Forced and free response of the Adriatic Sea level

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Summary. — The aim of this paper is to improve the knowledge of the variations of the sea level in the Adriatic Sea in the domains of forced and free oscillations. For this purpose, one-year long-time series of data collected at nine tide gauge stations placed on the eastern shoreline have been collected and processed by spectral analysis. The harmonic constituents have been calculated too. Semidiurnal and diurnal tides have got larger variations of amplitude on the islands than on the coast. The response of the sea level in the domain of synoptic and planetary formations is quite synchronous in the whole Adriatic for periods longer than 3.5 days, with a gap around 9.5 days. These formations excite the sea level first in the North Adriatic, and then, secondly in the Middle and South Adriatic. The seiches occurred at already known periods of 22-23, 10.8 and 7.5-8 hours, and at a new one of about 4 hours. 4 hour seiche occurs in the region inside the Middle Adriatic islands, and it is predominantly influenced by the Sirocco wind forcing.

PACS 92.10.Hm – Surface waves, tides and sea level.
PACS 92.10.Jm – Seiches.

1. – Introduction

The Adriatic Sea (fig. 1) is an elongated basin connected with the Mediterranean Sea through the Otranto Strait. The northern part is shallow (up to 50 metres), the middle part has a maximum depth of 280 metres and the southern part is a deep circular basin (depth up to 1200 metres) connected with the Middle Adriatic through the Palagruža Sill (about 170 metres).

The strongest winds in the Adriatic area occur in winter, and are called Bora and Sirocco [1]. Bora is a cold, katabatic wind blowing from the North-East, while Sirocco blows from the South-East. Their hour mean speed can reach 25 m/s, connected with the migrating cyclones: Sirocco blows on the front side of cyclones, while Bora blows on the back side.

Sea level oscillations in the Adriatic Sea are caused not only by tidal forces, but also by meteorological factors. Winds (especially Sirocco) superimposed on the atmospheric pressure forcing may strongly build up the water (especially in the North Adriatic) causing flooding of the coastal areas, *e.g.* the city of Venice [2, 3].

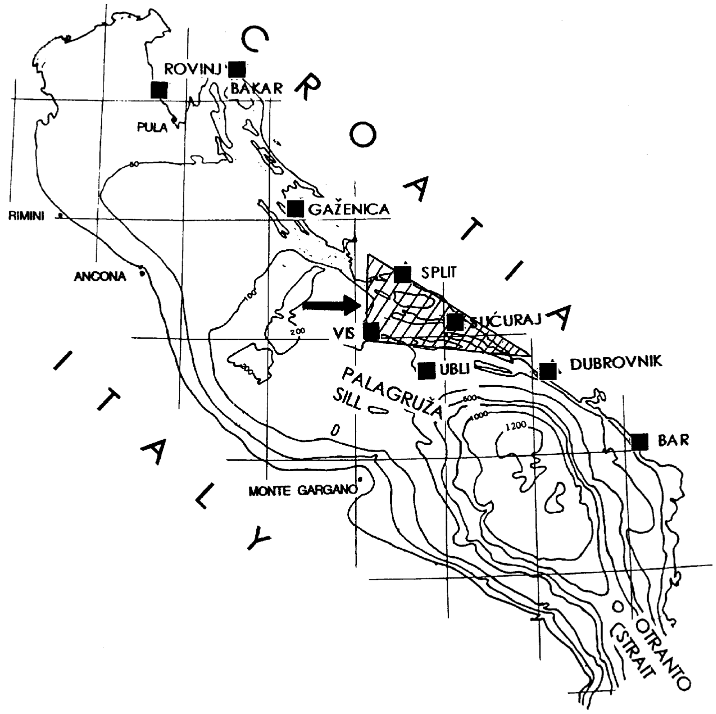

Fig. 1. – Bathymetry of the Adriatic Sea with position of tide gauge stations.

Tidal influence can be separated using harmonic analysis on the seven major components, while other components have little influence on the sea level oscillations [4]. Theoretical and empirical analyses of the Adriatic tides have been performed in numerous works [5-10].

Response of the Adriatic to meteorological influences can be analyzed in two different domains: in a domain of forced oscillation (storm surges) and in a domain of free oscillations (seiches). Storm surges are generated by planetary and synoptic scale formations with periods of more than a few days. They are under great influence of atmospheric pressure, but a dominant factor in their generation is wind (especially Sirocco), connected with synoptic formations [11-17]. Moreover, because of their great influence on human activities in the coastal areas of the North Adriatic, various prediction models of storm surges have been developed [18-20]. Free oscillations (seiches) are a sea level response on fast changes of meteorological parameters, with periods and amplitude distributions shaped by the basin topography. There are numerous works which empirically [21-27] and theoretically [28-30] examine the existence of seiches in the Adriatic.

