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A climatological study of the uninodal free oscillation in the Adriatic Sea

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The paper examines uninodal free oscillation of the Adriatic Sea and investigates its behavior in the climatological sense. Analysis is made on the hourly sea level data collected at four tide gauge stations situated on the east Adriatic coast, while the examined period is 1986-1997. Residual sea levels are calculated by subtracting the predicted tide from the original series. Uninodal seiche is extracted from the residuals using band-pass filter, furthermore, the filtered amplitudes (envelopes) are calculated. The annual mean seiche amplitude does not vary from year to year whereas annual maximum at Rovinj is always higher than 17 cm. The largest amplitudes occur in October-March period, however, the seiche can appear strongly, but very rarely, also during summer. The annual maximum of the seiche amplitude appears in about 40 % of cases in the northern Adriatic coupled together with the annual maximum of the residual sea level. Mean amplitude ratios between Bakar and Rovinj, Split and Rovinj and Dubrovnik and Rovinj stations are calculated to be of 0.86 ± 0.03 cm, 0.48 ± 0.03 cm and 0.23 ± 0.02 cm, respectively. The decay time calculated from the strongest seiche episode is estimated at 81 ± 19 h. The amplitude of the seiche in Rovinj is estimated to be of 53 cm for the return period of 100 years, consequently, the seiche coupled with the high tide may cause a significant damage along the northern Adriatic coast.

Key words: Adriatic Sea, seiche, climatological study, band-pass filtering, theory of extremes

INTRODUCTION

The Adriatic Sea (Fig. 1) is an elongated (about 800 km by 200 km) semi-enclosed basin situated in the northern part of the Mediterranean Sea, and connected with the deep Ionian Sea (4000 m deep) through the Otranto Strait (up to 800 m deep). The northern part is shallow (up to 100 m), the middle part has a maximum depth of 280 m and communicates with the south almost circular basin (depth up to 1200 m) through the Palagruža Sill (approximately 170 m deep).

Atmospheric westerlies bring cyclones over the Adriatic, more frequently in the autumn-winter period (October-March), producing surges which are higher in the North Adriatic. Consequently, at the end of surge-favourable sirocco wind blowing (ORLIĆ *et al.*, 1994), sharp changes of the wind conditions produce marked Adriatic free sea level oscillations (seiches). Coupling of storm surge including uninodal seiche together with high astronomical tide may produce flooding of the northern Adriatic coast (well known "acqua alta" in Venice, e.g. FINIZIO *et al.*, 1972). This may occur especially during October-December when steric effect can additionally raise the sea level by 6 cm on an average (VILIBIĆ, 1998).

The seiches of the Adriatic Sea have been widely examined since the beginning of this century (KESSLITZ, 1910; DEFANT, 1911). Previous studies were concentrated on the standing waves of the whole Adriatic Sea (BULJAN and ZORE-ARMANDA, 1976). Moreover, considerable efforts were directed to explore the seiches of bays and channels, which form a greater part of the East Adriatic coast (STERNECK, 1914; GOLDBERG and KEMPNI, 1937; ZORE, 1955; GODIN and TROTTI, 1975; VILIBIĆ and ORLIĆ, 1999). There are numerous works which empirically (VERCELLI, 1941; POLLI, 1958; ROBINSON *et al.*, 1972; MANCA *et al.*, 1974; GODIN and TROTTI, 1975; VILIBIĆ *et al.*, 1998) and theoretically (KASUMOVIĆ, 1959; BAJC, 1972; SGUAZZERO *et al.*, 1972; STRAVISI, 1973; MOSETTI and PURGA, 1983) examine the basic modes of the Adriatic free oscillations. As uninodal seiche amplitude is about 4 to 8 times higher than second mode amplitude, particularly in the northern Adriatic (RAICICH *et al.*, 1999), uninodal seiche was somewhat better investigated due to its impacts on the coastal infrastructure. The period of uninodal seiche varies in literature from about 23 h (early authors) to 21.2 h (CEROVEČKI *et al.*, 1997; RAICICH *et al.*, 1999). The seiche can last for more than ten days, with maximum initial range (double amplitude) higher than 1.2 m at Trieste, as the maximum amplitude occurs there (RAICICH *et al.*, 1999). The decay time is calculated to be 3.2 ± 0.5 days (CEROVEČKI *et al.*, 1997) or 78-96 h (RAICICH *et al.*, 1999). Damping of the oscillation is produced by bottom friction as well as by energy loss to the Mediterranean (CEROVEČKI *et al.*, 1999), while both the wind-field variability and basin topography may contribute to the partitioning of energy between various Adriatic modes (RAICICH *et al.*, 1999).

The uninodal seiche has been studied throughout the century, however a climatological study of its occurrence from longer time series has not been performed yet. Thus, this study analyses twelve-year hourly sea level data collected at four tide gauges located on the East Adriatic coast. Section 2 describes data collecting and methodology, Section 3 includes climatological analyses of the seiche, case study of February-March 1989 and the estimates of extreme envelope values, whereas conclusions are given in Section 4.

MATERIAL AND METHODS

Sea level data were collected at four permanent tide gauges situated on the East Adriatic coast: Rovinj, Bakar, Split and Dubrovnik (Fig. 1).

