ISSN: 0001-5113	**ACTA ADRIAT,**	**UDC: 551.46 (262.3)**
AADRAY	**39 (1): 53-60, 1998**	**Original scientific paper**

Variations of the Sa and Ssa tides in the Adriatic Sea

Ivica VILIBIĆ

State Hydrographic Institute, Zrinsko Frankopanska 161, 21000 Split, Croatia

This paper deals with the variations of Sa and Ssa tides in the Adriatic Sea calculated from the hourly sea level data collected at four tide gauge stations during the period 1986-1995. The amplitudes and phases show a very notable year-to-year variability, with higher values during the period of 1989-1993. Sa amplitudes are on average 20 % higher in the North than in the South Adriatic, while Ssa amplitudes are the same in the entire Adriatic. The Sa phase is between 180° and 230°, but the opposite phase is noticed in 1986 and 1988. The generating forces of the tides include steric effect, atmospheric pressure and evaporation minus precipitation; however interannual changes are primarily the result of air pressure changes. The Sa amplitude as the result of processes other than air pressure is 6.0 cm.

Key words: Adriatic Sea, sea level, air pressure, annual and semi-annual tides.

INTRODUCTION

Seasonal and semi-seasonal cycles of sea level fluctuations play an important role in the dynamics of the majority of world seas, with amplitudes mostly up to 5 cm (PUGH, 1987), but in some parts, such as the Chinese Sea may exceed 25 cm.

In the Mediterranean, YUCE and ALPAR (1994) analyzed seasonal fluctuations of the monthly mean sea level in the northern Levantine Sea. Two minima and maxima occurred in this region, with a maximum range between extremes of approximately 17 cm for the average monthly mean sea level. Annual cycle with a rapid decrease during winter was observed by LARNICOL *et al.* (1995) by analysing the TOPEX/POSEIDON satellite data for the entire Mediterranean over two years. The maximum mean sea level range was about 20 cm, with half of the observed variations related to steric effect, while the rest were believed to be due to evaporation minus precipitation forcing and internal hydraulic control in the Straits of Gibraltar.

In the Adriatic Sea, the seasonal cycle has been strongly observed in the sea surface temperature (ZORE-ARMANDA, 1991) with a rising annual temperature span from the South to the North Adriatic (SUPIĆ and ORLIĆ, 1992). Short-term sea level variations (from a few days to a few months) are predominantly under the influence of air pressure and wind (ORLIĆ and PASARIĆ, 1994; LEDER, 1988), while the steric effect (associated with the sea temperature cycle) also influences the seasonal sea level cycle. During the forty-year period VILIBIĆ *et al.* (1995) calculated the average span of the monthly mean sea level range at Split with a value of approximately 11 cm, with the maximum in November and minimum in July.

In this paper the amplitudes and phases of the semiannual Ssa and annual Sa tides will be calculated in the Adriatic Sea using hourly data obtained during a ten-year period. Despite the fact that Sa and Ssa include some gravitational tide (PUGH, 1987), these tides are known as "meteorological tides", meaning that they are primarily under the influence of the seasonal atmospheric cycle. Later, the variations will be related to the variations of air pressure, in particular to the difference between winter and autumn mean values, with a surprisingly high correlation coefficient.

DATA AND METHOD

The tidal analysis was done based on year long hourly data obtained during the 10-year period between 1986 and 1995 at four stations on the eastern Adriatic coast: Rovinj, Bakar, Split and Dubrovnik (exception of Dubrovnik in 1991 and 1992). The registration of the sea level at all four stations began in the fifties, but the digitalized data (hourly values) only became available in 1985. The software used for tidal analysis was the Tidal Analysis Software Kit - TASK (BELL *et al.*, 1996) based on tidal analysis from MURRAY (1964) and SHUREMAN (1941). TASK separates 63 tidal constituents from year long hourly series, including annual Sa and semi-annual Ssa tides. Furthermore, the spectral analysis by JENKINS and WATTS (1968) with 8 degrees of freedom was applied to monthly mean data in Split from 1955 to 1995, in order to obtain the quantitative amounts of energies of annual and semiannual cycles. Finally, the air pressure in Split was compared with Sa amplitudes using simple linear regression in order to explain the variations of the seasonal cycle in the Adriatic.