The aim of this work is to detect and describe the oscillations caused by tidal and meteorological forces along the eastern Adriatic coast. As will be seen, some new oscillations have been found (4 hour seiches). Furthermore, a better understanding of the behaviour of known oscillations is reached.

2. – Data processing

Sea level hourly values were collected in 1988 [31] from nine tide gauge stations: Bar, Dubrovnik, Ubli, Vis, Sućuraj, Split, Gaženica, Bakar and Rovinj (fig. 1). The stations Ubli, Vis, Sućuraj and Gaženica have got the portable tide gauge A. Ott-Kempten with registration ratio 1:10, and the rest were permanent tide gauges A. Ott-Kempten with registration ratio 1:5. The data were stored in the databank as integer values, so that the accuracy of the measurements is ± 0.5 cm for permanent stations. Portable stations, because of smaller charts causing additional errors when digitizing, have lower accuracy, estimated approximately ± 0.7 cm.

In order to determine semidiurnal and diurnal tidal constituents, the data were processed by an algorithm prepared by the USA National Oceanic and Atmospheric Administration [32], based on the tidal analysis by Shuremann [33]. The algorithm deals with a 29 day time series and separates 24 tidal constituents, but only seven major constituents are significant in the Adriatic Sea.

Spectral and cross-spectral analysis calculations, *i.e.* power spectra, coherence-squared spectra and phase difference spectra were computed via the Blackman-Tukey's method with 8 and 40 degrees of freedom [34-36]. Spectral estimates were smoothed using a Tukey window. Confidence intervals for power spectra and coherence-squared spectra were determined according to [34]. Power spectra for all stations are presented using linear-logarithm and logarithm-logarithm scale. The lin-log scale presentation satisfactorily visualises the frequency domain of free oscillations (frequencies up to 0.025 cph), while the log-log presentation better shows the influence of planetary and synoptic scale formations on periods longer than two days. Connection between oscillations at different stations can be reached by analysis of coherence-squared and phase difference spectra, thus obtaining the areas where synchronized oscillations are presented.

3. – Results

3·1. *Tidal oscillations.* – Harmonic analysis, performed on the sea level data, determines the amplitudes and phases of the seven major constituents in the Adriatic Sea (M_2, S_2, N_2, K_2, K_1, O_1 and P_1). Figure 2 displays monthly variations of major semidiurnal tide M_2 and major diurnal tide K_1 during 1988.

The harmonic component M_2, the amplitude of which has the largest values, slowly decreases from the South Adriatic (Dubrovnik 9.4 cm) to the assumed amphydromic point placed about 20 miles North-East of Ancona. The minimum amplitude is placed at Gaženica (5.6 cm). Towards the North Adriatic, its amplitude grows rapidly and at Rovinj it reaches 18.7 cm. Computations made by Polli [8] approximately follow these computations, but our results have the amplitude at Vis, Ubli and Sućuraj, which are island stations, 1-1.5 cm lower than Polli. Phases show a sharper distinction between the stations North and South of the assumed amphydromic point, for example at Gaženica it is 221° exceeding the value from Polli by more than 30°. Semidiurnal tides in the Adriatic can be described as counterclockwise propagating Kelvin waves in the semienclosed basin [37] or precisely as a co-oscillation of two Kelvin waves, an incoming and a reflected one [38].

Calculated amplitudes through 1988 varied within a centimetre (fig. 2), except at Vis and Ubli (not presented), where in June they decreased by 2 cm. The variations are