The analyzed time series contain hourly sea level values in the period 1986-1997, which are currently available in digital form. Dubrovnik tide gauge did not work in the period November 1991 - February 1992, due to the recent war that affected the region. The accuracy of the digitalized data is estimated to be ± 1 cm. Tides were removed from the data by subtracting the predicted tide (SHUREMAN, 1941) from the original series, using seven harmonic constituents which have considerable values in the Adriatic (HYDROGRAPHIC INSTITUTE, 1974). Residuals were reduced to the mean sea level taken from the reports on the sea level measurements (HYDROGRAPHIC INSTITUTE, 1956-1998).

The strength of free oscillation is demonstrated by spectral analysis performed on hourly residual sea levels according to JENKINS and WATTS (1968) by using 40 degrees of freedom. Fig. 2 shows the power spectra for all the stations in 1997.

The highest energy peak marks the uninodal seiche with periods of about 21-22 h. The highest energies are obtained in the North Adriatic, and then decrease monotonically towards the South Adriatic (RAICICH *et al.*, 1999). At Dubrovnik, the energy is 20 times lower than at Rovinj. The second peak (about 10.5-11.0 h) represents the second mode, with energy approximately 2 times lower than the first mode at Rovinj, but 4 times higher at Dubrovnik, thus in

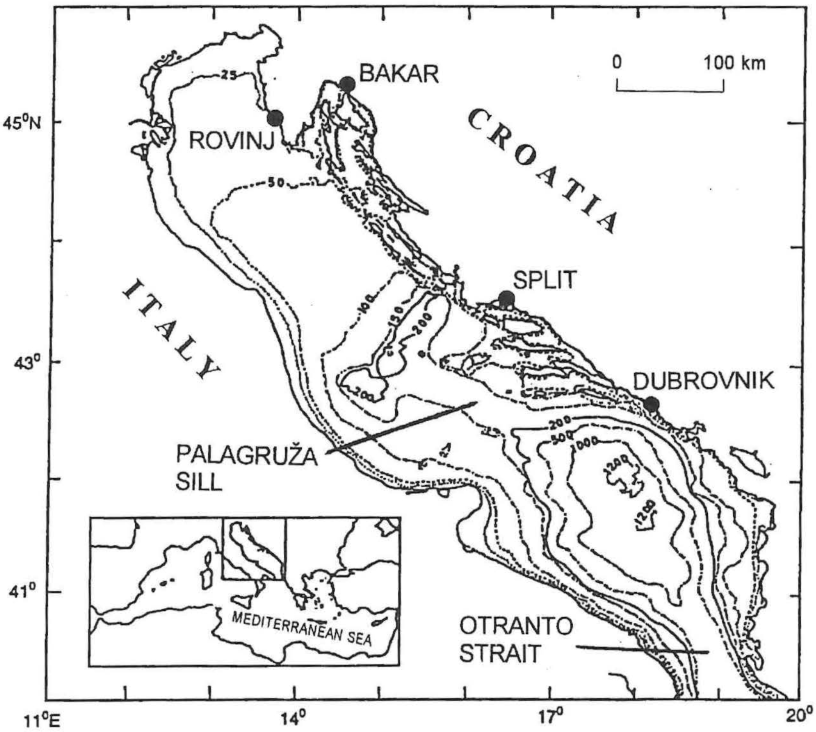

Fig. 1. Adriatic Sea bathymetry with position of tide gauges

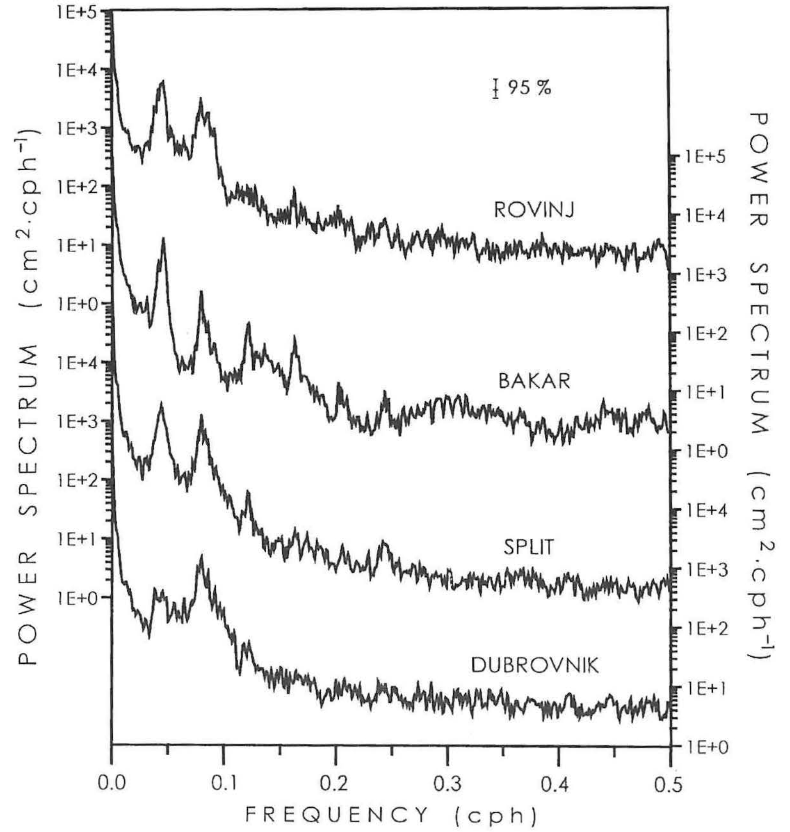

Fig. 2. Power spectra calculated for Rovinj, Bakar, Split and Dubrovnik. The spectral analysis is performed on hourly residual sea level data collected in 1997 (40 degrees of freedom)

