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Seasonal sea level variations in the Adriatic

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Seasonal changes of the Adriatic Sea level, obtained by analyses of monthly sea level data measured at the Split tide gauge station in 1958-2001, are reported. The data were correlated by multivariant analysis to (1) local meteorological data on air temperature, air pressure, and precipitation, collected at the Split station and data on winds obtained from ECMWF ERA40 Reanalysis fields and (2) forcing mechanisms series (air pressure, surface heat flux, surface water flux, river runoff, winds). Surface flux data were available for only the northern Adriatic and the Po River represented all river runoff. The surface flux explains 68% of the variance in sea level while changes in local meteorological parameters explained 53%. Most of the variance was induced by changes in air pressure (32%) and heat flux (28%), while other factors did not contribute much. By determining annual (Sa) and semi-annual (Ssa) cycles, the explained variance increased to 88% for Sa tide and 95% for Ssa tide; changes were caused mostly by changes in air pressure (about 50% of the variance). Changes in the Sa heat flux cycle did not affect changes in the Sa tide but did affect Ssa tide (about 26% of the variance), presumably due to nonlinear effects driven by winds.

Key words: seasonal and semi-seasonal cycles, sea level, meteorological variables, surface flux, steric effect, Adriatic Sea

INTRODUCTION

Although seasonal sea level fluctuations are low compared to other forces in most of the world's seas (up to 10 cm, LISITZIN, 1974; PUGH, 1987), they play an important role in semi-enclosed and coastal areas, especially those prone to strong seasonal variations in air or sea flux. The Mediterranean Sea is such a place, and seasonal variations in sea level range up to 20 cm (LARNICOL *et al*., 1995; FENOGLIO-MARC, 2001; CAZENAVE *et al*., 2002). The seasonal signal is usually stable (PLAG & TSIMPLIS, 1999), but it may vary significantly between years as a result of air pressure, winds, steric effects, and water mass changes. With a stable climate, seasonality can be an important factor in the occurrence of extremely high or low sea levels, affecting coastal areas and infrastructure as well as navigation on the sea. The mean sea level of the Adriatic is highest in November-December (CRISCIANI *et al*., 1994), with the number of extreme sea level incidents and heights reaching their maximums in the same period (RAICICH, 2003; VILIBIĆ, 2006). The number of negative surges is greatest in February-March when the mean sea level reaches its minimum.

One of the major components of seasonal sea level fluctuation is the steric effect (IPCC, 2001), caused by strong seasonal cycles in air or sea heat flux. Changes in flux are pronounced in the Adriatic (SUPIĆ & ORLIĆ, 1999) with a maximum in the northwest (ARTEGIANI *et al*., 1997) and decreasing towards the southeast. That is the reason the annual sea level cycle (Sa tide) is strongest in the northern Adriatic, with amplitudes up to 20% higher at Rovinj and Bakar than at Split and Dubrovnik (VILIBIĆ, 1998).

Above and beyond the steric effect, air pressure forcing may either cancel or enlarge seasonal sea level variations as an increase in air pressure decreases the sea level and vice versa. The theoretical value of the so-called inverse barometric (IB) factor is modeled as -1 cm/hPa (e.g., GILL, 1982). Values computed from measurements in the Adriatic Sea are about -1.4 cm/hPa (PASARIĆ *et al*., 2000) when taken from the original sea level values, or -1.8 to -2.0 cm/hPa when estimated from sea level anomalies on a monthly scale through single regression analysis (ORLIĆ, 1995). Problems may arise from the fact that other effects (winds, heat and water fluxes, etc.) are correlated with air pressure, contributing to sea level changes and enlarging the theoretical IB factor. A study by ZERBINI *et al.* (1996) showed that sea level changes in the Adriatic are not significantly correlated with winds, but the wind effect may appear through nonlinear effects (e.g., destruction of the pycnocline or steric changes resulting from strong winds). If computations are downscaled to daily sea level values, lower values can be obtained which are closer to the theoretical value (KASUMOVIĆ, 1958; KARABEG & ORLIĆ, 1982).

The impact of surface water flux on sea level cannot be neglected. In particular, evaporation (E) and precipitation (P) may be substantial, while the influence of river runoff (R) is greater in coastal waters. ARTEGIANI *et al.* (1997) computed the annual course of water flux (P-E) for the Adriatic and detected seasonal variability; summer (May-October) P-E values are 2-3 cm/month greater than in winter, whereas R values are opposite.

In this paper, multivariant regression analysis was applied to Split sea level data from 1958-2001 and to meteorological and derived variables to quantify seasonal changes, determine the influence of forcings, and quantify the connections between annual and semi-annual cycles in the sea and atmosphere. A simple statistic approach using two data sets (including a climatological time series in the water column) was used to support the regression analyses.

MATERIAL AND METHODS

Monthly sea level data, measured at the Split tide gauge on the coast of the middle Adriatic (43°30’N, 16°26’E) in 1958-2001, were subjected to analysis. The high-quality gauge measures hourly sea levels at an accuracy of ±1 cm. Meteorological factors (air pressure, air temperature, precipitation) were observed 1 km from the tide gauge at 100 m above sea level by the Meteorological and Hydrological Service of the Republic of Croatia. Unfortunately, wind speed and direction were not measured or digitized at the station throughout the entire study period and were therefore taken from ECMWF ERA40 reanalysis fields and averaged over four grid points in the Split area. Fortunately, substitution of wind data by reanalysis data does not greatly affect regression analyses in the mid Adriatic (PASARIĆ *et al*., 2000).

The second group of analyzed variables included surface heat (Q) and water flux ($W = P$-E, where P is precipitation and E is evaporation), estimated for the northern Adriatic in 1966-2000 (SUPIĆ & ORLIĆ, 1999; SUPIĆ & VILIBIĆ, 2006) and based on bulk computations using data from coastal meteorological and SST (sea surface temperature) stations. Unfortunately, there are no such estimates for the mid Adriatic, but such computations were successfully used to analyze deep water masses in the Adriatic (e.g., VILIBIĆ & ORLIĆ, 2001). River runoff was taken from the largest river, the Po, which brings about 35% of the fresh waters to the Adriatic (RAICICH, 1996) and, although eastern Adriatic rivers have different characteristics and annual courses, is a reasonable representative of runoff and is often used in Adriatic studies (e.g., ORLIĆ *et al*., in press).

Basic non-stationary statistical (averaging and deviations) and spectral analysis (JENKINS & WATTS, 1968) was applied on time series of the variables to determine the strength of their annual and semi-annual cycles. The STATISTICA® software package was used to study multivariant linear regression between monthly sea levels as a dependant variable and two sets of input variables: (1) air pressure, NE and NW winds, air temperature, and precipitation in 1958-2001, and (2) air pressure, NE and NW winds, surface heat, water fluxes, and river discharges in 1966-2000. The first set shows the connection between local meteorological variables and the sea level; the second shows the relationships between sea level changes and forces occurring in the wider area.

In addition to the time series, seasonal (3-month) averages of temperature and salinity in the mid Adriatic during 1911-1983 (ARTEGIANI *et al*., 1997) were used to estimate the mean annual course of steric expansion of the water column and validate the multivariant regression analyses. Density averages were calculated for layers at standard oceanographic depths affected by seasonal thermal and haline changes in the middle Adriatic (0-5, 5-10, 10-20, 20-30, 30-40, 40-50, 50-75, 75-100, 100-150, 150-200 m; BULJAN & ZORE-ARMANDA, 1976). The rate of steric expansion was computed by assuming a vertical hydrostatic balance. This simple analysis includes the annual water and river fluxes ($P-E+R$) as calculated by ARTEGIANI *et al*. (1997) and averaged for the whole Adriatic. However, P and E were computed with large error bars due to the lack of open Adriatic meteorological data, while R has a spatially non-homogeneous influence that, when averaged for the whole Adriatic, incorporates quite large errors. The Split area is affected by river runoff that modifies the freshwater fluxs and haline changes in the area.