RESULTS

Monthly means of the sea level are available from 1955 to 1994, so that the spectral analysis can be applied to that time series. The power spectrum in Split (Fig. 1) shows significant peaks of energy. The seasonal peak is the strongest here while the semiseasonal one is slightly lower (about 25 %). The period of 14 months has the pole tide (nutation of the instantaneous axis of the Earth's rotation, PUGH,

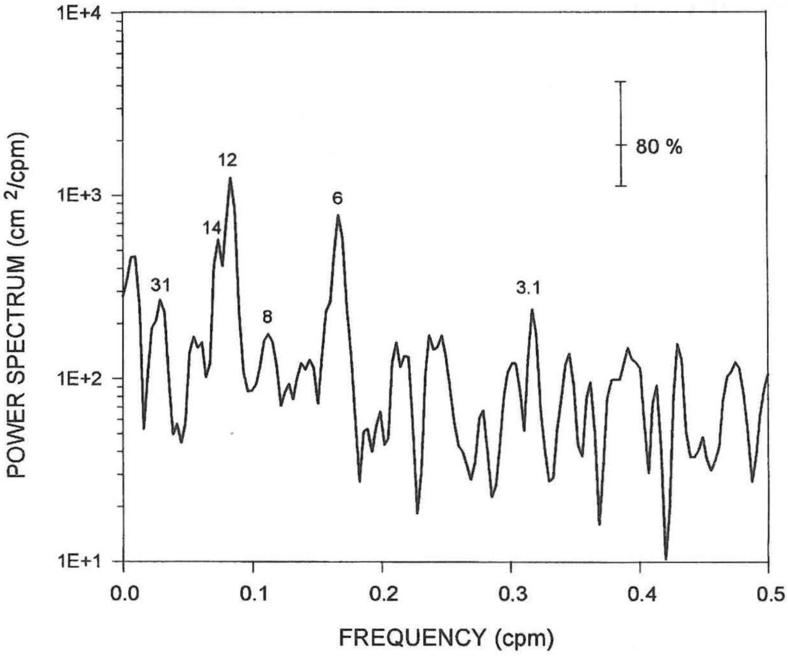

Fig. 1. Power spectrum of monthly mean sea levels at Split during the period of 1955-1995

1987). Greater energy also occur at the period of 3.1 months, while the peak at 31 months is related to long-term oscillations of air pressure (VILIBIĆ and LEDER, 1996) and air temperature (MOSETTI *et al.*, 1989).

The high amount of energy in the seasonal and semiseasonal cycles in the Adriatic, detected by spectra leads to the more careful investigation of this process. Fig. 2 contains monthly mean sea levels in Split during the period of 1986-1995, when periods of both a weakened and strengthened seasonal cycle can be observed. The highest levels generally occurred in the autumn, when the maximum monthly level is marked in October 1992 (approximately 23 cm above mean sea level). However, a few months later (in February 1993) the minimum occurred with a value of 21 cm below mean sea level. Moreover, the winter months during the period 1989-1993 had very low sea levels, while autumn months had unusually higher ones. This anomaly is related to the generation of cold surface waters in the northwest Atlantic (PALMER, 1986), producing a stable winter anticyclonic situation over the southern part of Europe (PASARIĆ and ORLIĆ, 1992). High air pressure, observed in the winters during 1989-1993 (Fig. 3), influenced the sea levels due to the inverse barometer law, in the Adriatic with 1.5 to 2 times higher values of barometric factor than the theoretical one (ORLIĆ, 1995).

Finally, the calculation of Sa and Ssa amplitudes and phases from hourly data are given in Tables 1 and 2, and Figs. 4 and 5. The Sa amplitude series shows significant variations between the years, from almost zero in 1988 to 13 cm in 1993. Generally, the amplitude is the highest in the North Adriatic (Rovinj and Bakar), about 20 % higher in average than at Split and Dubrovnik, but in some years (1986, 1994, 1995) the Sa signal is equal or higher in the South Adriatic. The phase has values generally between 180° and 230°, meaning that the maximum Sa values occur in the period July-September. But, in 1986 and 1988 the phase opposes the values (in 1986 about 320°, in 1988 with a wide span), moreover, the amplitudes in 1988 were small, so processes exist which strongly influence the behaviour of the Sa tide.