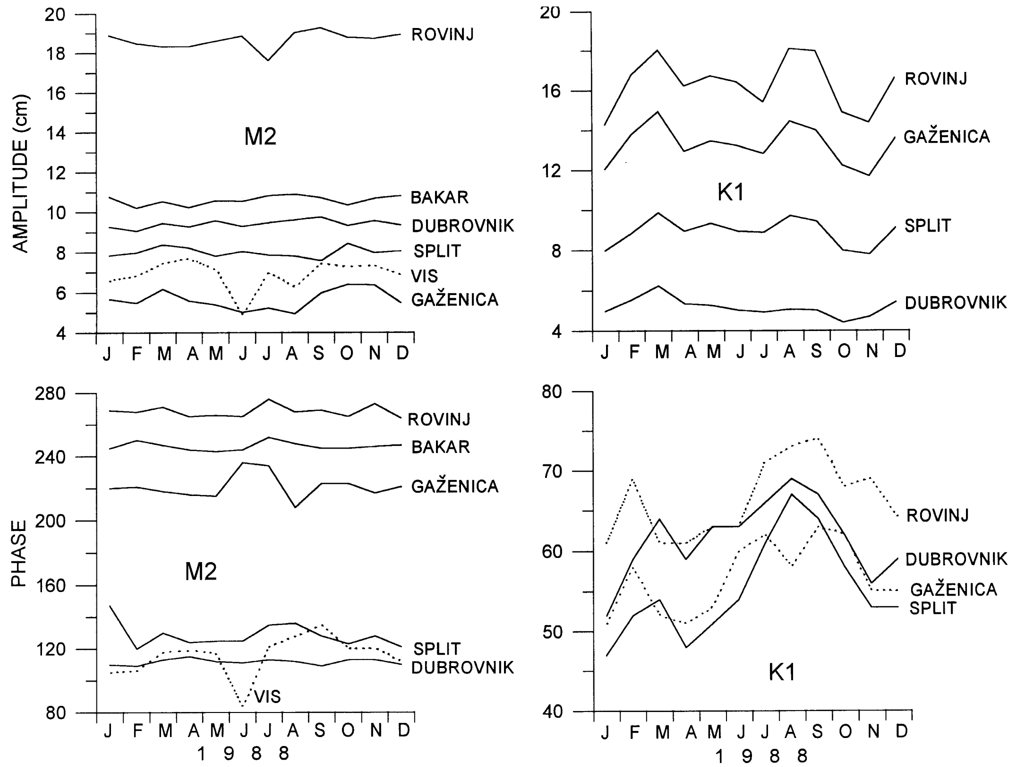

Fig. 2. – Monthly variations of the tides M_2 and K_1 during 1988 (to avoid confusion not all the stations are presented).

excited by different response of the Adriatic to the gravitational forcing [37]. At the same time the phase fell by 40° at Vis and Ubli, and at Gaženica it rose by 20°. Knowing that the period of the binodal seiche of the Adriatic has a value around 11 hours [27], the variations are partially the result of the influence of the binodal Adriatic seiche on the tide.

Other major semidiurnal constituents have similar propagation. The amplitude of S_2 and K_2 is about 30% lower at Gaženica than those obtained in ref. [8] and the phases approximately follow the M_2 tide.

The harmonic constituent K_1 with the largest amplitude of the diurnal tides in the Adriatic, has amplitudes similar to [8], but the phases differ. At Bar the phase is approximately 10° larger than Polli's, while at Split, Vis, Sućuraj, Ubli and Gaženica it is (5–10)° larger than Polli's. Approximate equality in phases can be explained if diurnal tides are assumed to be propagating Kelvin waves, as for the semidiurnal tides.

Variations of the K_1 amplitude during 1988 show the increasing of the amplitude and phase in February-March and September-October periods. The amplitude varies approximately 25% from the mean value, and the phase about 15° simultaneously in the whole Adriatic. During the year the inclination of the propagation front on the eastern shoreline changes due to the monthly variations of the harmonic constituents, partly as a result of the contamination caused by the uninodal seiche of the Adriatic (periods around 22-23 h). The tides O_1 and P_1 have the same behaviour.

3·2. *Forced oscillations.* – Figure 3 presents power spectra of hourly residual sea level during 1988 in log-log scale at three stations: one in the South (Bar), one in the Middle (Split) and one in the North (Rovinj) Adriatic. One can observe a wide peak on periods of about 5-6 weeks (frequencies about 0.001 cph), which is the main period of atmospheric planetary (Rossby) waves. The coherence-squared spectra (fig. 4) with values greater than 0.8 (lowest value between Dubrovnik and Rovinj) and phase difference values of about 0° indicate a quite simultaneous response of the whole Adriatic Sea to these frequencies, as observed in ref. [35]. The response is about 1.5 times larger in the North than in the South Adriatic. The influence of Rossby waves on the sea level changes in the Adriatic Sea has been described in ref. [39].

A significant peak also appears at periods of about 15 days (frequencies about 0.003 cph) at all stations (fig. 3), as a result of large-scale synoptic formations. At the end of 1988 (in November and December) their appearance (especially high anticyclones) was more frequent than usual [14]. The coherence-squared values (fig. 4) are greater than 0.75 in the whole Adriatic, so the sea level oscillations are simultaneous in those periods. Phase difference has slightly rising values from the