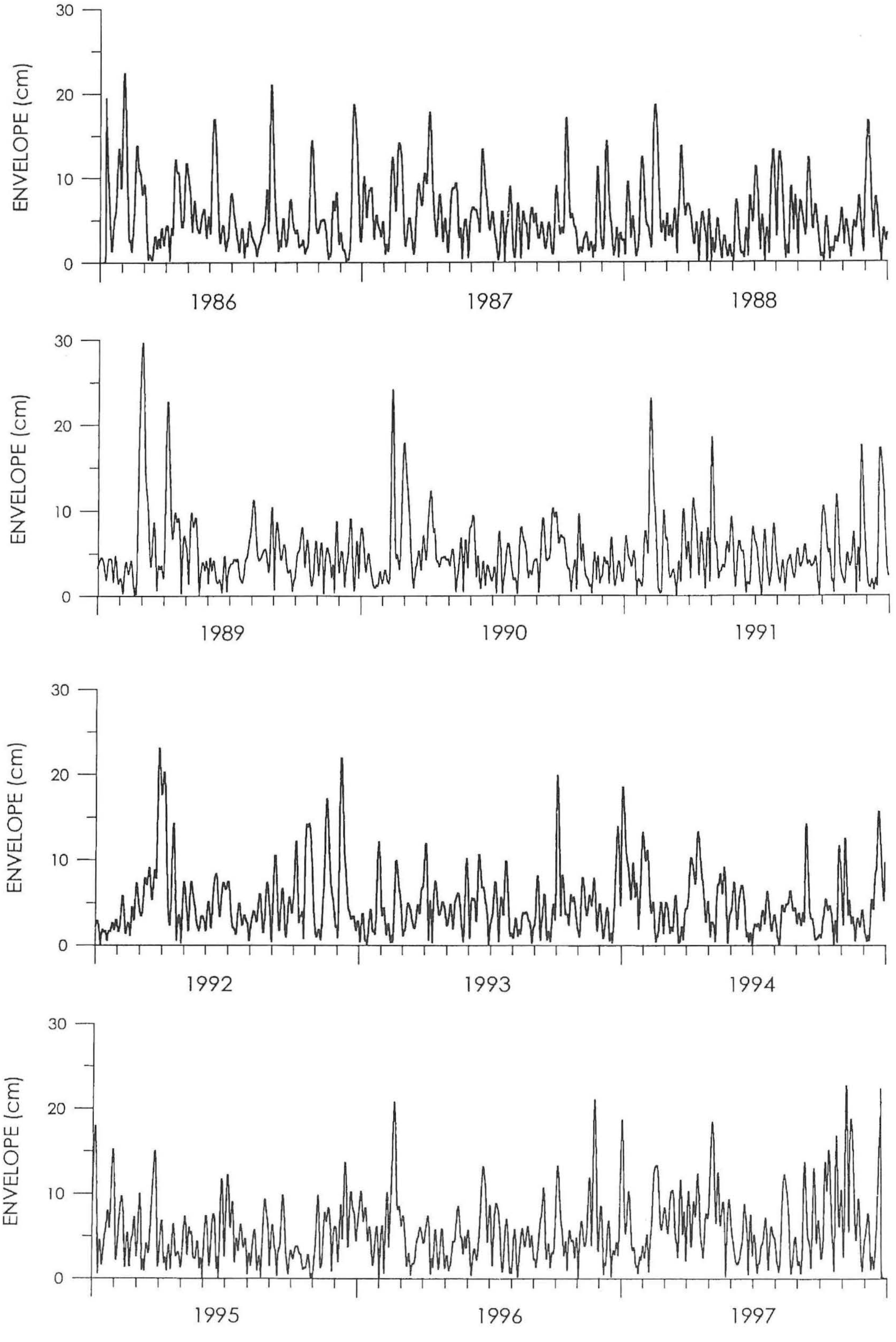

Fig. 3. Envelope series at Rovinj in the period 1986-1997. The envelope is obtained from band-pass filtered residual sea levels (cut-off periods 24.3 h and 19.2 h, half-length 192 h)

1997 second mode had occurred rather frequently in comparison to the first mode of the seiche (VILIBIĆ *et al.*, 1998). The peaks at 8.2, 6.0, 4.8 and 4.0 h, best visible at Bakar but also at other tide gauges, are probably related to higher modes of the whole Adriatic or to the modes of some parts such as the north and middle Adriatic (VILIBIĆ *et al.*, 1998).

Finally, the uninodal seiche was extracted from the residual sea levels using a band-pass symmetric filter with cut-off frequencies at 0.0412 and 0.0520 cph (equivalent periods of 24.3 h and 19.2 h), while half-length of the filter equaled 192 h. In order to extract continuous series of the main seiche amplitudes, the envelopes of band-pass filtered residual sea levels were calculated according to FARNBACH (1975). The envelope series at Rovinj in the period 1986-1997 is plotted in Fig. 3.

RESULTS

Seiche climatology

The envelopes at Rovinj (Fig. 3) seem to be very disarranged in 1986 and 1987, where the seiche appeared intensely throughout the year, even during the summer season (in August 1986 the envelope reached 22 cm).