Finally, harmonic analysis (SHUREMAN, 1941; BELL *et al*., 2000) was used to extract annual and semi-annual cycles of all parameters, usually called Sa and Ssa tides in sea level analyses (DOODSON, 1921). The computations were performed on 5-year intervals to minimize bias (BLEWITT & LAVALÉE, 2002) and resulted in time series for Sa and Ssa amplitudes and phases, which were individually subjected to multivariant regression analysis. The best correlations were achieved when comparing modified Sa/Ssa sea level amplitudes (Sa/Ssa amplitude multiplied by the cosine of the Sa/Ssa phase) with equivalent amplitudes in the two data sets mentioned above.

RESULTS AND DISCUSSION

Basic relationships

The seasonal sea level cycle is easily visible with large intra-annual (Ssa) variations (Fig. 1). Air pressure and precipitation cycles share a similar structure, while seasonality is lower in the wind cycle. As expected, the air temperature series has a dominant seasonal cycle with up to 20% variability between years. As surface heat flux is dominantly driven by direct solar flux, which also drives changes in temperature, the surface heat flux cycle is similar to that of the air temperature (Fig. 2). Surface water flux is driven by precipitation, evaporation (which can be quite variable due to wind effects that are stronger in the winter), humidity, and differences between air and sea temperatures (SUPIĆ & ORLIĆ, 1999). River runoff changes seasonally due to precipitation and snow melting, and may substantially differ even between two consecutive months, with great intra-annual variations.

The sea level had a strong annual cycle with sharp jumps in some months (Fig. 3). The mean sea level in March was 2-3 cm lower than in February and April, amounting to about 20% of the total range. The difference between March and April was significant at a 95% level, more likely due to some forcing mechanism than to the sampling choices. Air pressure was relatively stable with a standard deviation of 2 hPa and dropped about 2 hPa in April. NW winds reached a maximum in March while NE winds were strongest in November (in fact,

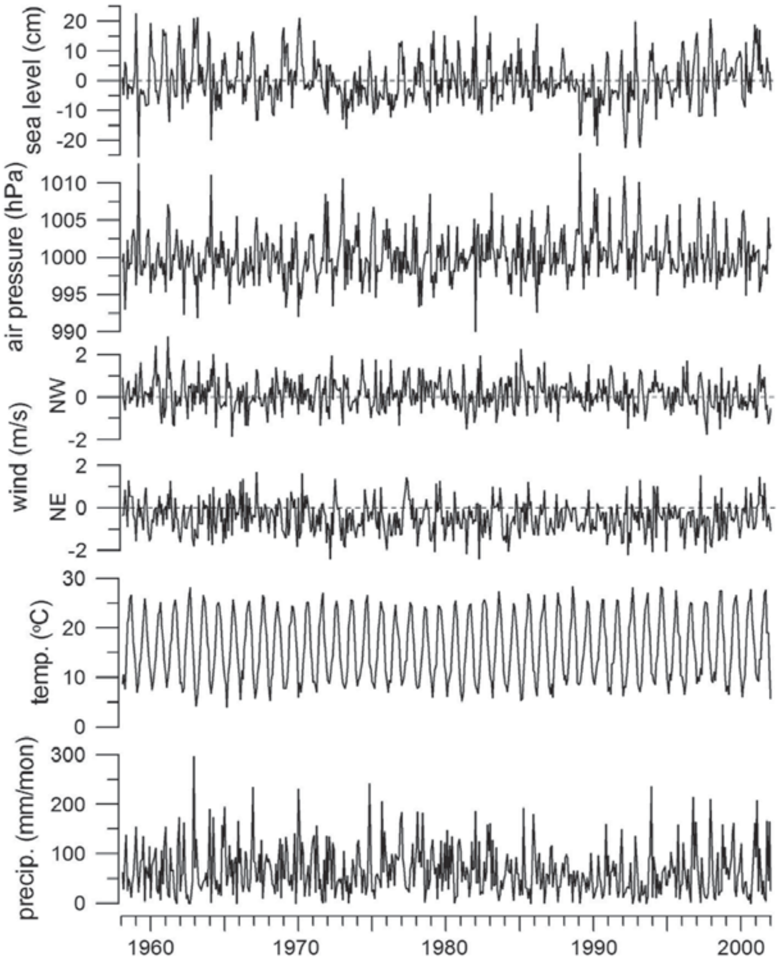

Fig. 1. Monthly mean sea level, air pressure, NE and NW winds, air temperature, and precipitation at Split in 1958-2001 (wind data taken from ECMWF ERA40 Reanalysis)

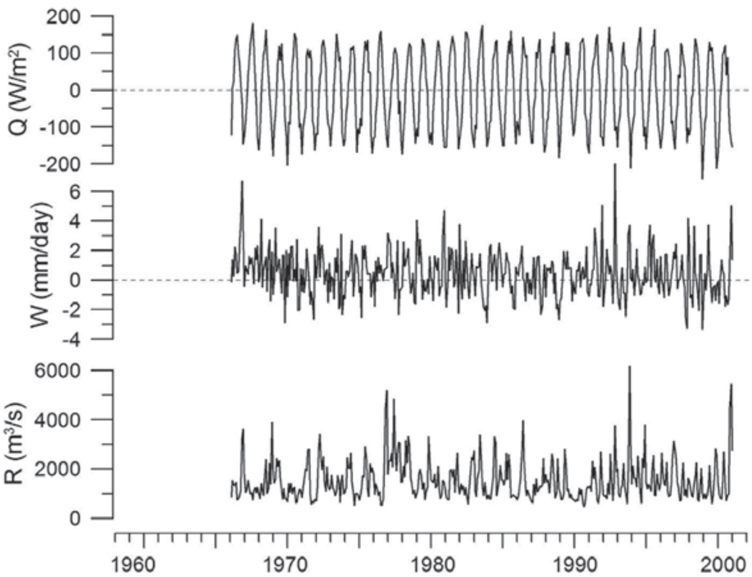

Fig. 2. Monthly mean surface heat (Q) and water (W) fluxes, computed for the north Adriatic (SUPIĆ & ORLIĆ, 1999; SUPIĆ & VILIBIĆ, 2006), and Po River discharge (R) in 1966-2000