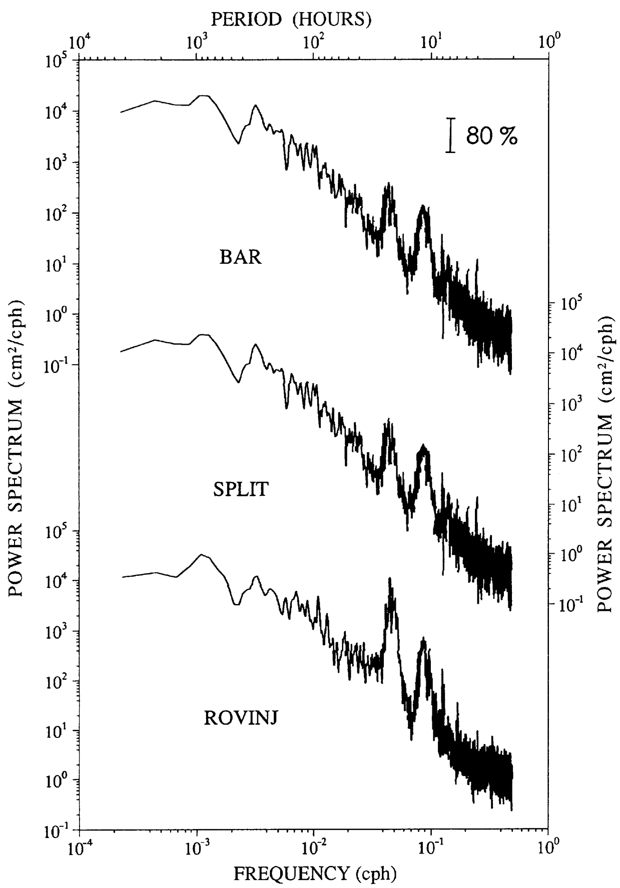

Fig. 3. – Power spectrum (8 degrees of freedom) performed on hourly sea levels at Bar, Split and Rovinj (log-log scale).

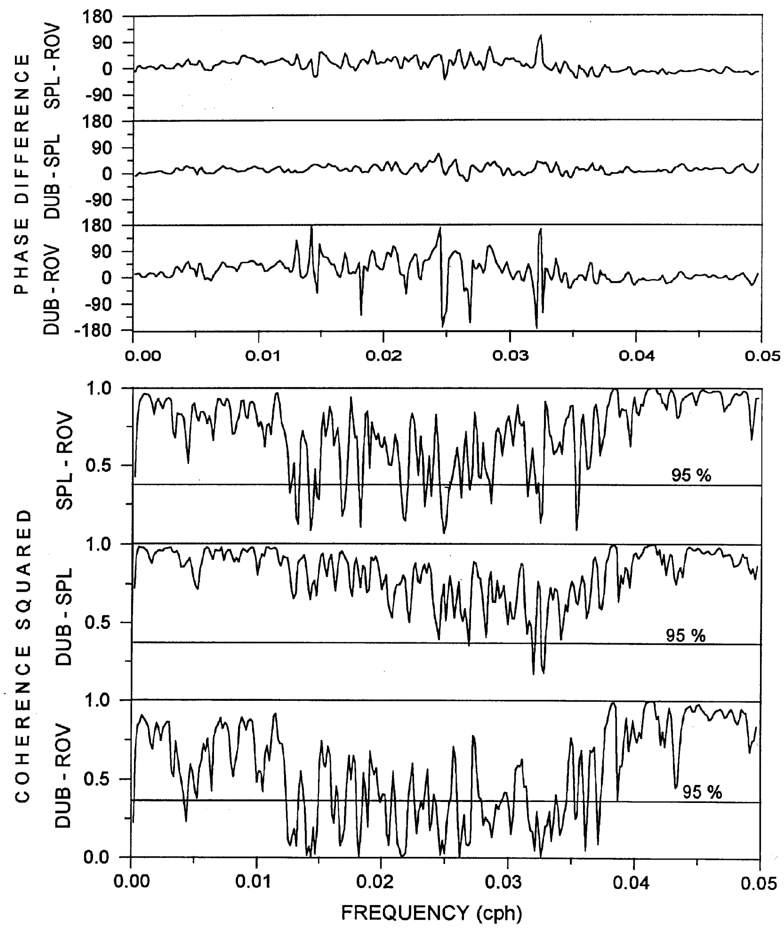

Fig. 4. – Enlarged view of the coherence-squared and phase difference spectra (0.00–0.05 cph) between Dubrovnik, Split and Rovinj (8 degrees of freedom).

South to the North Adriatic Sea (*e.g.*, Dubrovnik-Split about 10°, Dubrovnik-Rovinj about 30°, fig. 4), as a consequence of westerlies causing the migrating cyclones to reach first the North Adriatic.

More or less isolated peaks at periods from 2 to 10 days belong to smaller synoptic formations, for example frontal zones and fast cyclones. At these periods, especially between 30 and 100 hours, energies in the North Adriatic are up to 8 times larger than in the South Adriatic (fig. 3). So, the response of the sea level in the North Adriatic to pressure and wind forcing is stronger than in the South Adriatic [35, 40].