Thus, the seiche can appear intensely in the part of a year when there is no persistent synoptic activity over the Adriatic in general. On the contrary, in the following years the seiche appeared intense during the winter period (October-March), exclusively. It should be pointed out that the band-pass filter curs the first oscillation of each episode by 40 %, consequently, the real amplitude is larger than the calculated envelope by 70 %. In fact, as it will be shown later, the maximum envelope at Rovinj, which occurred in March 1989 (~ 29 cm), has proper amplitude of the first oscillation of about 45 cm.

The mean seiche activity was obtained by averaging the envelopes for each year. Fig. 4 shows the annual envelopes averaged for all the stations during twelve year of observations.

The averages seem not to vary much from year to year. At Rovinj they range between 4.5 cm in 1993 and 6.9 cm in 1997. The mean value in the whole period is 5.4 cm at Rovinj, 4.7 cm at Bakar, 2.6 cm at Split and 1.3 at Dubrovnik. Consequently, the mean amplitude at Bakar, Split and Dubrovnik has 87 %, 48 % and 24 % of its mean value at Rovinj, respectively.

The maxima of envelopes for each year are shown in Fig. 5. They are fluctuating more than the mean values, however, the highest value does not exceed the doubled lowest one.

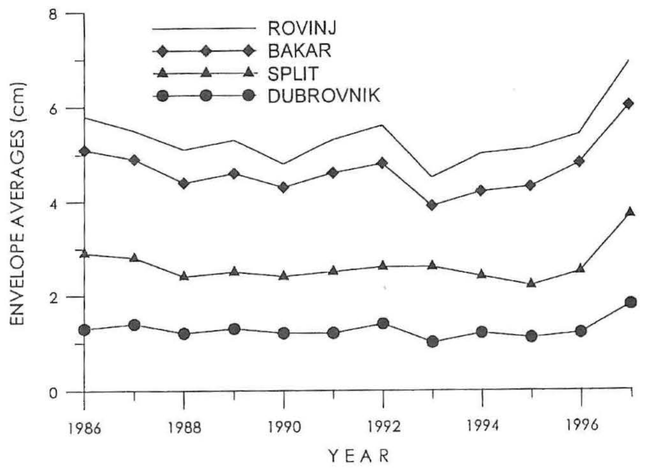

Fig. 4. Time series of the annual averages of the seiche envelopes at Rovinj, Bakar, Split and Dubrovnik

Thus, a rather intense seiche activity occurred regularly at least once a year. The highest amplitudes compared with one in Rovinj were in Bakar, Split and Dubrovnik have 89 %, 53 % and 25 %, respectively. Nevertheless, the maximum envelope in 1987 is placed in Bakar.

More accurate correlation among the stations can be obtained by analysing hourly envelope values. Hence, the regression fits are calculated for each year separately and the mean envelope ratios are achieved. However, the envelopes lower than 2 cm are not included into the analysis, in order to minimize the influence of other processes that may partially pass through the band-pass filter.

Fig. 6 represents the correlation between Rovinj and other stations in 1989. Following average regressions are obtained by analyzing all the years:

envelope (Bakar) = (0.86 ± 0.03) *envelope* (Rovinj)
envelope (Split) = (0.48 ± 0.03) *envelope* (Rovinj)
envelope (Dubrovnik) = (0.23 ± 0.02) *envelope* (Rovinj)

The ratios calculated using annual mean and maximum values are roughly within the range calculated here, consequently, it is possible to obtain the amplitude ratios using only the extreme annual seiche episodes.

The residual sea level (Fig. 7) exhibits an annual maximum of about 90 cm above mean sea level at Rovinj, decreasing its values towards Dubrovnik. For comparison, during the seiche episode from October-November 1966, the maximum residual sea level was about 115 cm at Bakar (CEROVEČKI *et al.*, 1997) and about 150 cm at Venice (FINIZIO *et al.*, 1972). Maximum annual residuals had the lowest values in 1988, due to a reduced seiche activity (Fig. 5) and reverse seasonal cycle of air pressure over the Adriatic which diminish the influence of steric effect (VILIBIĆ, 1998). On the contrary, during 1992 and 1993, seasonal sea level cycle strengthened, enlarging the probability of occurrence of high residual sea levels; however, it is necessary to have strong seiche events to produce extremely high residual sea levels.

The next step is to obtain the information about the influence of strong seiches on the maximum residual sea levels. Fig. 8 shows the difference between the annual maximums of residual sea levels and the same parameter but occurred during the episodes where the maximum seiche amplitudes were recorded.

It can be seen that the annual maximum of residual sea levels coincides with the annual maximum of envelopes during 5 years in Rovinj and Bakar, 4 years at Split and 1 year in

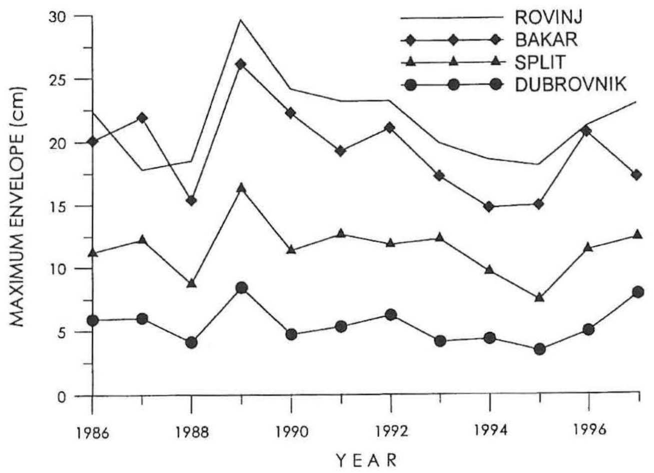

Fig. 5. Time series of the annual maxima of the seiche envelopes at Rovinj, Bakar, Split and Dubrovnik