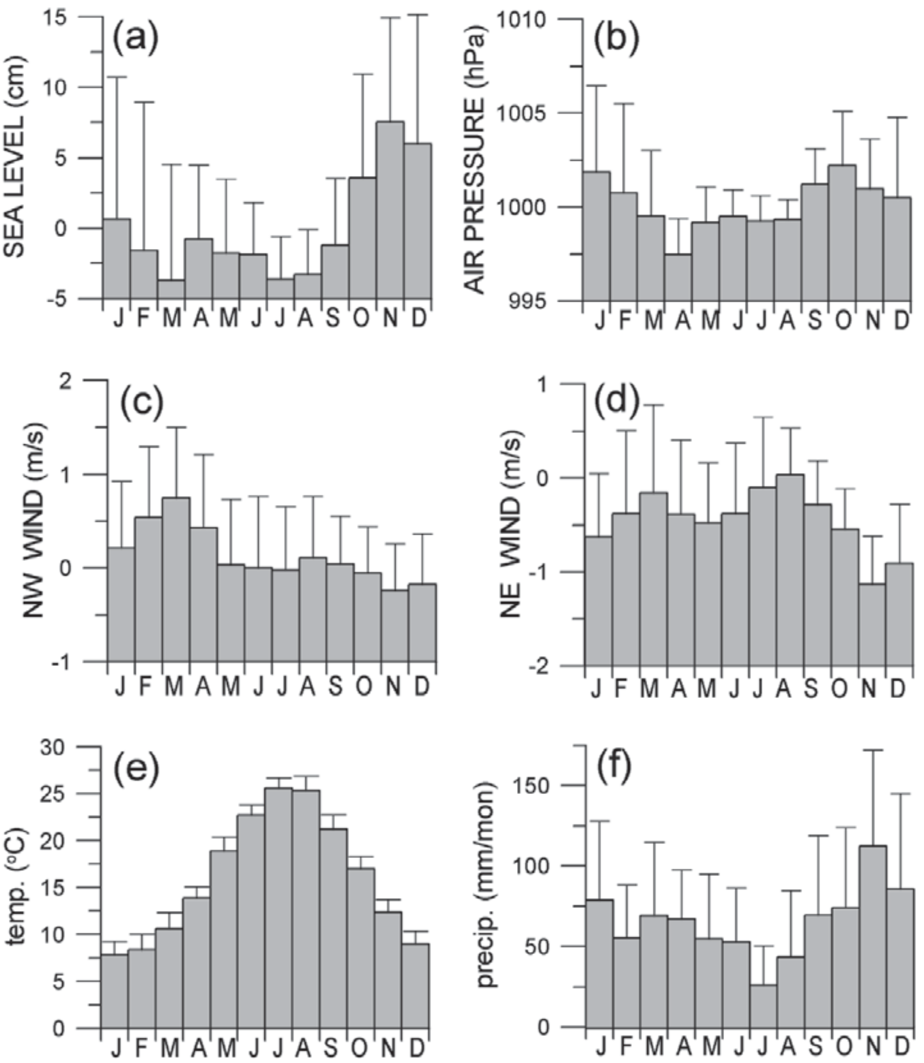

Fig. 3. Annual sea level, air pressure, NE and NW winds, air temperature, and precipitation (means± standard deviations)

negative, i.e., SW). Temperature and surface heat flux (Fig. 4) were greatest in June/July, with a well-developed annual cycle, whereas precipitation, river runoff, and surface water flux were lowest in high summer (July), and had the greatest Sa and Ssa variations.

Simple regression analysis

Fig. 5 shows the preliminary analysis of sea level using the air pressure time series as the only input since it is more conservative and uniform in space than other parameters (winds vary in eastern coastal Adriatic areas). The air pressure series includes the effects of winds and, to some extent, water flux, two factors that are analyzed separately below. This simple analysis quantifies the strength of steric effects by using departures (anomalies) from the mean annual cycle to compute the IB factor of -1.94 cm/hPa, close to that obtained by ORLIĆ (1995).

The reason for such a large IB is that other processes induced by temporal and spatial air pressure variations, such as winds associated with atmospheric systems, may induce changes in sea level and therefore presumably correlate with air pressure. Water flux (*P-E+R*) can also influence sea level anomalies, especially during extreme events such as a large rainfall in a short period, enhanced evaporation due to strong dry

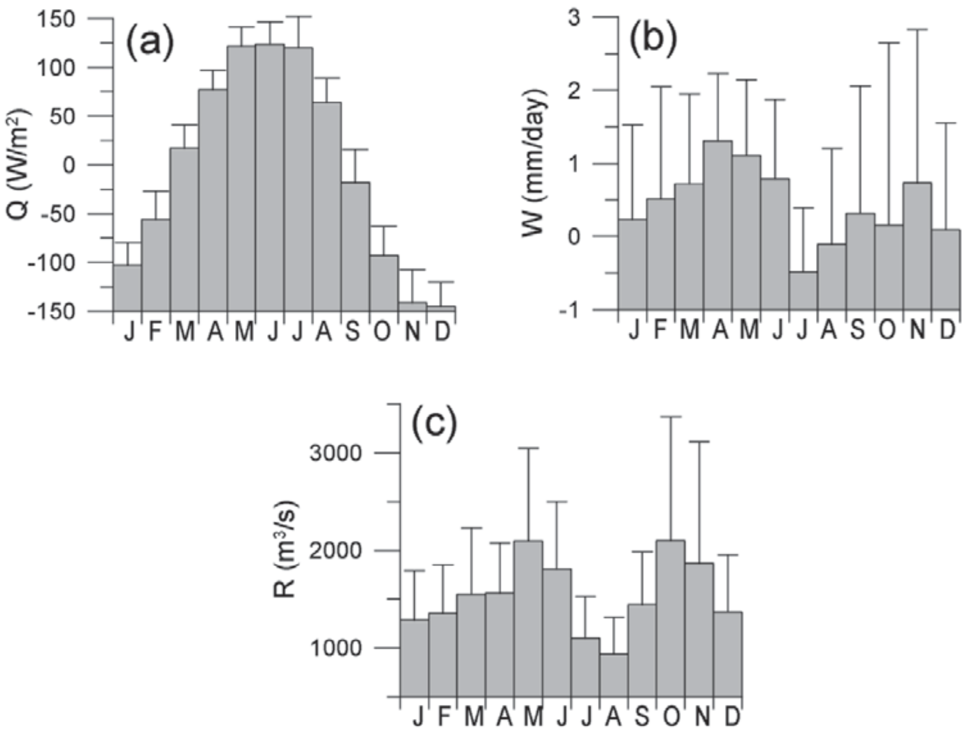

Fig. 4. Annual surface heat, water flux, and river discharge (means±standard deviations)

Bora winds, or peaks in river runoff. However, it is impossible to separate these influences within the 2IB factor, so they are treated as a unified effect. In contrast, the steric effect is presumably incorporated in the mean annual sea level cycle as changes in the surface heat flux cycle do not greatly differ between years (SUPIĆ & ORLIĆ, 1999).

The major difference between Figs. 5a and 5c is the strength of the seasonal cycle, which is greater after 2IB correction. Another difference is the behavior of the sea level in March and April: the level is higher in April when IB correction is applied but lower when using 2IB correction. The latter seems more logical as sea heating in April is not strong enough to reverse the annual course.

Correction for *P-E+R* (ARTEGIANI *et al*., 1997) was applied to the series already corrected with the 2IB factor by subtracting the monthly *P-E+R* values (i.e., differences from the annual mean) from the sea levels (Fig. 5d). Annual *P-E+R* cycles affect sea levels with a lag due to the time required for adjustment of the water to forcings, similar to the steric effect and its adjustment to surface heat forcing. However, strong irregular month-to-month changes and advection effects presumably lower the response lag. The Adriatic opens to the Mediterranean and water imbalances are compensated for through the Otranto Strait. Therefore, qualitative analysis was performed by adjusting *P-E+R* values for lags (that may be 0-3 months long) and a lag of one month was chosen. The cycle reaches its minimum in April/May, 1-2 months after the sea begins to absorb heat at the surface, usually in late February/early March (SUPIĆ & ORLIĆ, 1999). Therefore, the lag in steric effect, which increases the sea level due to thermal expansion, is 1-2 months, characteristic to enclosed mid-latitude seas such as the Adriatic. After that, the corrected sea level cycle increases from May to October due to thermal expansion; the sharp jump in October is presumably due to destruction and deepening of the pycnocline (BULJAN & ZORE-ARMANDA, 1976; ARTEGIANI *et al*., 1997).