In the frequency interval from 0.012 cph to 0.037 cph the coherence-squared spectrum has generally lower values (fig. 4) and between Dubrovnik and Rovinj it is mostly insignificant. At frequencies lower than 0.012 cph the sea level oscillations are significantly connected in the whole Adriatic, except at a gap occurring around frequencies of 0.0045 cph (9.5 days). The values between Dubrovnik and Split are significant at all frequencies up to 0.05 cph, except at small gaps about 0.033 cph.

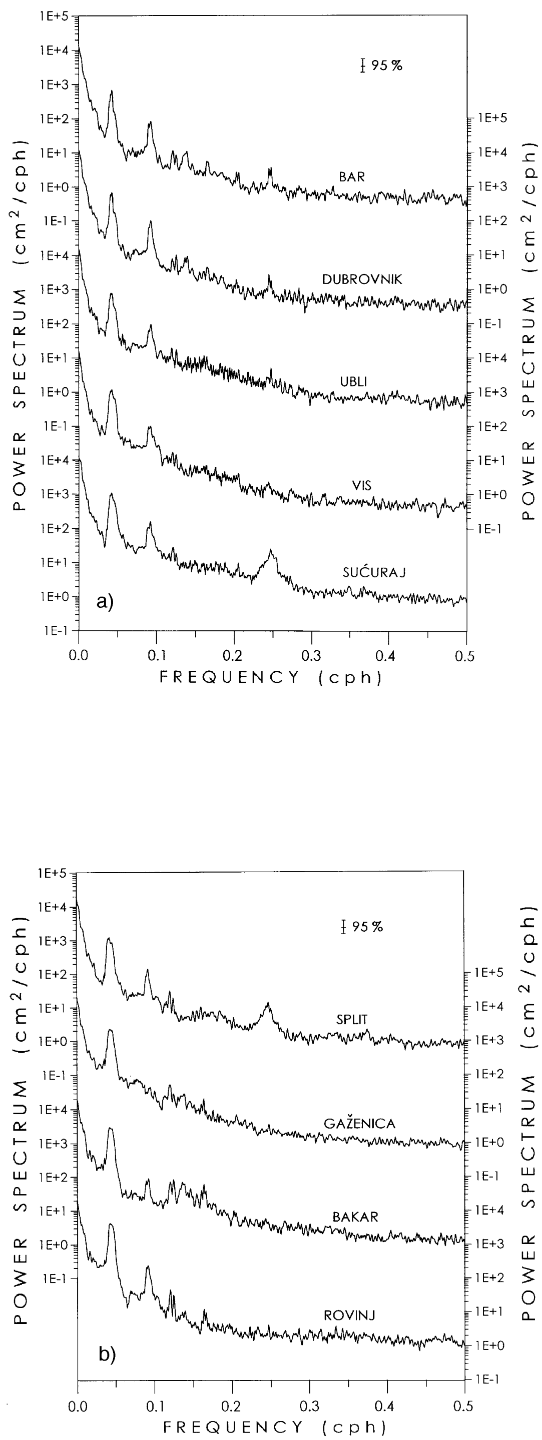

Fig. 5. – Power spectra (40 degrees of freedom) performed on hourly sea levels at stations Bar, Dubrovnik, Ubli, Vis, Sućuraj, Split, Gaženica, Bakar and Rovinj (lin-log scale).

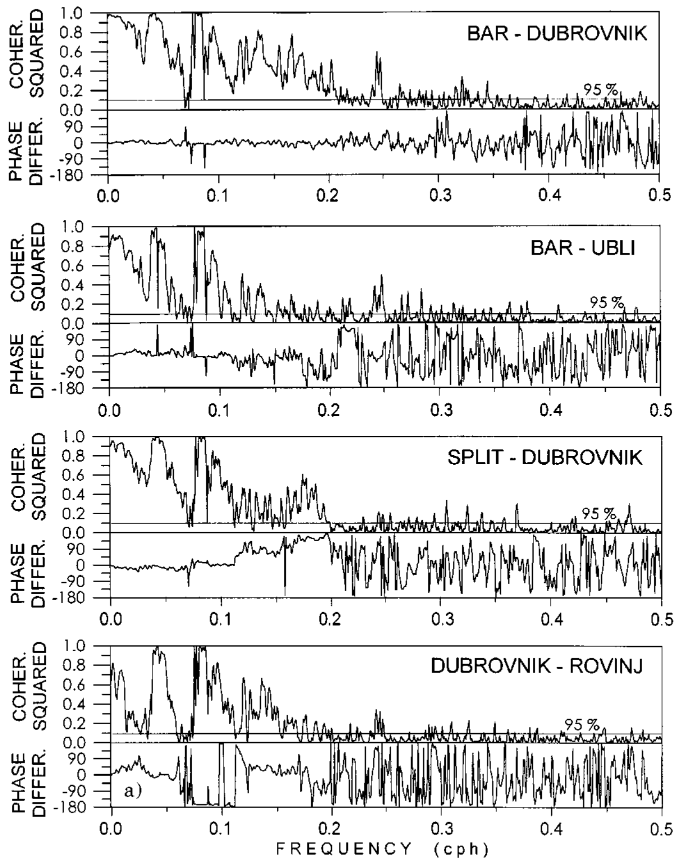

Fig. 6. – Coherence-squared and phase difference spectra performed on hourly sea levels between all nine stations.