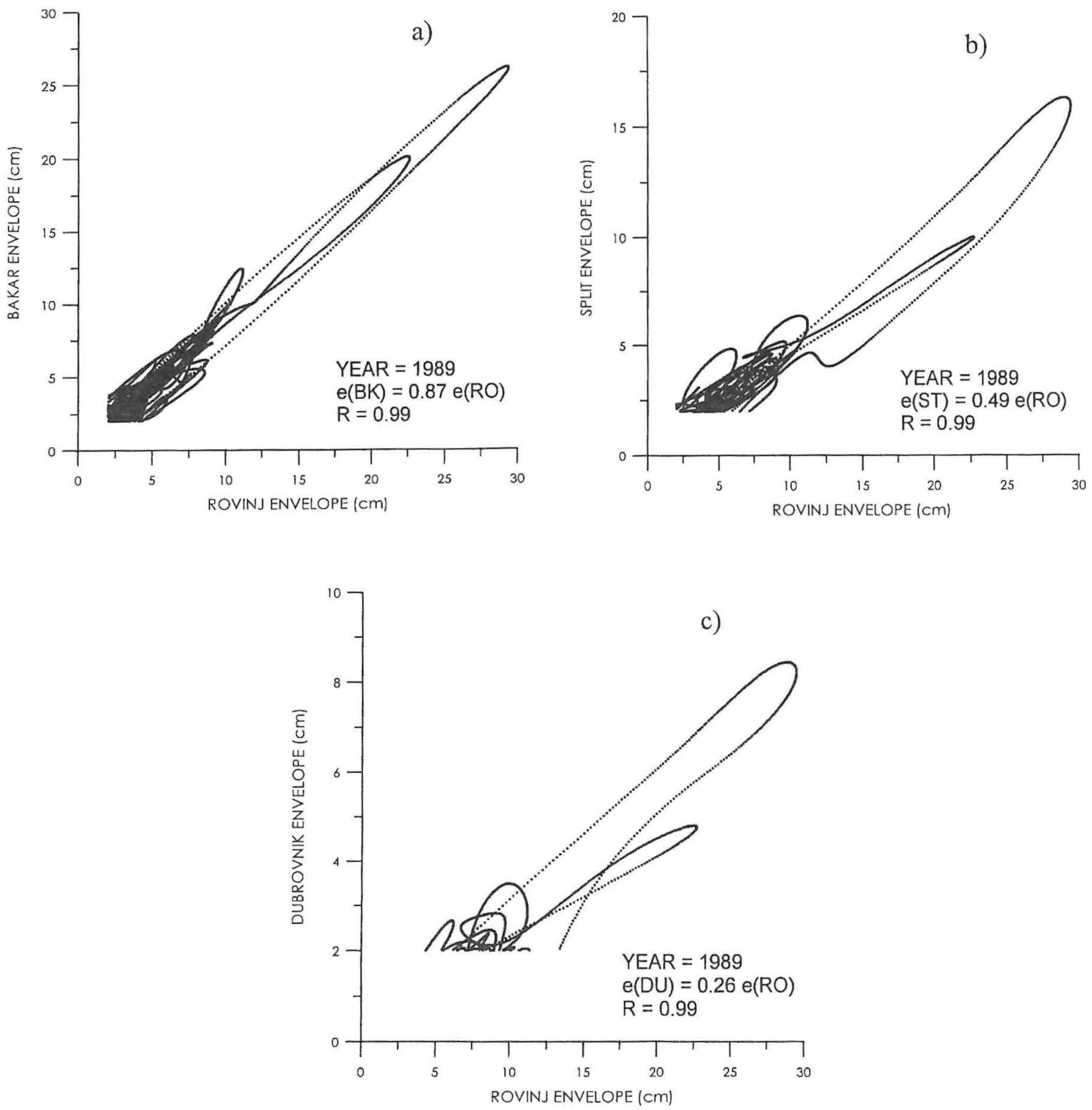

Fig. 6. Envelope correlation diagrams in 1999 between (a) Bakar and Rovinj, (b) Split and Rovinj, and (c) Dubrovnik and Rovinj. The envelopes lower then 2 cm are not included, in order to remove the influence of the digitalization errors and the influence of any processes other then the seiche which may partially pass through the filter

Dubrovnik. Obviously, the influence of the seiche to the total residual sea level decreases together with its amplitude from the North to the South Adriatic. But, the uninodal Adriatic seiche maximum coincides with the maximum annual residual sea level in the North Adriatic in about 40 % of the cases, being responsible for the damages in that coastal zone. However, in some years (as in 1987 and 1991), strong uninodal seiche can occur during low residual sea levels, therefore avoiding any flooding and damage in the coastal zone.