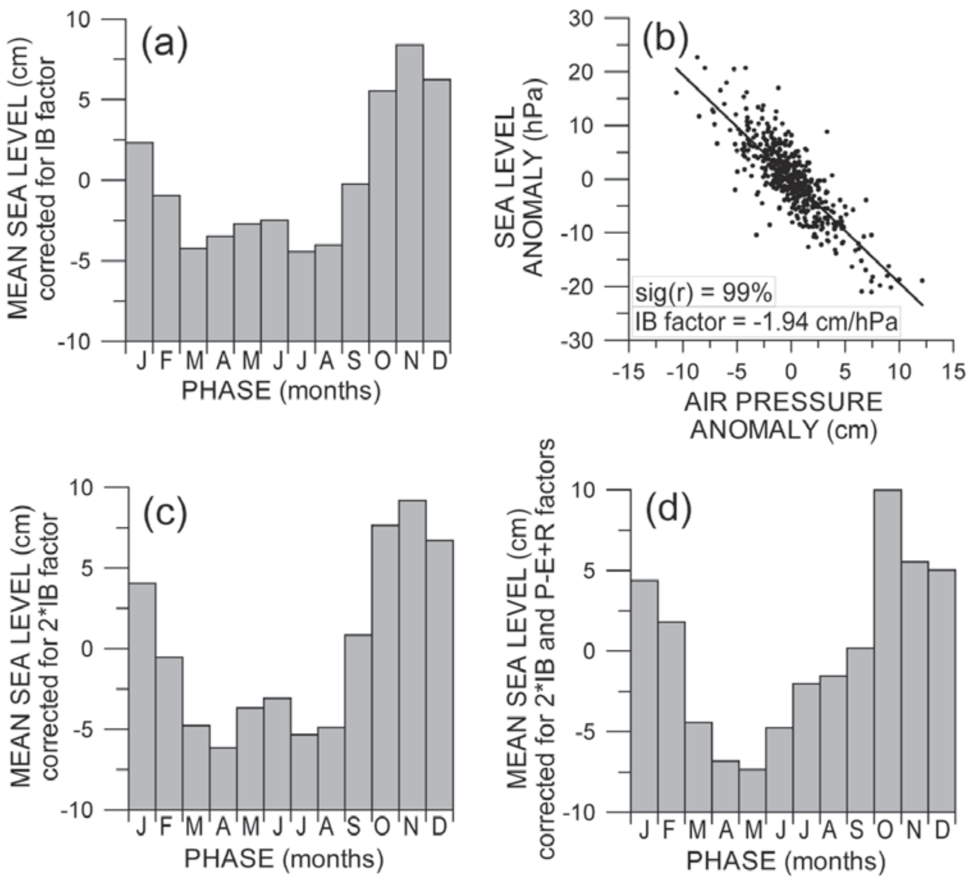

Fig. 5. Annual sea level at Split (a) corrected for inverse barometric (IB) factor, (b) in relation to air pressure anomalies, (c) corrected for 2 x IB-factor, and (d) corrected for 2 x IB-factor and P-E+R (ARTEGIANI et al., 1997)

Most of the rest of the given signal in Fig. 5d is assumed to be the result of steric expansion. The rate of steric expansion is calculated from seasonal (3-monthly) averages of temperature and salinity in the mid Adriatic (ARTEGIANI *et al*., 1997), computed for 1911-1983. Density averages were calculated for layers at standard oceanographic depths (0-5, 5-10, 10-20, 20-30, 30-40, 40-50, 50-75, 75-100, 100-150, 150-200 m) affected by seasonal thermocline changes in the mid Adriatic. Finally, the rate of steric expansion was computed by assuming vertical hydrostatic balance.

There was a major steric difference of 8 cm between autumn (October-December) and winter (January-March). The mean range of steric expansion rates is somewhat lower than estimated from Fig. 5d, where it equals about 13 cm. Conclusively, the annual sea level cycle, corrected for the 2IB factor and *P-E+R*, incorporates other dynamics that are probably related to regional processes in the Split area such as seasonal changes of salinity (resulting from river runoff) and isolation from open waters.

We roughly estimated seasonal sea level changes that result from local haline influences by assuming that salinity is constant throughout the open sea but varies within a range of 2 ppt in the coastal area of Split due to precipitation and river runoff (RAICICH, 1996). Thus, the seasonal rate of sea level changes was estimated at 0.15 cm for every meter of depth in coastal waters. If the average depth of coastal waters is 40 m, the corresponding rate of haline changes is about 6 cm. As the maximum river discharge occurs in October-November in the eastern Adriatic (RAICICH, 1996), the minimum salinity usually occurs at that time. Therefore, the seasonal haline effect in coastal waters is probably greatest in November, at the same time that the seasonal thermal effect is greatest. The result is a larger seasonal thermal+haline signal in coastal waters than in the open sea, driven by regional haline variations due to seasonal inputs of fresh water.

Multivariant regression analysis

Two sets of input (independent variables) were used in the multivariant linear regression analysis to quantify changes in the sea level as an output (dependant variable). First we correlated the monthly sea level series to the air pressure, NW (longitudinal) and NE (transversal) winds, air temperature, and precipitation series. Regression coefficients, normalized regression coefficients, partial correlations, and variance are given in Table 1. All input variables were significant at a 95% level. Most of the sea level variance can be explained by air pressure (29.6%) and precipitation (15.1%) changes, while wind and air temperature changes had little effect. Inverse barometric factors dropped to -1.19 cm/hPa, relatively close to the theoretical value. Precipitation changes probably correlated with local river runoff and together reach a rate of 5.3 cm/100 mm, close to the rough estimate of the local haline effect (6 cm) in the simple statistical analysis above. Together, all variables explain only 53% of the variance, but one should keep in mind the effects of physical processes that are not fully captured in the above basic meteorological variables and the effects of processes in the wider Adriatic region that are superimposed onto local effects.

The second set of variables (air pressure, NW and NE winds, surface heat and water flux, river runoff) describe physical processes in the wider area and produce a different picture (Table 2). Again, most of the sea level variance can be explained by air pressure changes (32.6%), but the regression coefficient (or IB factor) was higher (-1.57 cm/hPa) than with the first set of variables. An important factor is surface heat flux changes (explaining 28.8% of the sea level variance), which act dominantly through steric expansion of the water column. The regression coefficient of -0.04 cm/W/m^2 results in about 11 cm per 270 W/m^2 (annual heat flux change, see Fig. 4a) which, again, is similar to the estimate obtained by simple regression analysis. Together, water flux and river discharge explain about 7% of the variance, but they do not represent local effects since *W* was computed for the north Adriatic and *R* refers to Po River discharge. Presumably, this is the reason the explained variance, although higher than in the previous multivariant analysis, is not so high (68%). It may be possible to improve this value by introducing local processes that were not captured by the above variables.

Inter-annual variations of annual and semi-annual cycles

The strength of annual and semi-annual cycles was illustrated by applying spectral analysis to the variables (Figs. 6 and 7). The

Table 1. Regression coefficients (b), normalized regression coefficients (β), partial correlations (r_p), variance explained (Var), and multiregression correlation coefficient (R) estimated by multivariant regression analysis between monthly sea level (dependent variable) and NW and NE winds, air temperature, precipitation, and air pressure (independent variables) in 1958-2001

	b	*β*	r_p	*Var (%)*
NW wind	-1.03±0.36	-0.094±0.033	-0.125	1.6
NE wind	-1.39±0.34	-0.133±0.033	-0.174	3.0
Air temperature	-0.138±0.041	-0.115±0.034	-0.146	2.1
Precipitation	0.0534±0.0056	0.333±0.035	0.388	15.1
Air pressure	-1.187±0.080	-0.488±0.033	-0.544	29.6

R = 0.727

Table 2. As in Table 1, between monthly sea level (dependent variable) and NE wind, air pressure, heat flux, water flux, and river discharge (independent variables) in 1966-2000

	b	*β*	r_p	*Var (%)*
NE wind	-1.12±0.31	-0.101±0.028	0.176	1.9
Air pressure	-1.573±0.073	-0.671±0.031	-0.725	32.6
Heat flux	-0.0397±0.0021	-0.543±0.029	-0.681	28.8
Water flux	0.69±0.15	0.142±0.031	0.219	3.0
River discharge	0.00319±0.00061	0.150±0.029	0.250	3.9