These results lead to the conclusion that the oscillations of the frequencies on the periods of fast synoptic perturbances (1-3 days) are not simultaneous in the whole Adriatic Sea, but some smaller regions, *i.e.* the South and Middle Adriatic, reach that behaviour contemporaneously. The oscillation on periods larger than 3.5 days is simultaneous in the whole Adriatic, except around 0.0045 cph.

3·3. *Free oscillations.* – Seiche activity in 1988 can be assessed satisfactorily analyzing power spectra, coherence-squared spectra and phase difference spectra of hourly residual sea levels (figs. 5 and 6).

Uninodal seiche of the whole Adriatic Sea, with period 22-23 hours [9, 27], can be clearly detected in the figures. Theoretical efforts were made by various authors [10, 41-44]. From the power spectra analysis the ratio of the amplitudes between the stations can be determined, *e.g.* between Rovinj and Bar it is about 3. Coherence-squared values are about 0.95, and phase difference values about 0° at all stations. This proves the existence of uninodal bay oscillations, while numerous peaks about 22-23 hours show that they occurred few times during 1988.

At periods of about 10.8 hours a significant amount of energy occurs. This peak is

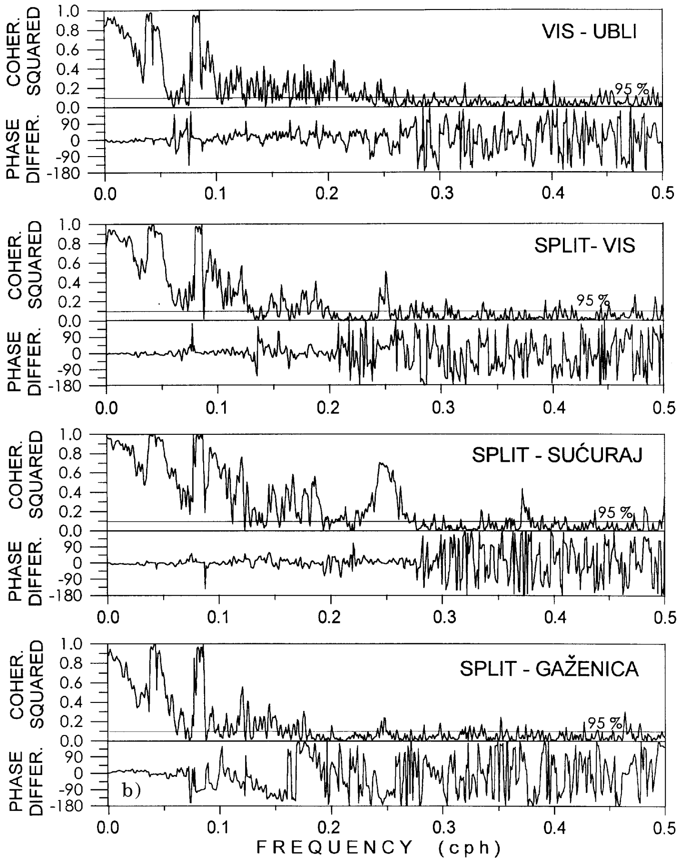

Fig. 6. – *Continued.*

clearly presented at all stations, except at Gaženica where there is no significant energy at all (fig. 5). The coherence-squared values (fig. 6) are larger than 0.6 between all the stations, excluding Gaženica. The phase difference spectra between the stations in the South and Middle Adriatic and in the North Adriatic (Rovinj) are about 180°. The shift can be observed between Split and Bakar (about $-130°$), and Bakar and Rovinj (about $-40°$). This is probably due to the position of the station Bakar, placed in the semienclosed region, where the bottom topography influences spreading of oscillations. This fact has to be improved by the experiment with more measuring stations. The energies at periods of about 11 hours were also investigated in the past, and belong to the binodal seiche of the whole Adriatic [27] with two nodal lines: the first is in the Otranto Strait and the second lies between Zadar and Ancona [10]; consequently, there are such oscillations at Gaženica.

