Genoa, and Marseilles (0.85 to 0.95) and lower in the case of Alicante (0.65 to 0.85); they are only sporadically significant at the stations on the south Mediterranean coast. The phase difference has values of about 15°, between Trieste and Genoa, about –55° between Genoa and Alicante, about –15° between Genoa and Marseilles and about 170° between Genoa and Oran. Phase differences determine the occurrence of oscillation, first in the northwestern Mediterranean (Alicante) and then propagating to the southeast, reaching Marseilles, Trieste and Genoa. Meanwhile, Oran has the opposite phase. From these facts it may be surmised that this oscillation is also related (as a 5.1-year oscillation) to the fluctuation of the Atlantic cyclone paths over Europe (excited by sea surface changes in the North Atlantic), moving southeastward and first reaching the northwestern Mediterranean.

The peak for Zagreb air pressure at 3.0 years can also be well determined at Trieste, Genoa, Marseilles and Alicante. But, coherence-squared values for Alicante are low, and partly insignificant (0.45-0.65). Coherence-squared values between Trieste, Marseilles and Genoa are higher than 0.95, and the phase difference is around 0°. It can be therefore concluded that this period belongs to the secular variation of secondary cyclonal activity over the Gulf of Genoa Bay and the Adriatic shelf.

At the period around 7.5 years there is a peak on the air pressure spectrum at Zagreb. At the same time the peak with a period of 8 years appears on the air temperature spectrum (Fig. 2*b*). The correlation between air pressure at Zagreb and the sea level at Trieste (Fig. 5*a*, the coherence squared value is 0.75) dominates over the correlation between the air temperature at Zagreb and the sea level at Trieste (Fig. 5*c*, the coherence-squared value is 0.5) on the period around 7.5 years. On the other hand, at the period around 8 years, the correlation between the air pressure at Zagreb and the sea level at Alicante (Fig. 5*d*, the coherence squared value is 0.8) dominates over the correlation between the air pressure at Zagreb and the sea level at Alicante (Fig. 5*b*, the coherence-squared value is 0.5). This is in agreement with the fact determined on the power spectra of atmospheric parameters, the conclusion being that the polar tide (Gray and Christie, 1983) has a major influence on the air pressure and the sea level of the areas further from the Atlantic coast. The El-Niño events, with one energy maximum around 8 years (Quinn *et al.*, 1978), have a predominant influence on the air temperature values, and on the sea level of the areas closer to the Atlantic coast. Power spectra and coherence-squared spectra between the sea level stations in the Mediterranean show the occurrence of poorly developed both peaks, but not at all stations and stronger at Trieste and Genoa (closer