R = 0.826

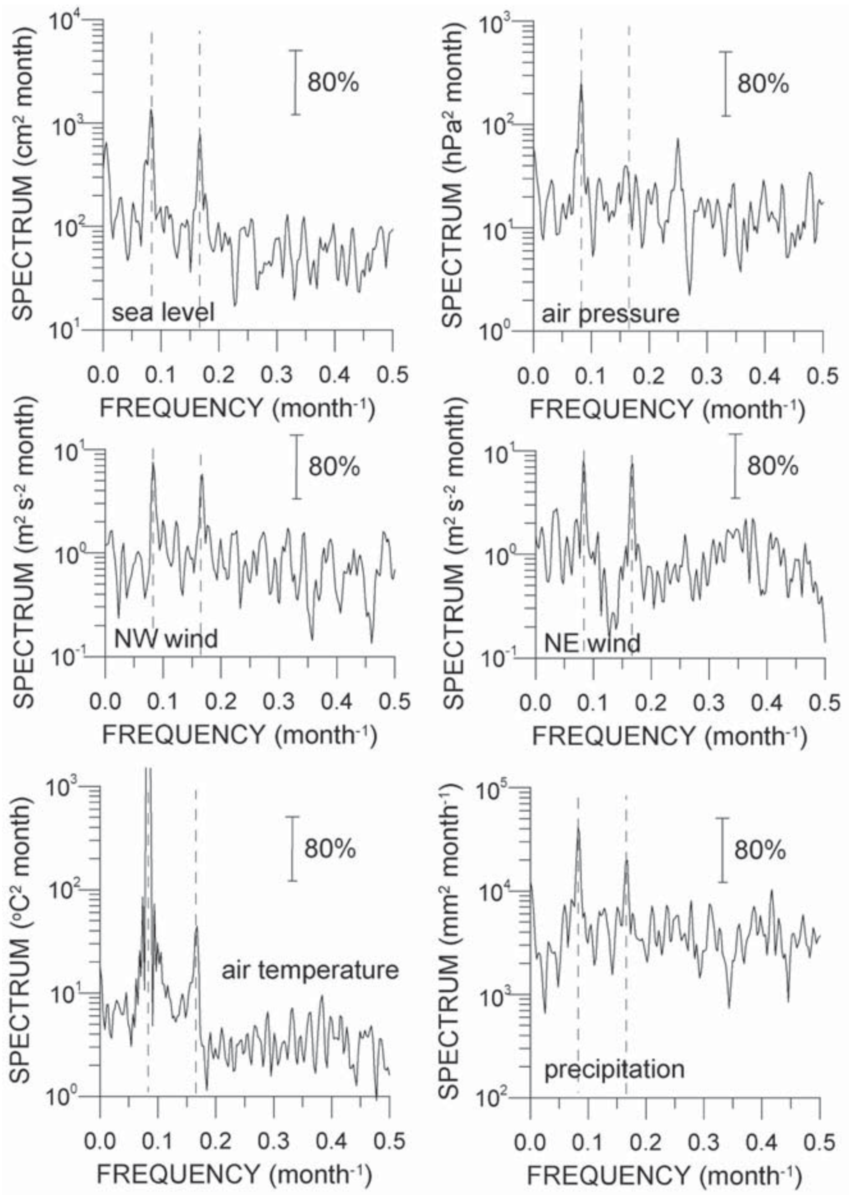

Fig. 6. Spectrum analysis of sea level, air pressure, NE and NW winds, air temperature, and precipitation at Split

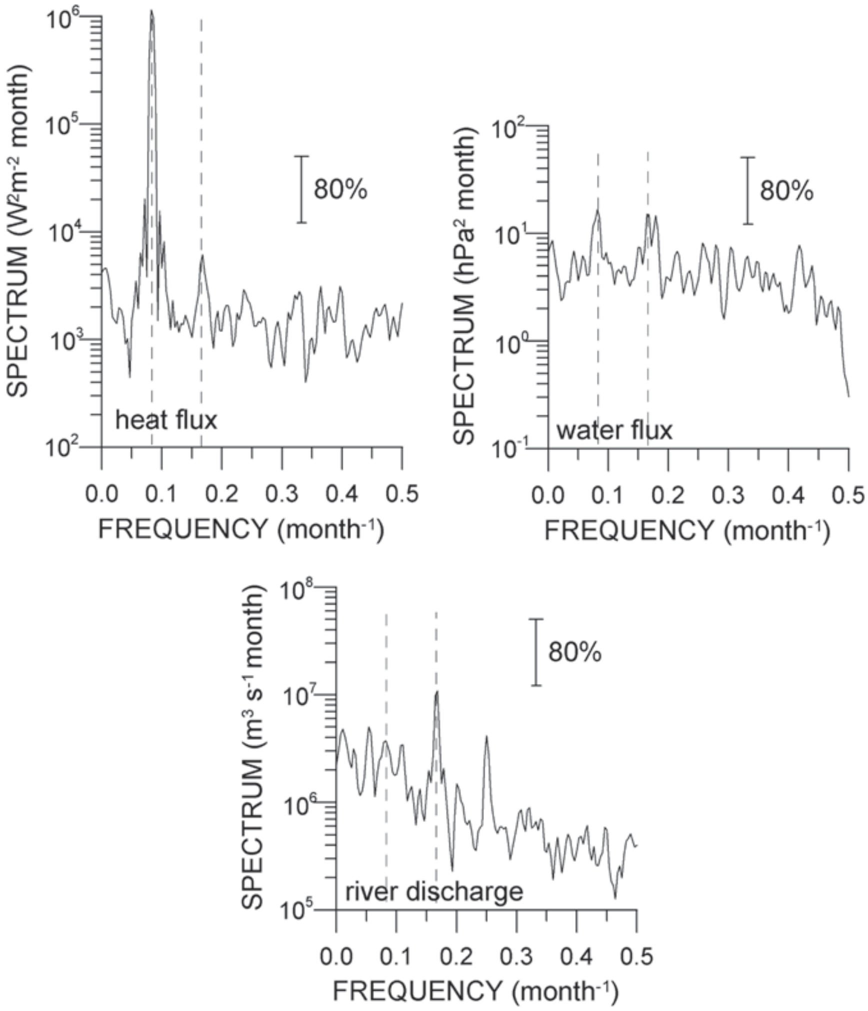

Fig. 7. Spectrum analysis of surface heat, water flux, and river discharges

sea level spectrum contained two significant peaks, at 12 months for Sa and six months for Ssa, but the semi-annual oscillation disappeared in the air pressure spectrum, being substituted by ter-annual oscillation (four months). Together with precipitation, both wind components had significant energies at 12 and 6 months, where the Ssa cycle was somewhat lower in respect to the surrounding noise. The temperature and surface heat flux spectra were two orders of magnitude larger in the Sa cycle than in the Ssa, but both cycles were above the significance level. In contrast to the air pressure, the river runoff spectrum reached a maximum at six months but had no significant peak in the Sa period, presumably due to the two strong peaks in river discharge (RAICICH, 1996): in spring due to melting snow and in autumn due to maximum precipitation. The surface water flux had significant energy in both periods, but not as pronounced as in the other spectra.

All of the variables had significant energy in both the Sa and the Ssa periods, except air pressure in the Ssa period and river discharge in the Sa period. Therefore, to study them separately from other intra-annual oscillations, these two variables were extracted from the series by using harmonic analysis to obtain amplitudes and phases (BELL *et al.*, 2000) over 5-year intervals. The series of Sa and Ssa amplitudes and phases for all variables are found in Figs. 8 and 9 for the Sa cycle and Figs. 10 and 11 for the Ssa cycle.