On periods of about 7.5-8 hours the maximum energies are presented at all the stations except Split, Vis, Sućuraj and Ubli. Significant peaks can be also detected on coherence-squared spectra between the rest of the stations, *i.e.* Bar-Dubrovnik 0.8, Dubrovnik-Rovinj 0.6-0.7, Gaženica-Bakar 0.55-0.6, etc. Phase difference between Bar and Dubrovnik is about 0°, Dubrovnik and Rovinj 30°, Gaženica and Bakar $-20°$, and

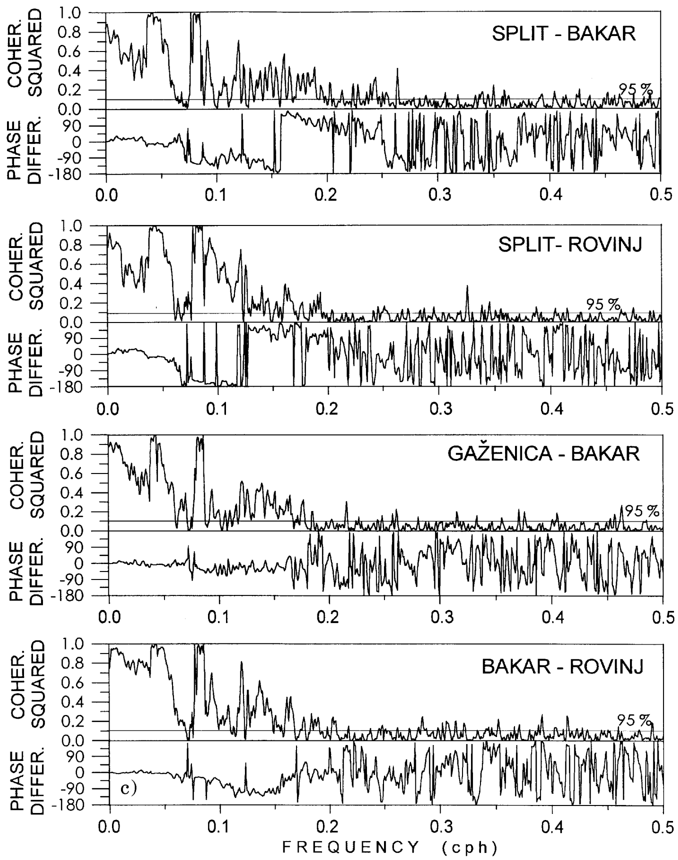

Fig. 6. – *Continued.*

Bakar and Rovinj −130°. The energies at this period can be related to the trinodal oscillation of the whole Adriatic, with nodal lines in the Otranto Strait, between Split and Monte Gargano, and between Pula and Rimini [27]. Some phase shift is presented between the South and North Adriatic (about 30°), and, again, in the region of Bakar station. Using a three-dimensional numerical model, Orlić *et al.* [40] determine three separated gyres with minima of sea level height in the centres excited by Bora forcing exactly between the nodal lines; so the trinodal seiche is probably generated by the Bora wind.

3·4. *Four hour seiche.* – On a period of about 4 hours, a maximum of energy can be noticed at Bar and Dubrovnik. At the same time, a wide peak occurs at Split and Sućuraj. Coherence-squared spectra (fig. 6) show no significant correlation between the stations in the South and Middle Adriatic (Split-Dubrovnik, Vis-Ubli), but a very strong connection between Split and Sućuraj, and a weaker one between Bar, Dubrovnik and Ubli. In this period there is no significant energy at Vis, but coherence-squared spectra values between Split and Vis are significant. So, there