Ssa amplitude shows similar, yet, different behaviour in this period. Once, the minimum is in 1988 and maximum in 1993, but with smaller differences between different parts of the Adriatic. The maximum amplitude is in order of maximum Sa amplitude. The phase has values

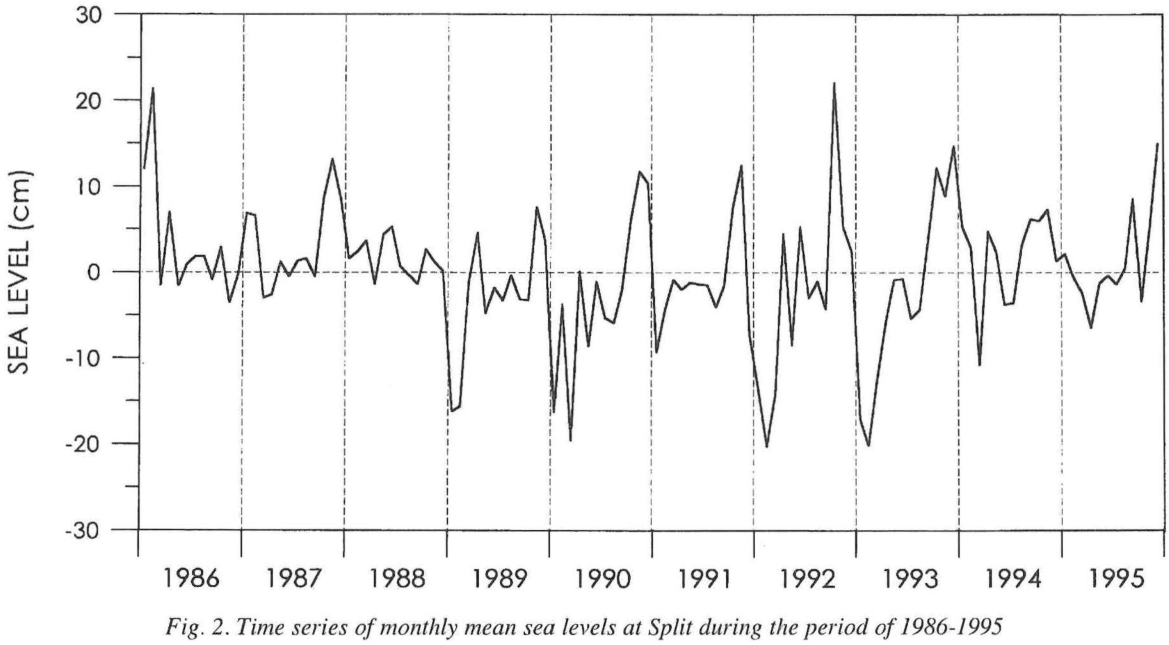

Fig. 2. Time series of monthly mean sea levels at Split during the period of 1986-1995

Table 1. Sa amplitude and phase at Rovinj, Bakar, Split and Dubrovnik during the period of 1986-1995

	DUBROVNIK		SPLIT		BAKAR		ROVINJ	
YEAR	H (cm)	g (deg)	H (cm)	g (deg)	H (cm)	g (deg)	H (cm)	g (deg)
1986	3.9	309	4.8	322	4.2	335	1.9	314
1987	6.2	243	6.0	245	5.8	221	6.7	216
1988	0.5	287	1.0	23	2.4	32	1.9	111
1989	2.8	167	2.7	151	3.0	141	4.6	147
1990	8.3	212	7.4	207	8.0	204	9.0	197
1991			3.2	193	4.5	179	5.9	173
1992			9.0	175	9.6	182	10.1	180
1993	8.6	191	9.6	190	12.3	183	12.5	181
1994	5.2	218	4.3	222	4.7	217	5.0	209
1995	5.3	231	4.8	232	4.6	226	4.7	212

Table 2. Ssa amplitude and phase at Rovinj, Bakar, Split and Dubrovnik during the period of 1986-1995