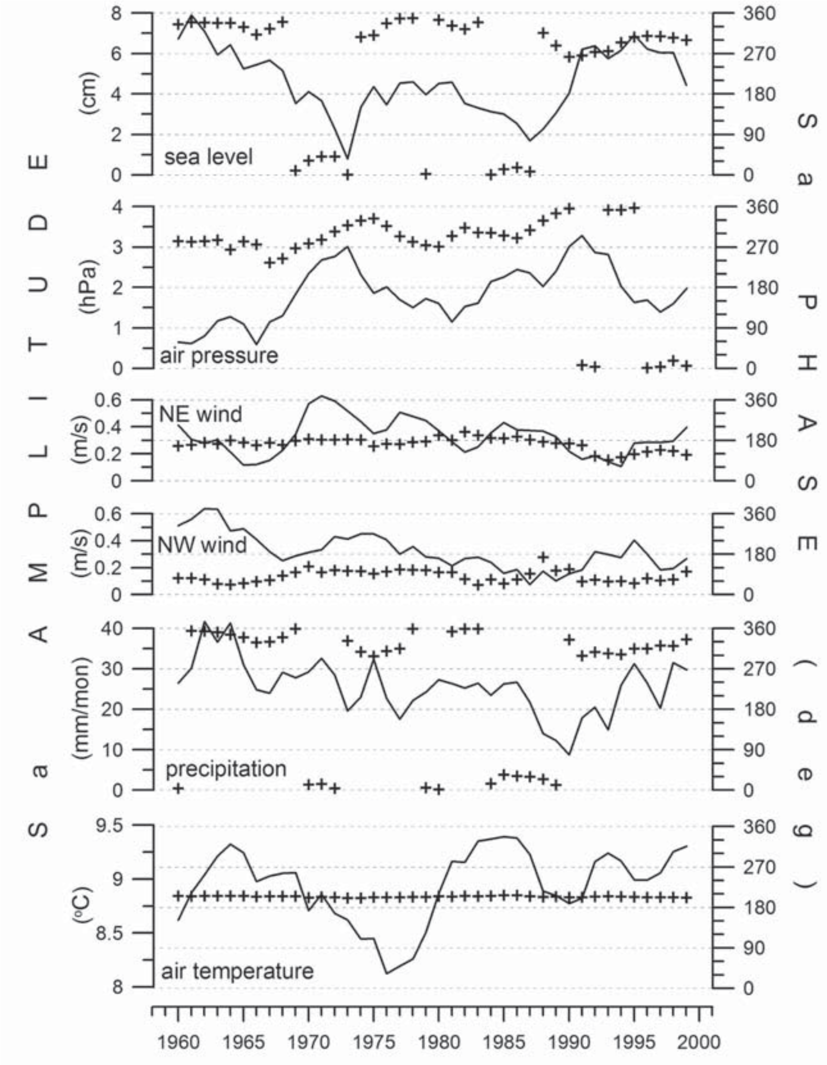

Fig. 8. Annual Sa amplitudes (line) and phases (+) of sea level, air pressure, NE and NW winds, air temperature, and precipitation at Split in 1960-1999. Computations were performed for 5-year intervals using harmonic analysis (BELL et al., 2000)

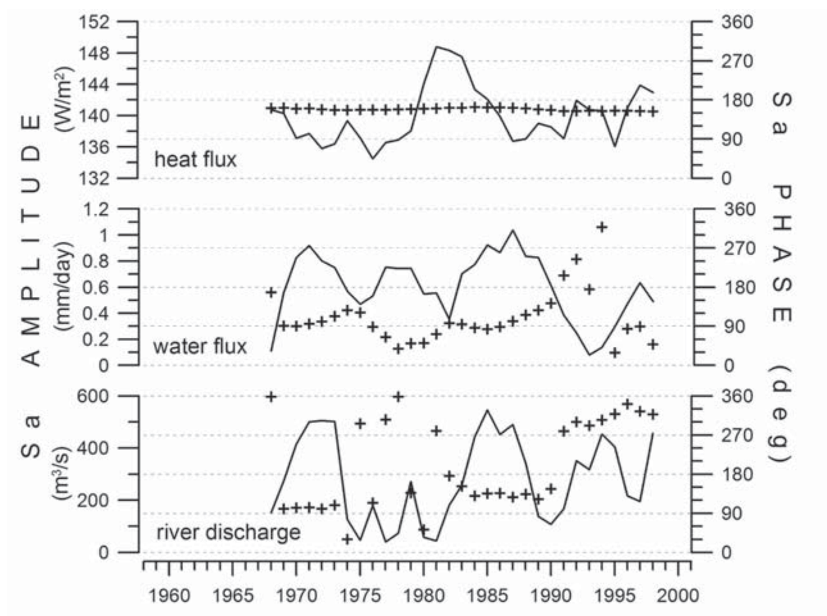

Fig. 9. As in Fig. 8, for surface heat, water flux, and river discharge in 1968-1998