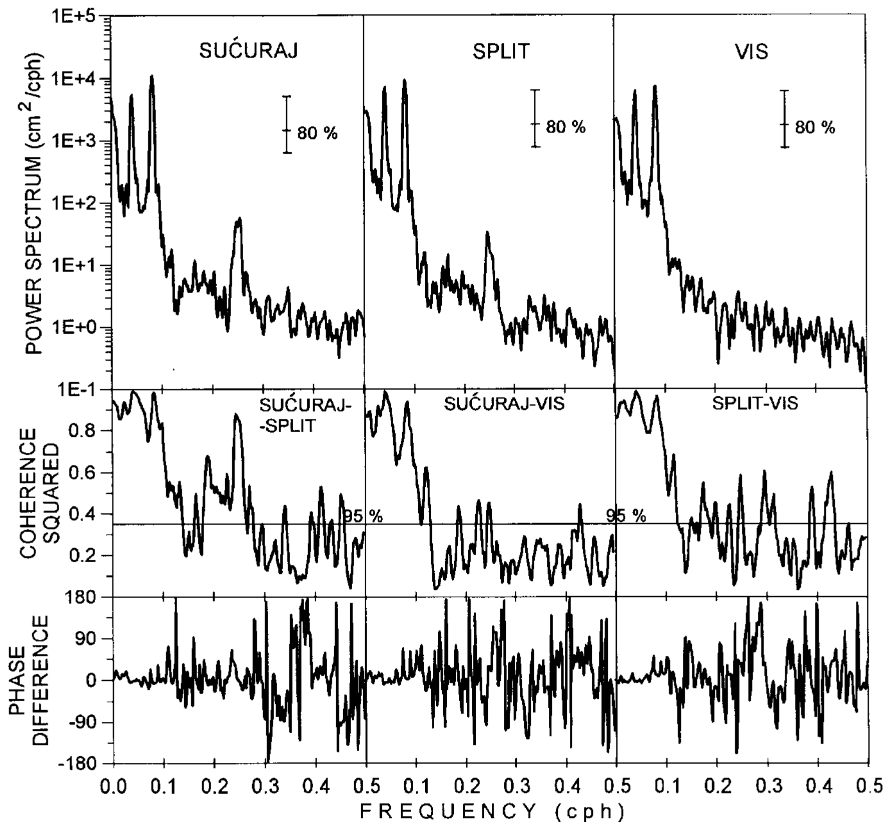

Fig. 7. – The case of four-seiche occurrence in March 1988: estimates of power spectra, coherence-squared spectra and phase difference spectra (8 degrees of freedom) performed on hourly sea levels at Sučuraj, Split and Vis during the period 1-31 March 1988.

occurred two separated seiches: the first in the region of South Adriatic and the second in the basin inside the Middle Adriatic islands which will be here discussed.

The area limited by the peninsula Pelješac and the islands of Korčula, Vis and Šolta (marked in fig. 1) with depths between 40 and 80 metres decreasing towards River Neretva delta, is shallower than the outside region with depths up to 170 metres towards Palagruža Sill, and 280 metres towards Jabuka Pit. The area is open to the west and southwest. Leder [18] indicates rise of water at Split during Sirocco forcing. This is probably a major mechanism which, coupled with the fast changes after, causes the intense seiches.

The spectral and cross-spectral analysis (8 degrees of freedom) is made on the data from 1st to 31st March (fig. 7). Power spectrum at Sućuraj has a peak on the periods about 4 hours, with energies 20 times larger than the surrounding energies. This peak also significantly occurs at Split with lower energies, but not at Vis. Coherence-squared spectra between Sučuraj and Split at 4 hour periods are significant with a value of 0.9. The phase difference spectra have values of about 0°. This seiche occurs not only in the winter period, but also during the whole year. For example, during July 1987 this seiche occurred very intensely with energies almost 5 times larger than in the above-presented episode.

Furthermore, simple frictionless Merian formulae extracted from one-dimensional barotropic linear model of rectangular bay (*e.g.*, in [45]), give the period T of the uninodal bay seiche:

$$T = \frac{4L}{\sqrt{gh}} ,$$

where L is the bay length, h is the mean depth and $g = 9.81\ \mathrm{ms}^{-2}$. The corresponding period for $L = 95$ km and $h = 65$ m, which are rough values for the considered region, has a value $T = 4.1$ h. So, it can be concluded that an oscillation with a period of about 4 hours belongs to uninodal bay oscillation of the considered region, with the nodal line lying somewhere between the islands of Šolta, Vis and Korčula, close to the open boundary of the region. A more precise location of the nodal line demands more measuring stations.

4. – Summary and conclusions

In order to obtain the behaviour of variations of the sea level along the eastern coast of the Adriatic Sea on the scale from two hours up to a month, harmonic, spectral and cross-spectral analyses are performed on one-year-long time series of the hourly sea level data from the tide-gauge stations situated along the eastern Adriatic coast. From the results, the following conclusions can be reached:

1) The semidiurnal tide constituents show a distinction of phases between the North and South stations and the assumed amphidromic point, with some variations through the year, leading to the conclusion that semidiurnal tides are partly contaminated by seiches with period close to the tide ones. Diurnal tides in the Adriatic are also interfering with the uninodal free oscillations.

2) Simultaneous response of the whole Adriatic is reached for frequencies lower than 0.012 cph (3.5 days), with a gap on frequencies of about 0.0045 cph (9.5 days). The South and the Middle Adriatic together have almost quite simultaneous response for frequencies larger than 0.05 cph (20 hours).

3) The Bakar station shows a phase shift on the binodal and trinodal Adriatic seiche activity (periods 10.8 and 7.5 hours). This is probably the result of the friction influence inside the local Bakar basin which has complex topography and numerous islands. This assumption should be improved with more complex experiment.

4) A new seiche with a period of four hours has been found and investigated in the region inside the Middle Adriatic island area. Significant coherence-squared and no phase difference spectra between Split and Sućuraj determine the seiche as a uninodal bay free oscillation, confirmed by the simple one-dimensional barotropic linear model. The nodal line approximately lies at the entrance of the basin, but for more precise location more tide gauge stations are needed.

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