	DUBROVNIK		SPLIT		BAKAR		ROVINJ	
YEAR	H (cm)	g (deg)	H (cm)	g (deg)	H (cm)	g (deg)	H (cm)	g (deg)
1986	3.8	269	4.1	272	4.3	265	4.7	269
1987	2.5	141	2.9	152	3.5	137	2.5	140
1988	1.3	115	1.3	135	0.6	167	0.8	144
1989	4.7	81	5.2	84	5.7	88	6.0	87
1990	7.6	114	7.9	115	8.4	114	7.9	110
1991			5.7	71	5.9	69	5.9	59
1992			9.6	92	11.4	93	10.5	90
1993	8.3	93	9.1	100	9.6	93	8.6	90
1994	2.0	83	2.1	97	3.5	105	2.5	107
1995	2.5	206	3.0	189	2.8	190	2.5	199

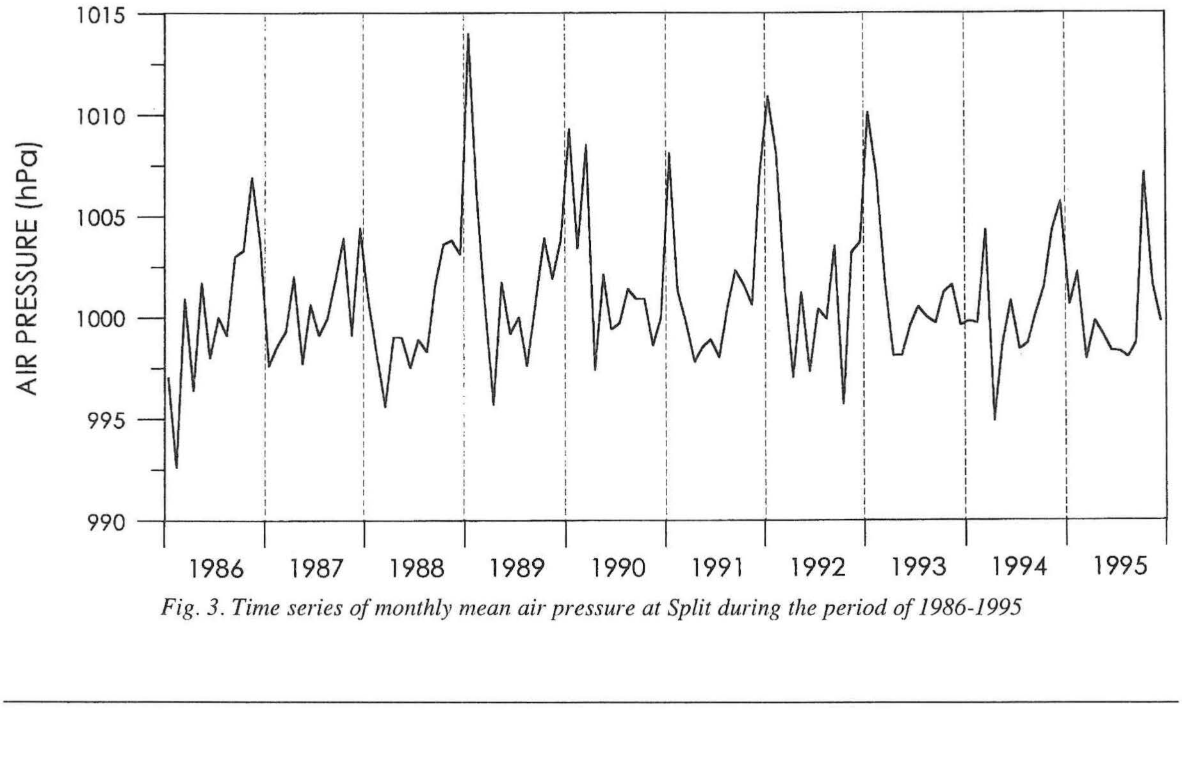

Fig. 3. Time series of monthly mean air pressure at Split during the period of 1986-1995