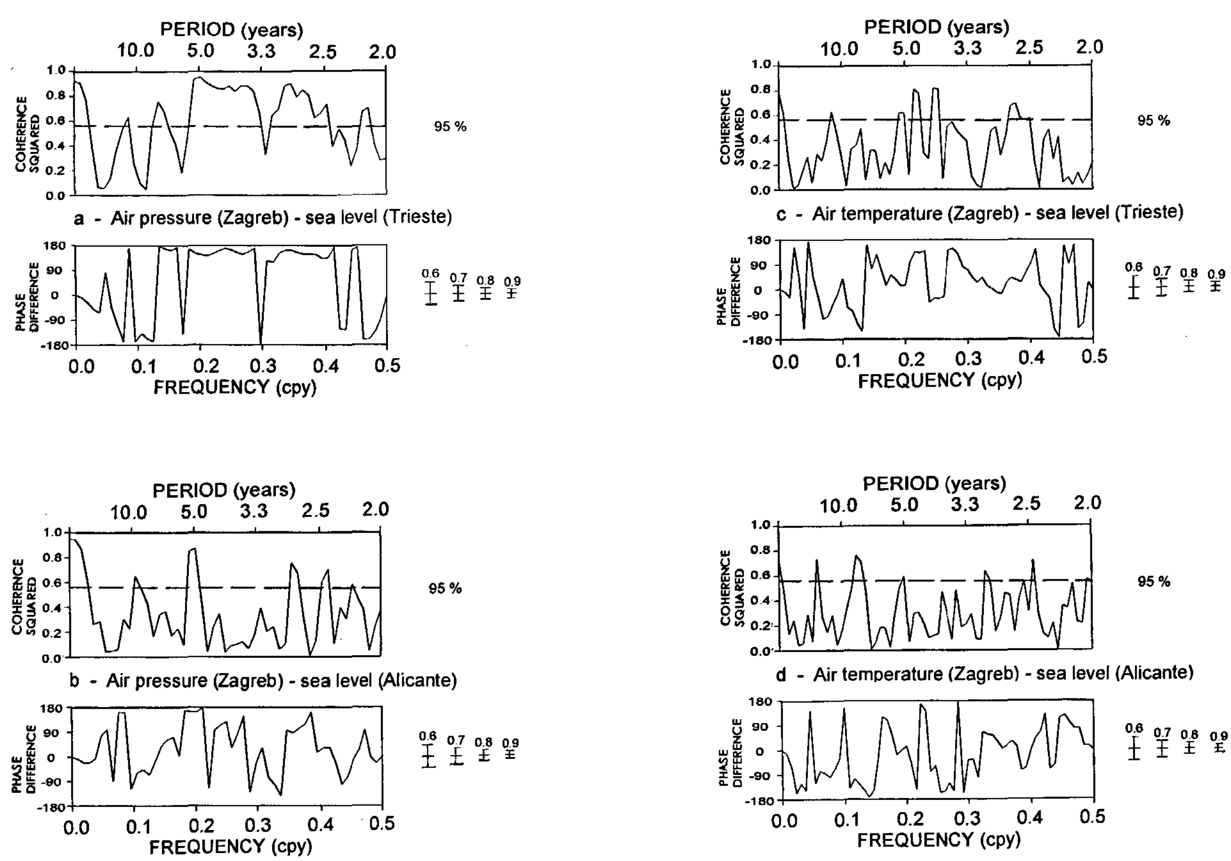

Figure 5

Coherence-squared spectra and phase-difference spectra between annual mean air pressure and temperature at Zagreb and annual mean sea level.

to Zagreb). Therefore, it can be concluded that the polar tide and El-Niño events do not have a great influence on the secular sea-level oscillations in the Mediterranean Sea.

Two separate peaks occur in the air pressure and temperature spectra at Zagreb on the periods of 2.15 and 2.25 years. In the past, these have been considered as a single oscillation, but this analysis determines them as being separate. The significant correlation between the air pressure at Zagreb and the sea level at Trieste and Alicante, and sporadically the significance between the sea levels at all stations, show that these oscillations, known as oscillations of zonal wind and temperature (Shah and Godson, 1966; Hamilton, 1983) do not have a great influence on the sea-level oscillations.

The period of 11.2 years, known in the literature as the solar tide or period of oscillation of sun-spot number (Currie, 1994), was determined on the basis of signals from a variety of sources (Currie, 1992; Currie *et al.*, 1993). The peak on this period occurs on the air temperature and pressure power spectra (Figs. 2*a* and 2*b*). The sea-level spectra show a peak that is well developed at Oran (Fig. 3*e*), but less developed at Alicante, Marseilles, La Goulette and Sfax (the time series at Sfax is too short to make a clear peak; La Goulette is situated on the coast where the sea deepens rapidly and where currents are tangential to the coast, so that the energy mass is smaller than at the other stations). At Genoa and Trieste, the energy is not great on this period, but nevertheless significant. The coherence-squared values between Alicante, Oran, La Goulette and Sfax are significant, but sporadic with Genoa, Marseilles and Trieste. The coherence-squared values between the air pressure and temperature at Zagreb (Figs. 5*a* and 5*c*), and the sea level at Trieste are significant, but with the sea level at Alicante (Figs. 5*b* and 5*d*) they are insignificant. Therefore, it may be concluded that the solar tide is more developed on the southern coast of the Mediterranean, especially at Oran (under the influence of the Sahara desert) than on the north coast and in the interior of the European continent.

CONCLUSIONS

Spectral and cross-spectral analyses have been applied to time series of annual air pressure and temperature at Zagreb, and the annual sea-level data at seven stations in the Mediterranean. Some small gaps are interpolated by linear regression with the neighbouring stations. The north coast has high-quality data; the south coast has a shorter time series, but most of the eastern Mediterranean has no series; longer than 30 years.

Various long-period discrete climatic oscillations, well or less wellknown, have been determined. The major long-term sea level fluctuations are mostly due to long-term atmospheric pressure forcing, associated with long-period oscillations of primary and secondary synoptic scale formations. The quasi-meridional fluctuation of the paths of the Atlantic cyclones was detected at the period around 5.1 years, related to oscillations of secondary cyclones over the Gulf of Genoa, the Adriatic shelf and to some extent over the western Mediterranean, with periods of 3.0 to 3.5 years. The period around 2.7 years belongs to the oscillation of currents and sea surface temperature in the North Atlantic. Quasi-biennial oscillations of the zonal wind and temperature were detected at the periods 2.15 to 2.25 years. El-Niño events and the polar tide excite the oscillations around 8 and 7.5 years, respectively. These oscillations are more developed on the north coast of the Mediterranean, except the 11.2-year lunar oscillation of sun-spot activities, which is best shown at Oran.

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