By analysing monthly averages and standard deviation of the residual sea level at Rovinj (Fig. 9) (similar behavior can be also observed at the other stations), it is evident that the lowest

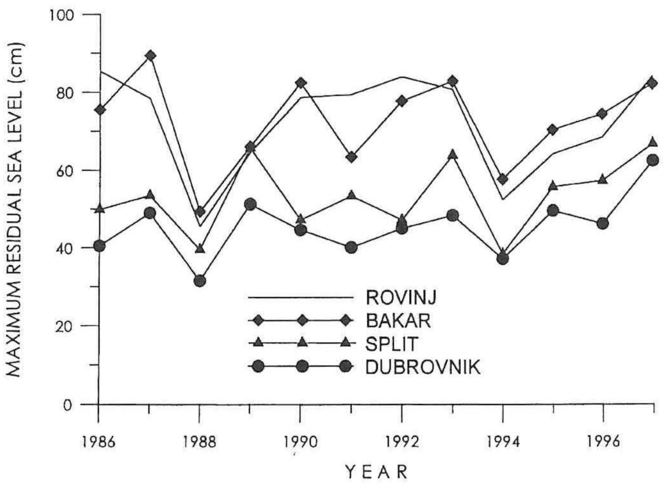

Fig. 7. Annual maxima of residual sea levels at Rovinj, Bakar, Split and Dubrovnik

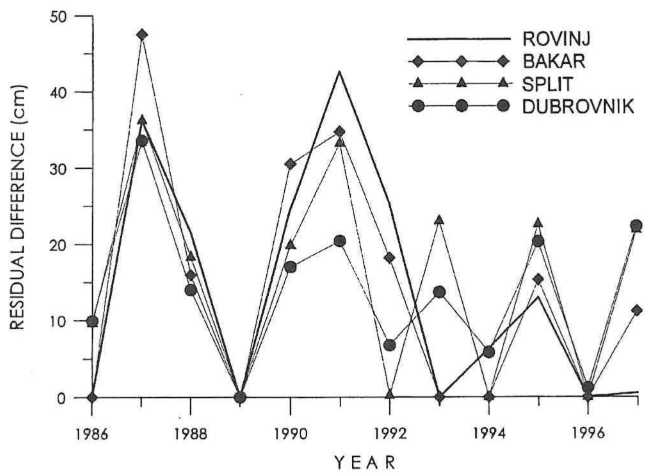

Fig. 8. The difference between the annual maximum residual sea levels and the maximum residual sea levels recorded during the episode when the annual maximum seiche envelope occurred

sea levels occurred during the period January-March. At the same time standard deviation is the highest in January and February, almost two times higher than in the rest of the months. These values are relatively abnormal there; the averages and standard deviations in the period 1955-1993 are 6-10 cm higher and 3-5 cm lower, respectively (VILIBIĆ *et al.*, 1997). Anomalies occurred in the winter season during the period 1989-1993 are probably influenced by the episodes of cold surface temperature in the North Atlantic and by El Nino affecting air pressure fields over Europe (PASARIĆ and ORLIĆ, 1992). At the same time, strong seiche episodes (maximum envelope higher than 15 cm) occurred mostly in the period October-March. In the April-May period the strong seiche can appear rather frequently, while during summer season (June-September) the strong seiche rarely appears.

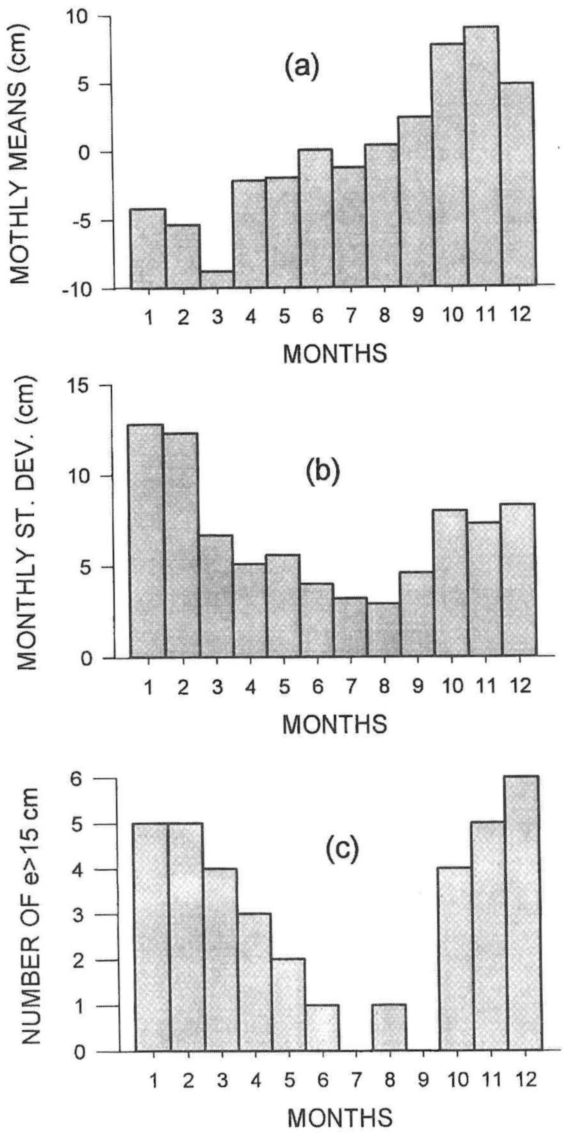

Fig. 9. Annual course of (a) monthly mean sea level, (b) its standard deviation, and (c) the number of the episode with envelopes larger then 15 cm appeared at Rovinj in the period 1986-1997

Seiche episode in February-March 1989

Herein the seiche episode occurred in February-March 1989 will be analysed, having the maximum envelope in the period 1986-1997. Residual sea levels and the seiche envelopes are plotted in Fig. 10a.