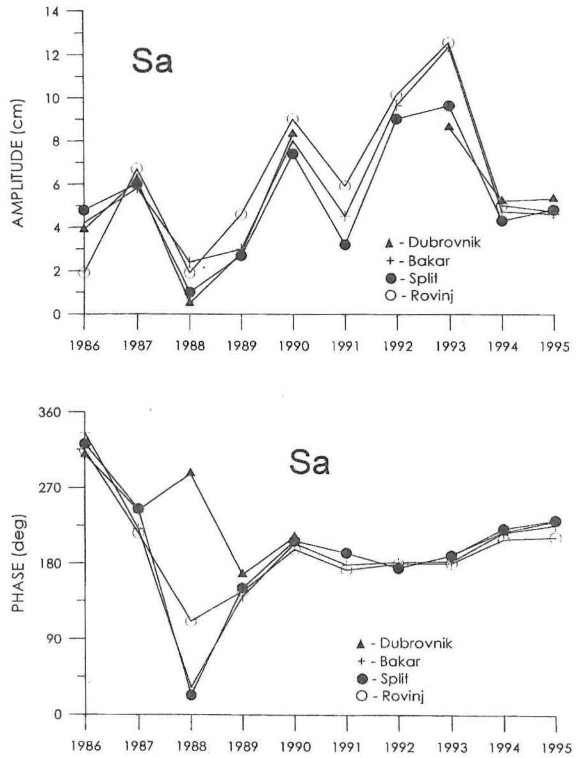

Fig. 4. Sa amplitudes and phases at Dubrovnik, Split, Bakar and Rovinj during the period of 1986-1995

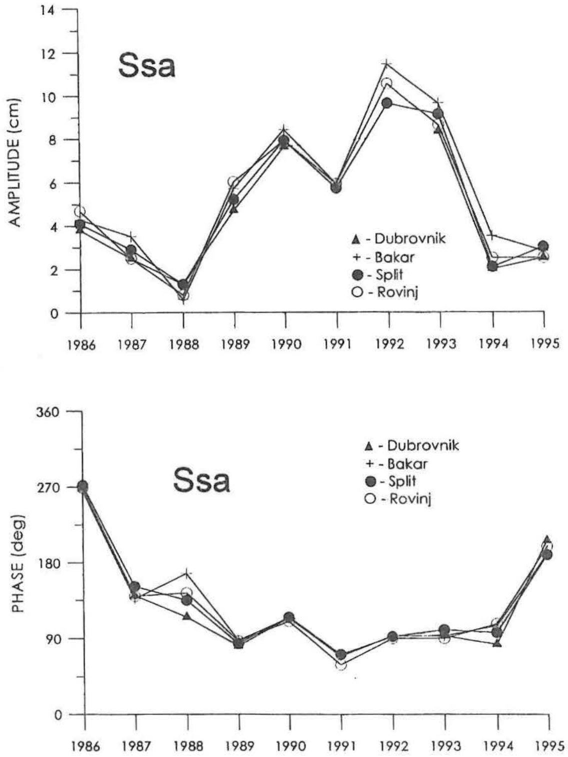

Fig. 5. Ssa amplitudes and phases at Dubrovnik, Split, Bakar and Rovinj during the period of 1986-1995

most often between 80° and 150°, so the maxima of the Ssa tide occur in March to May and September to November. The minima are situated in December-February and June-August. However, in 1986 and 1995, the phases were out of the usual values, they are about 270° and 190° in 1986 and 1995, respectively.

The well-known fact that air pressure influences sea level by inverse barometer law leads to the examination of its influence on Sa and Ssa tides. A way to do this is to examine the annual differences in air pressure, which can be the generator of Sa cycle variations. The parameter can be defined in the following way:

$$\mathbf{p}_d = \mathbf{p}_2 + \mathbf{p}_3 + \mathbf{p}_4 - \mathbf{p}_{10} - \mathbf{p}_{11} - \mathbf{p}_{12}$$

where **p** is the monthly mean air pressure where subscripts mark the months. This parameter will be correlated to the Sa amplitude in such a way that the amplitudes when opposite phases occurred (in 1986 and 1988) are assumed to be negative. The correlation diagram for Split is plotted in Fig. 6. The correlation coefficient is 0.9, which is significant for 99 % interval. Such a high value of the correlation coefficient leads us to conclude that air pressure is predominant process which influence the behaviour of the Sa tide in the Adriatic. It can be calculated from the linear fit that the Sa tide will disappear if the difference between air pressure in the periods February-April and October-December reaches the value of 6.8 hPa. On the contrary, if there is no difference, the Sa amplitude would have the value of 6.0 cm. So, the contribution of steric effect and evaporation minus precipitation over the Adriatic to the Sa amplitude is exactly 6.0 cm.