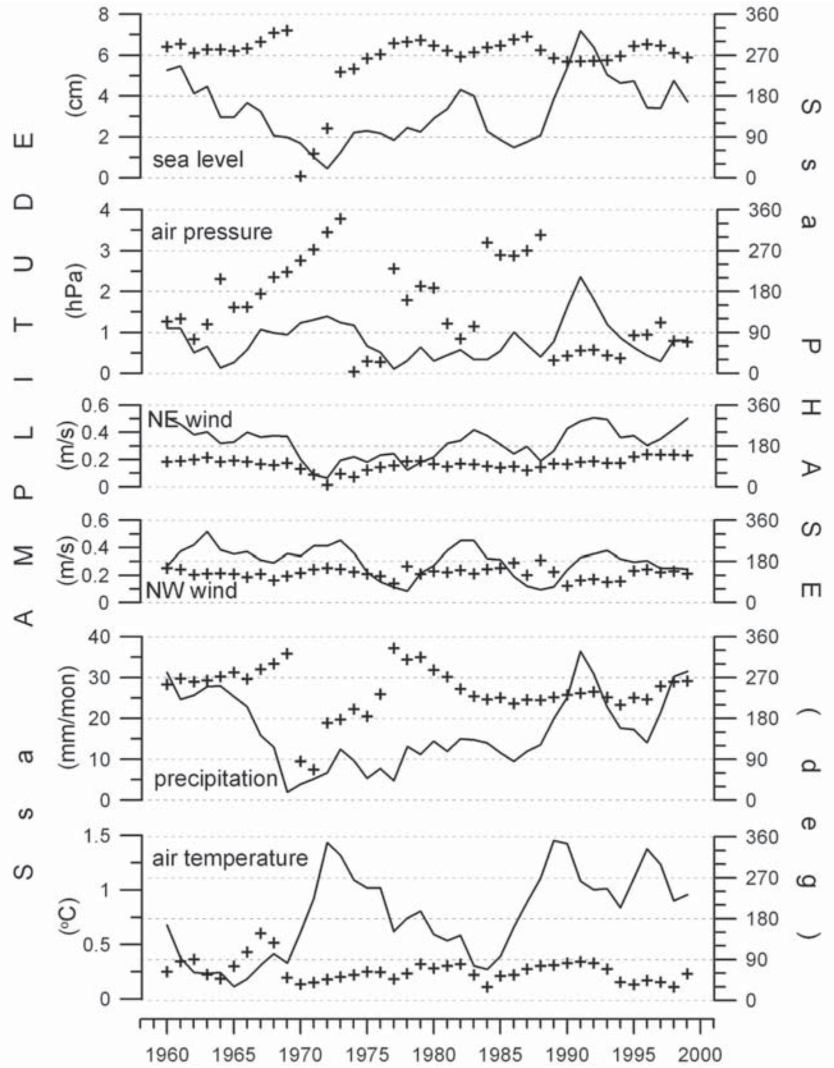

Fig. 10. As in Fig. 8, for semi-annual Ssa cycle

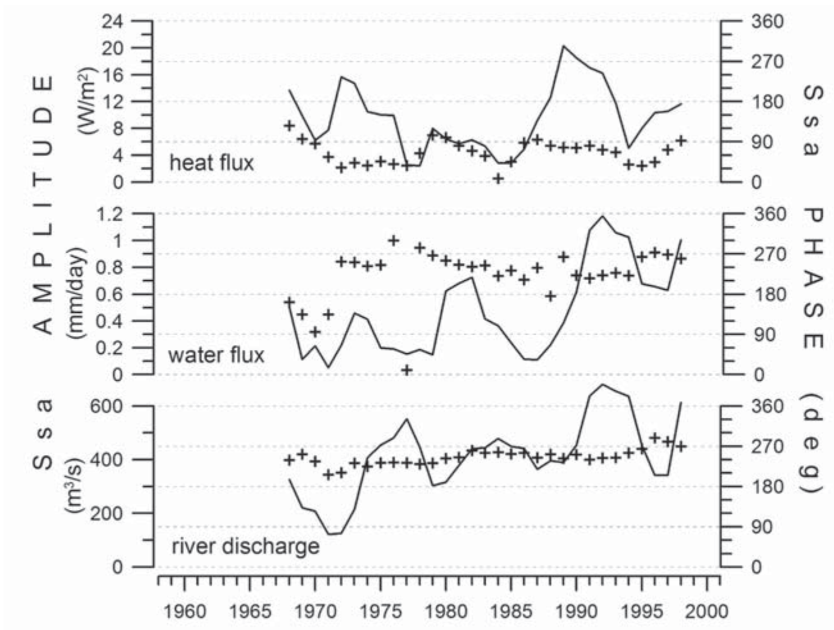

Fig. 11. As in Fig. 9, for semi-annual Ssa cycles

There were inter-annual changes in Sa amplitudes and phases particularly in water flux. (There is a similar change in river discharge but this variable was insignificant, as shown in the spectrum analysis.) There was a rather large Sa amplitude variation in sea level (1-8 cm, Fig. 12a), air pressure (0.5-3.5 hPa, Fig. 12b), winds (0.1-0.6 m/s), and precipitation (10-40 mm/month), but the phases were relatively stable (the span was less than 90° for all variables). The maximum in sea level appeared in October-January (Fig. 12a), in air pressure in September-January (Fig. 12b), in NE winds in April-June, in NW winds in February-April, and in precipitation in October-January. The quite stable Sa cycles had air temperature and surface heat fluxes (maximum for air temperature in July and for surface heat flux in June), although the amplitude differed between years by about 20% for air temperature and 10% for surface heat.

Similar stability and amplitudes were found in the Ssa sea level, winds, and surface water flux as in the Sa cycle. Precipitation and surface heat flux stability were somewhat lower, while changes in the air pressure were chaotic (and insignificant in the spectrum analysis). On the contrary, river discharge was relatively stable with amplitudes of 200-650 m^3/s.

To quantify the influence of the Sa/Ssa cycles on the Sa/Ssa sea level cycle (Sa/Ssa tide), multivariant regression analysis was again applied but separately to the Sa and Ssa tides. Due to the fact that the tides differ in amplitude and phase, a new time series of modified Sa and Ssa amplitudes for input variables was constructed as $A_n = A\cos\varphi$, where A is the amplitude and φ is the phase of the Sa/Ssa cycle. This construction includes amplitude and phase characteristics in the proper relationship with respect to influence on the sea level cycle (e.g., an opposite phase lag between Sa or Ssa tide and any Sa or Ssa cycle results in lowering the tide and vice versa), so that strong correlations and variance explanations will result.

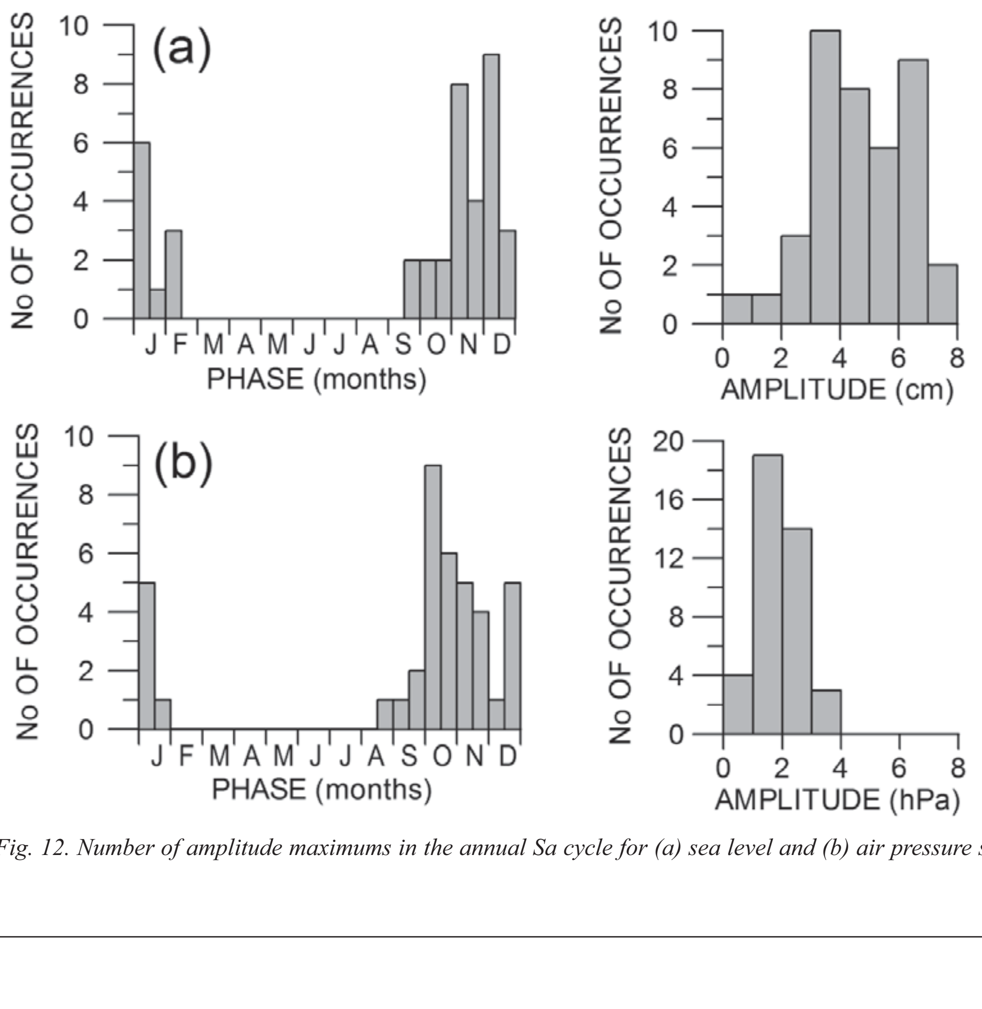

Fig. 12. Number of amplitude maximums in the annual Sa cycle for (a) sea level and (b) air pressure series

Tables 3 and 4 list regression coefficients, normalized regression coefficients, partial correlations, and sea level variance explanations for the Sa cycle variables significant at a 95% level. Again, annual air pressure cycles played a major role in the Sa tide with IB factors near the theoretical values, -0.95 cm/hPa (Table 3) and -1.14 cm/hPa (Table 4). Unexpectedly, changes in the annual surface heat flux cycle did not affect the Sa tide, probably because of nonlinear effects with other parameters (e.g., winds) that strongly affect the intra-annual steric cycle (destruction of the pycnocline usually happens only in September-November). Again, better correlation was reached when using the set of variables that describe physical processes (Table 4), where three significant variables (air pressure, water flux and river discharge) explain about 88% of the Sa tide variance.