It can be noticed that intense seiche occurred during 27 February and decayed to 3 March, when the second and stronger episode was announced. On 4 March the seiche had the largest range, at Rovinj about 90 cm, decreasing its values to the South Adriatic. Maximum residual sea level was recorded during 27 February, with the values of 65 cm, 66 cm, 66 cm and 51 cm above mean sea level at Rovinj, Bakar, Split and Dubrovnik stations, respectively. Therefore, the maximum residuals have got approximately the same values in the North and Middle Adriatic, whereas in the South Adriatic the values were slightly smaller. This situation is not the typical one and it can be related to the predominant influence of the air pressure on the sea level rise rather than sirocco wind. On the contrary, during the episodes with strong flooding in the north Adriatic, sirocco raises the sea level more in the North than in the Middle and South Adriatic (ORLIĆ *et al.*, 1994).

The seiche envelopes (Fig. 10b) had the maximum values of 29.1 cm, 26.1 cm, 16.3 cm and 8.4 cm at Rovinj, Bakar, Split and Dubrovnik, respectively.

The decay time can be calculated here, thus, 7 March from 00 h to 24 h is chosen to be the best period (the period of non-forced seiche damping). The decay times had the values of 100 h, 93 h, 64 h and 65 h at Rovinj, Bakar, Split and Dubrovnik, respectively, what determines the mean value of 81 h with the standard deviation of 19 h. These values are consistent with the values calculated by CEROVEČKI *et al.* (1997) who analysed twelve seiche episodes between 1963 and 1986 (decay time 3.2 0.5 days) and RAICICH *et al.* (1999) having the decay times of 78 and 96 h.

Extreme return envelope values

The estimation of return extreme values will be done using the distribution of the extremes (e.g. GUMBEL, 1958):

$$F(x) = e^{-e^{-y}} ,$$

where $F(x)$ represents the probability that all the data are smaller than the input variable x, which is connected by the transformed variable y by three separate solutions (FISHER and

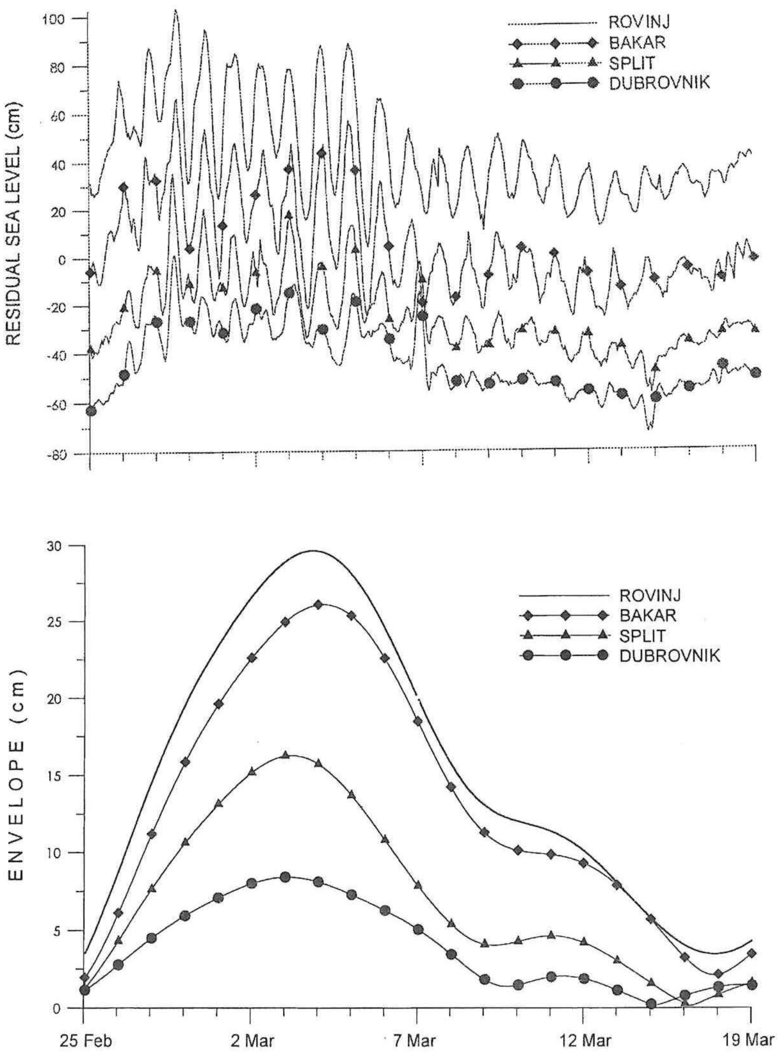

Fig. 10. Time plot of (a) the residual sea levels and (b) the seiche envelopes from 25 February to 19 March 1989 collected at Rovinj, Bakar, Split and Dubrovnik tide gauges. Residual sea level records has been offset vertically for presentation purposes

TIPPETT, 1928). Here will be used the first FISHER-TIPPETT solution:

$$y = \frac{x - A}{B},$$

which is favorable for small series.

The theory is applied on annual maximum envelopes in the period 1986-1997. Fitting the extreme distribution by using maximum likelihood method, the parameters *A* and *B* are calculated to be 20.1 cm and 2.46 cm, respectively. Moreover, the return period *T(x)* can be calculated as

$$\frac{1}{T(x)} = 1 - F(x).$$

Return periods for seiche envelopes together with standard errors are plotted in Fig. 11.