The Ssa tide also depends on air pressure variations. High air pressure during winter and low air pressure during autumn occurred in the period of 1989-1993. Consequently, a sharp change in sea level can produce an enlargement in amplitude of the higher harmonics of the Sa, especially of the first one (Ssa).

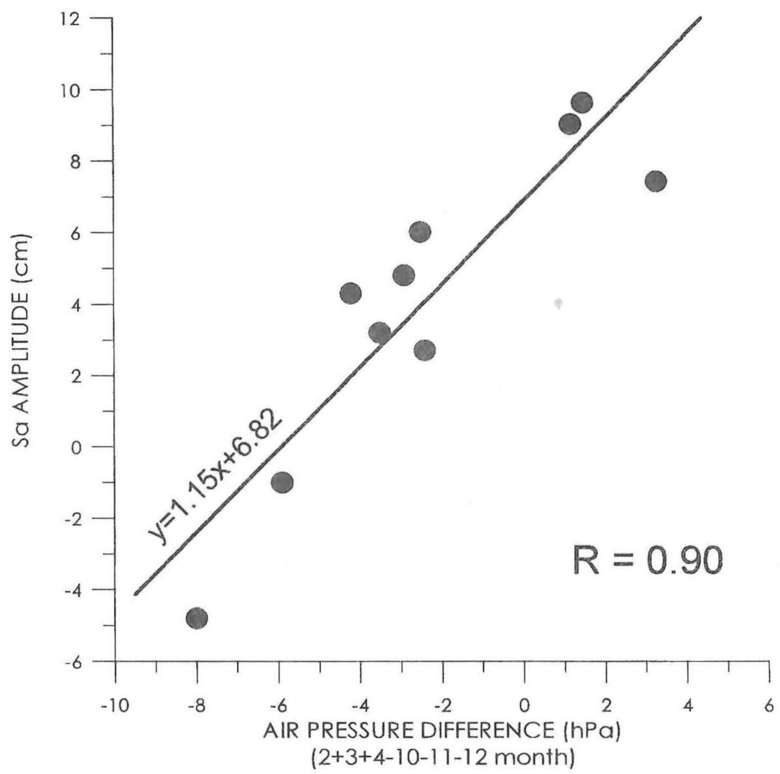

Fig. 6. Sa amplitude as the function of air pressure difference (sum of February, April and May minus sum of October, November and December). The correlation coefficient R equals 0.90

CONCLUSIONS

Annual Sa and semiannual Ssa tides are examined in this paper over a 10-year period (1986-1995). A portion of this period is characterized by stable winter situations and a decreasing sea level, while in the autumn sea levels are higher than in the forty-year period of sea level measuring. Consequently, the amplitudes and phases show very notable year-to-year variability, with higher values during the period of anomaly (1989-1993). The maximum Sa value is about 13 cm, while Ssa amplitude can reach up to 12 cm. Amplitudes are usually higher in the North Adriatic (Rovinj and Bakar); about 20 % higher in average than in the South Adriatic (Split and Dubrovnik). The Ssa amplitude is approximately the same in the entire Adriatic. The Sa tide usually reaches a maximum in the period July-September, while the maxima of Ssa tide commonly occur in March to May and September to November. However, in some years the Sa phases can change oppositely, or with any other value depending on the generator of the tides. Despite a small gravitational influence on the tides, they are primarily generated by steric effect, atmospheric forcing (air pressure) and evaporation minus precipitation influence. Assuming that the first and the last processes have a rather regular annual cycle, the correlation between air pressure and the tides is calculated. The correlation coefficient between Sa amplitude and air pressure has very high values, meaning that the interannual variations of Sa amplitude is directly forced by air pressure. Furthermore, the contribution of processes other than air pressure forcing is calculated with a value of 6.0 cm.