The semi-annual Ssa tide was even better explained by local and physical variables (Tables 5 and 6). Four local variables (air pressure, NE wind, precipitation, and air temperature) explain about 91% (Table 5) of the Ssa tide variance, even more (95%; Table 6) when using the Ssa cycle of air pressure and river discharge. The Sa heat flux cycle explains almost 26% of the Ssa tide, supporting the conclusion reached earlier, that there is a nonlinear effect between annual heat flux cycle and other parameters. Although insignificant in the spectrum analysis, the Ssa air pressure cycle explains most of the Ssa tide. IB factors in both regression analyses were high (-2.31 and -1.55 cm/hPa), underlining the nonlinear generation of Ssa tide and effects that cannot be resolved by linear multivariant regression analysis.

Table 3. As in Table 1, between modified Sa sea level amplitude (dependent) and modified Sa amplitudes of air pressure, precipitation, and air temperature (independent) in 1960-1999

	b	β	r_p	*Var (%)*
Air pressure	-0.95±0.20	-0.525±0.113	-0.622	31.8
Precipitation	2.2±1.5	0.184±0.128	0.413	14.1
Air temperature	2.35±0.67	0.341±0.098	0.514	21.7

R = 0.822

Table 4. As in Table 1, between modified Sa sea level amplitude (dependent) and modified Sa amplitudes of air pressure, surface water flux, and river discharge (independent) in 1968-1998

	b	β	r_p	*Var (%)*
Air pressure	-1.14±0.14	-0.743±0.092	-0.841	50.1
Water flux	-1.45±0.52	-0.261±0.093	0.475	16.0
River discharge	0.00201±0.0059	0.260±0.076	0.550	21.4

R = 0.936

Table 5. As in Table 1, between modified Ssa sea level amplitude (dependent) and modified Ssa amplitudes of air pressure, NE winds, precipitation, and air temperature (independent) in 1960-1999

	b	β	r_p	*Var (%)*
Air pressure	-2.31±0.25	-1.462±0.159	-0.875	44.9
NE wind	2.47±0.92	0.292±0.109	0.465	12.7
Precipitation	-0.044±0.015	-0.349±0.119	0.497	14.5
Air temperature	-0.141±0.039	-0.440±0.123	0.575	19.4

R = 0.956

Table 6. As in Table 1, between modified Ssa sea level amplitude (dependent) and modified Ssa amplitudes of air pressure and river discharge and modified Sa amplitude of surface heat flux (independent) in 1968-1998

	b	*β*	r_p	*Var (%)*
Air pressure	-1.548±0.083	-0.980±0.053	-0.963	47.3
Heat flux (Sa)	0.054±0.010	0.268±0.051	0.710	25.7
River discharge	0.00197±0.00044	0.215±0.048	0.651	21.6

R = 0.973

CONCLUSIONS

The importance of seasonal changes in the Adriatic sea level, especially annual and semi-annual cycles (Sa and Ssa tides), was quantified by analyzing monthly data from the Split tide gauge in 1958-2001 together with two sets of parameters: (1) air pressure, winds, air temperature, and precipitation as measured close to the tide gauge and (2) air pressure, winds, surface heat, water flux, and river runoff in the broader area. Among the first set of parameters, the outcome of multivariant regression analysis showed the importance of air pressure (30% variance explained) and precipitation (15%) on sea level changes while the other parameters did not contribute much to the variability. Using the second set of parameters, such analysis showed that air pressure (33%) and steric (29%) changes primarily affected the sea level while surface water flux, river runoff, and winds were of lesser importance.

The sea level had two minimums: a sharp one in March with strong inter-annual variability (high variance) and a more stable one in July/August. When air pressure correction was applied, the first minimum moved to April/May (as a result of the steric shrinking of the water column during winter) and the maximum in October increased. Simple estimates reached by using seasonal (3-month) climatological thermohaline data produced an average rate of steric expansion of 8 cm, similar to results of the multivariant regression analysis where average steric expansion induced by surface heat flux was about 11 cm per year.

Year-to-year computations of the annual (Sa) cycle show that the moderate inter-annual variability of the sea level was induced primarily by the air pressure cycle (50% variance explained), but also by the less stable cycles of surface water flux (15%) and river discharge (21%). The amplitude of the annual sea level cycle (Sa tide) over 5-year intervals was as low as 1 cm and high as 8 cm, with a mean value of 4.6 cm, whereas the maximum amplitude of air pressure was 4 hPa, with a mean amplitude of 1.9 hPa. Changes in the annual cycle of surface heat flux did not significantly affect changes in the Sa tide, but impacted the semi-annual Ssa tide (22% of the variance explained), presumably due to nonlinear coupling with winds that are dominantly responsible for rapid destruction of the pycnocline in autumn. This is probably also the reason why the IB factor between the Ssa tide and air pressure cycles was larger than expected (-2.3 cm/hPa when using the local parameters in the first set of variables and -1.6 cm/hPa when using the second set of broader physical variables). The percentage of sea level variance explained by the physical variables was relatively high (88% for the Sa tide and 95% for the Ssa tide), while the rest of the variance was probably due to the use of imprecise variables (e.g., general Adriatic winds, surface heat and water flux that was computed for north Adriatic, river discharge data from only the Po River).

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Sezonske promjene razine Jadranskog mora

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SAŽETAK

U radu su dokumentirane sezonske promjere razine Jadranskog mora, načinjene koristeći podatke mjesečnih visina razine mora mjerenih na mareografskoj postaji u Splitu u razdoblju od 1958. do 2001. godine. Koristeći multivarijantnu linearnu regresijsku analizu ti podaci su uspoređeni s: (1) lokalnim meteorološkim parametrima mjerenim na meteorološkoj postaji u Splitu (temperatura zraka, tlak zraka, oborine) i vjetrom preuzetim iz ECMWF ERA-40 meteoroloških polja, te (2) dostupnim nizovima stvarnih sila u širem području koje djeluju na površinu mora (tlak zraka, površinski protoci topline i vlage, vjetar). Iako su površinski protoci računati u sjevernom Jadranu, a rijeka Po je predstavljala sve jadranske rijeke, ovakav skup ulaznih varijabli objašnjava 68% varijance razine mora, dok lokalne varijable objašnjavaju samo 53% varijance. Najveći dio promjena razine mora je uzrokovan promjenama tlaka zraka (32% varijance) i površinskih protoka topline (28% varijance), dok preostali čimbenici ne doprinose bitno tim promjenama. Ako se promatraju samo godišnja (Sa harmonijska komponenta) i polugodišnja (Ssa harmonijska komponenta) oscilacija razine mora, tada udio objašnjene varijance raste na 88% za Sa komponentu te čak 95% za Ssa komponentu. Promjene tih ciklusa su najvećim dijelom uzrokovane promjenama tlaka zraka (oko 50% varijance). Zanimljiva činjenica jest da promjene u godišnjem ciklusu površinskih protoka topline ne uzrokuju promjene u godišnjim oscilacijama razine mora, već uzrokuju varijabilnost polugodišnje Ssa komponente (objašnjavaju oko 26% varijance), po svoj prilici zbog nelinearnih efekata uzrokovanih vjetrom koji se javljaju pri steričkom širenju stupca mora.

Ključne riječi: godišnja i polugodišnja oscilacija, razina mora, meteorološki parametri, površinski protoci, sterički efekt, Jadransko more