For return period of 100 years e.g. the seiche with the envelope of 31.4 ± 2.9 cm is expected to occur once in a century. Consequently, the real amplitude of the first oscillation of the seiche, as stated in the first paragraph of **Seiche climatology,** is higher for about 70 %, hence, the seiche with the maximum amplitude of 53.4 ± 4.9 cm is expected to appear at Rovinj once in a century. At Bakar,

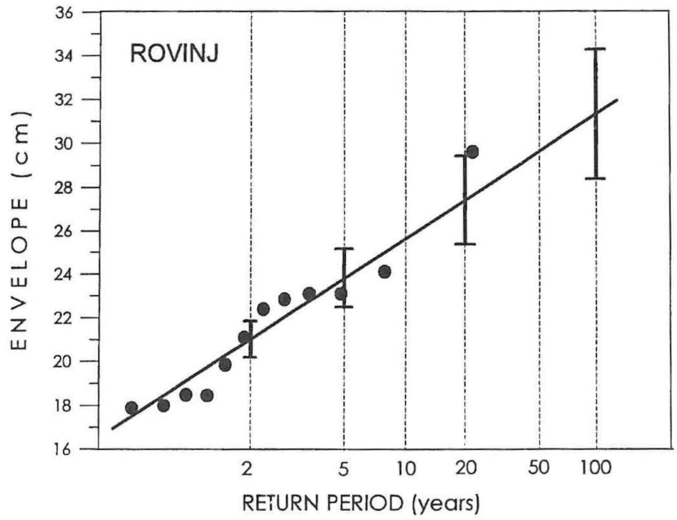

Fig. 11. Extreme envelope values at Rovinj together with standard errors calculated for return periods up to 100 years. Input data are annual maxima of the seiche envelopes, while fitting was done using maximum likelihood method

this value is 45.9 ± 4.2 cm, while during the episode October-November 1966 the total range of the first oscillation was about 115 cm (CEROVEČKI *et al.*, 1997). However, the first oscillation at Bakar contains not only the main Adriatic seiche motion but also the seiches of some smaller areas such as Rijeka Bay with the period of about 2 h (GOLDBERG and KEMPNI, 1937). The result of superposition can be a higher range of the first oscillation of residual sea level at Bakar than at Rovinj.

CONCLUSIONS

The uninodal Adriatic seiche has been widely examined throughout the century, however, this paper attempts to improve the knowledge in the sense of climatology. As the first, average activity of the seiche is denoted; it is shown that the mean annual seiche amplitude does not vary much from year to year. Furthermore, during all the examined years the seiche appeared at least once with the maximum envelope (filtered amplitude) higher than 17 cm (at Rovinj). The most active period in a year is October-March, nevertheless, the seiche can appear strongly but very rarely during the summer season. Due to the highest residual sea levels that occur in the period October-December, the highest probability of flooding coupled by seiche is obtained there, whereas during the winter period (January-March) the probability is lower but significant. Moreover, the annual maximum of the seiche amplitude appears in about 40 % of cases in the northern Adriatic when the annual maximum of sea level residual occurs; however, the annual maximum of the seiche can appear during low residual sea levels as happened in Februry-March 1989. Mean amplitude ratios between the stations are calculated with the values of 0.86 ± 0.03 cm, 0.48 ± 0.03 cm and 0.23 ± 0.02 cm between Bakar and Rovinj, Split and Rovinj and Dubrovnik and Rovinj, respectively. The seiche appears once in a century with the estimated amplitude of 53 cm at Rovinj, thus, if coincided with the high tide during the active synoptic season, it may cause rather significant damages in the coastal infrastructure along the northern Adriatic coast, as it happened during the episode in October-November 1966.

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Klimatološka analiza osnovnog seša u Jadranu

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SAŽETAK

U radu je obavljena klimatološka analiza uninodalne slobodne oscilacije Jadranskog mora. Analiza je obavljena na podacima satnih vrijednosti razine mora sa četiri mareografske postaje smještene na istočnoj obali Jadrana u razdoblju 1986-1997. Računate su rezidualne razine mora oduzimanja plimnih oscilacija koje su dobivene pomoću harmonijske analize iz vrijednosti ukupnih razina mora. Nadalje, osnovni jadranski seš je izdvojen iz rezidualnih razina mora pomoću pojasnog filtera, a također su izračunati i vremenski nizovi amplituda (ovojnica) seša. Godišnja srednja vrijednost amplitude seša ne pokazuje izrazitu međugodišnju varijabilnost, dok je njena maksimalna vrijednost u Rovinju uvijek viša od 17 cm. Najviše amplitude se pojavljuju u razdoblju listopad-ožujak. Međutim, seš se može izraženije pojaviti u rijetkim situacijama i tijekom ljeta. Godišnji maksimum amplitude seša se poklapa s godišnjim maksimumom rezidualne razine mora u oko 40 % slučajeva u području sjevernog Jadrana. Srednji omjer amplituda između postaja Rovinj i Bakar iznosi 0,86 ± 0,03 cm, postaja Rovinj i Split 0,48 ± 0,03 cm, te između postaja Rovinj i Dubrovnik ima vrijednost 0,23 ± 0,02 cm. Vrijeme gušenja izračunato pri analizi situacije s maksimalnom amplitudom seša iznosi 81 ± 19 h. Amplituda seša u Rovinju je procijenjena s vrijednošću od 53 cm za povratni period od 100 godina. Stoga superpozicija seša na žive morske mijene može prouzročiti značajne štete uz obale sjevernog Jadrana.