REFERENCES

BELL, C., I. VASSIE and P. WOODWORTH. 1996. Tidal analysis software kit. Proudman Oceanographic Laboratory, Bidston, 15 pp.

JENKINS, G.M. and D.J. WATTS. 1968. Spectral analysis and its applications. Holden Day, 532 pp.

LARNICOL, G., P-Y. LE TRAON, N. AYOUB and P. DE MEY. 1995. Mean sea level and surface circulation variability of the Mediterranean Sea from 2 years of TOPEX/POSEIDON altimetry. J. Geophy. Res., 100, C12: 25163-25177.

LEDER, N. 1988. Storm surges along the east coast of the Adriatic sea. Acta Adriat., 29 (1): 5-20.

MOSETTI, F., F. CRISCIANI and S. FERRARO. 1989. On the relation between sea level and air temperature. Boll. Ocean. Teor. Appl., 7: 263-272.

MURRAY, M.T. 1964. A general method for the analysis of hourly heights of the tide. Int. Hydrogr. Rev., 41 (2): 91-101.

ORLIĆ, M. 1995. Vodostaj Jadranskog mora i klima. 1st Croatian Water Conference. Dubrovnik, Book I: 553-559.

ORLIĆ, M. and M. PASARIĆ. 1994. Vodostaj Jadranskog mora i globalne klimatske promjene. Pomorski zbornik, 32/94: 481-501.

PALMER, T.N. 1986. Gulf stream variability and European climate. Meteorological Magazine, 115: 291-297.

PASARIĆ, M. and M. ORLIĆ. 1992. Response of the Adriatic Sea level to the planetary-scale atmospheric forcing. Geophysical Monograph, 69, IUGG 11: 29-39.

PUGH, D.T. 1987. Tides, surges and mean sea level. John Wiley, Chicester, 472 pp.

SHUREMAN, P. 1941. Manual of harmonic analysis and prediction of tides. US Dept. of Commerce, Coast & Geodetic Survey, Special Publication, 98, 317 pp.

SUPIĆ, N. and M. ORLIĆ. 1992. Annual cycle of sea surface temperature along the East Adriatic coast. Geofizika, 9: 79-97.

VILIBIĆ, I. and N. LEDER. 1996. Long-term variations of Mediterranean Sea level calculated by spectral analysis. Oceanologica Acta, 19: 599-607.

VILIBIĆ, I., N. LEDER, A. SMIRČIĆ and Z. GRŽETIĆ. in press. Dugoročne promjene razine mora na hrvatskoj obali Jadrana, Conference on Croatian sea fisheries at the beggining of XXI Century, Split.

YUCE, H. and B. ALPAR. 1994. Water level variations in the Northern Levantine Sea. Oceanol. Acta, 17: 249-254.

ZORE-ARMANDA, M. 1991. Natural characteristics and climatic changes of the Adriatic Sea. Acta Adriat., 32 (2): 567-586.

Accepted: 30 June 1998

Varijacije Sa i Ssa plimnih komponenti u Jadranskom moru

Ivica VILIBIĆ

Državni hidrografski institut, Zrinsko Frankopanska 161, 21000 Split, Hrvatska

SAŽETAK

Rad ima za temu varijacije Sa i Ssa plimnih komponenti u Jadranu računatih iz satnih vrijednosti razine mora sakupljenih na četiri postaje u periodu 1986-1995. Amplitude i faze imaju izrazitu višegodišnju promjenjljivost, s većim vrijednostima u periodu 1989-1993. Srednje vrijednosti amplitude Sa komponente su 20 % više u sjevernom Jadranu, dok su za Ssa srednje vrijednosti uglavnom posvuda iste. Faza Sa komponente ima vrijednosti između 180° i 230°, no suprotne faze su primijećene 1986. i 1988. Generirajuće sile ovih komponenti su sterički efekt, atmosferski tlak te ciklus vrijednosti evaporacije minus oborine, no međugodišnja promjena je prvenstveno rezultat promjene tlaka zraka. Vrijednosti Sa amplitude bez uključivanja utjecaja tlaka zraka iznosi 6.0 cm.