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Some new observations on the long-term salinity changes in the Adriatic Sea

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In order to explain salinity fluctuations in the open Middle Adriatic, the data series for station Stončica have been analyzed by the principal component technique. The results were compared to the meteorological factors. The conclusion is that salinity fluctuations in the surface layer (0-20m) were correlated with the water flux, while the intermediate layer (30-100m) responded to the pressure gradient between the northern and the southern Adriatic, which is the indication for the water advection from the Mediterranean. To describe the advection mechanism, additional attention was paid to the pressure field, analyzing frequency of cyclones and anticyclones over the larger area (from 70W-40E and 20N-80N).

Key words: salinity and temperature fluctuations, Adriatic Sea, principal component analysis, air pressure centers

INTRODUCTION

The Adriatic Sea is a small, semi-enclosed sea connected to the eastern Mediterranean via the Strait of Otranto. Its northernmost part is very shallow and under the strong influence of the North Italian rivers, especially the Po River. The middle Adriatic is deeper, reaching 280 m in the Jabuka Pit. It is separated from the southern Adriatic by the Palagruža Sill (180m depth). The southern Adriatic is much deeper, (the deepest part in the South Adriatic Pit reaches 1233 m). The transect Split-Gargano lays over the Sill, in the middle Adriatic, and is a region with a strong temporal variability of the thermohaline structure, as being exposed to the influences, both from the northern and southern Adriatic. The dynamics on the investigated transect is controlled also by the topographic effect of the Palagruža Sill (ZORE-ARMANDA and BONE, 1987). Generally, current flows from the Adriatic into the Mediterranean in the surface and bottom layers, while the Mediterranean water enters the Adriatic in the intermediate layer. In winter, in the northern Adriatic, very cold dense water is formed, which sinks to deep layers of the Jabuka Pit, and is advected across the Palagruža Sill (ZORE-ARMANDA, 1963). The area of transect is also under the influence of saltier water advected from the southern Adriatic. The most important feature of the Mediterranean waters advecting into the Adriatic (in the intermediate layer) is their high salinity (BULJAN and ZORE-ARMANDA, 1976). This high salinity is a property of the Levantine Basin, which has one of the highest salinity of the world ocean (>39 psu) (TZIPPERMAN and MALANOTTE-RIZZOLI, 1991; MORCOS, 1972). Intensification of the inflow of the Mediterranean waters, called "ingressions"

(BULJAN, 1953), results in transient salinity increase in the middle Adriatic. Since the temperature of the Levantine water is higher than that of the Adriatic water, ingressions are observed in the temperature as well (ZORE-ARMANDA, 1969a).

Different water types are observed in the middle Adriatic in different years (ZORE-ARMANDA, 1963). Northern Adriatic Water (NAW) is observed only in the bottom layer, while Levantine Intermediate Water (LIW) appears in the intermediate layer of the Palagruža Sill. Horizontal advection is subject to inter-annual variability. In years with higher air pressure gradient between northern and southern Adriatic, intermediate water with higher salinity was found. In years with lower air pressure gradient, when advection from the Mediterranean was weaker, LIW was not present but only the water from the South Adriatic Pit.

The following example point to the fact that feedback processes in the atmosphere-ocean system play an essential role in thermohaline processes and that fluctuations in the atmosphere are closely related to the thermohaline fluctuations in the sea. In the year 1963 the water from Jabuka Pit with 38.30-38.40 psu was found in deeper layers at stations near the western Adriatic coast, accompanied with very low temperature values in the bottom layer (9.0-9.9 ^{0}C). This water evidently originated from the northern Adriatic, when in winter surface water cools down, and due to its high density, reaches bottom layers of the Jabuka Pit. Temperature in deeper layers in the Adriatic rarely drops bellow 11^{0}C, and such low temperatures occur only exceptionally.

In the same year (1963) considerable air temperature drop in the Northern hemisphere was observed (NAMIAS, 1963; LAMB, 1972).

Besides atmospheric input from the northern Adriatic, atmospheric influence is observed in the middle Adriatic via ingressions. Higher salinity in the intermediate layer is the indication of stronger advection of the Mediterranean water. Relating these phenomena to atmospheric conditions, ZORE-ARMANDA (1963, 1969b) stated that the horizontal pressure gradient over the eastern Mediterranean is the most important factor enhancing the water exchange between the two basins. At the same time, the location of the Iceland cyclone and the Siberian anticyclone centers were found responsible for the pressure differences (ZORE-ARMANDA, 1969c, 1972). It was observed that such changes could be related to the conditions of a wide area of the North Atlantic and Europe (ZORE-ARMANDA, 1974).

Therefore, inter-annual salinity changes in the whole water column in the middle Adriatic depend on the three different processes: advection from the North Adriatic, advection from the South Adriatic (and/or Mediterranean) and atmospheric input.

DATA AND METHODOLOGY

The data used in this study consist of historical salinity measurements obtained from January 1961 to December 1980 (BULJAN and ZORE-ARMANDA, 1979; ZORE-ARMANDA *et al.* 1991) on the regular monthly basis at oceanographic station Stončica (Fig. 1). This was the only station with at least monthly measurements. The number of measurements per month for Stončica station is shown in Fig. 2. The data from standard oceanographic depths (0, 10, 20, 30, 50, 75 and 100m) were used.

In order to calculate horizontal pressure differences between the northern and the southern Adriatic, mean monthly air pressure data were taken from meteorological stations Trieste and Palagruža.

For the analysis of pressure conditions of a wide area, mean monthly surface maps (DEUTSCHER WETTERDIENST ZENTRALAMT) from 1956-1980 were analyzed. In the region between 70^{0}W 40^{0}E and from 20^{0}N-80^{0}N spatial grid was defined of 10^0 x 10^0 grid-point distance. Occurrence of local minimum and maximum of surface pressure centers, were

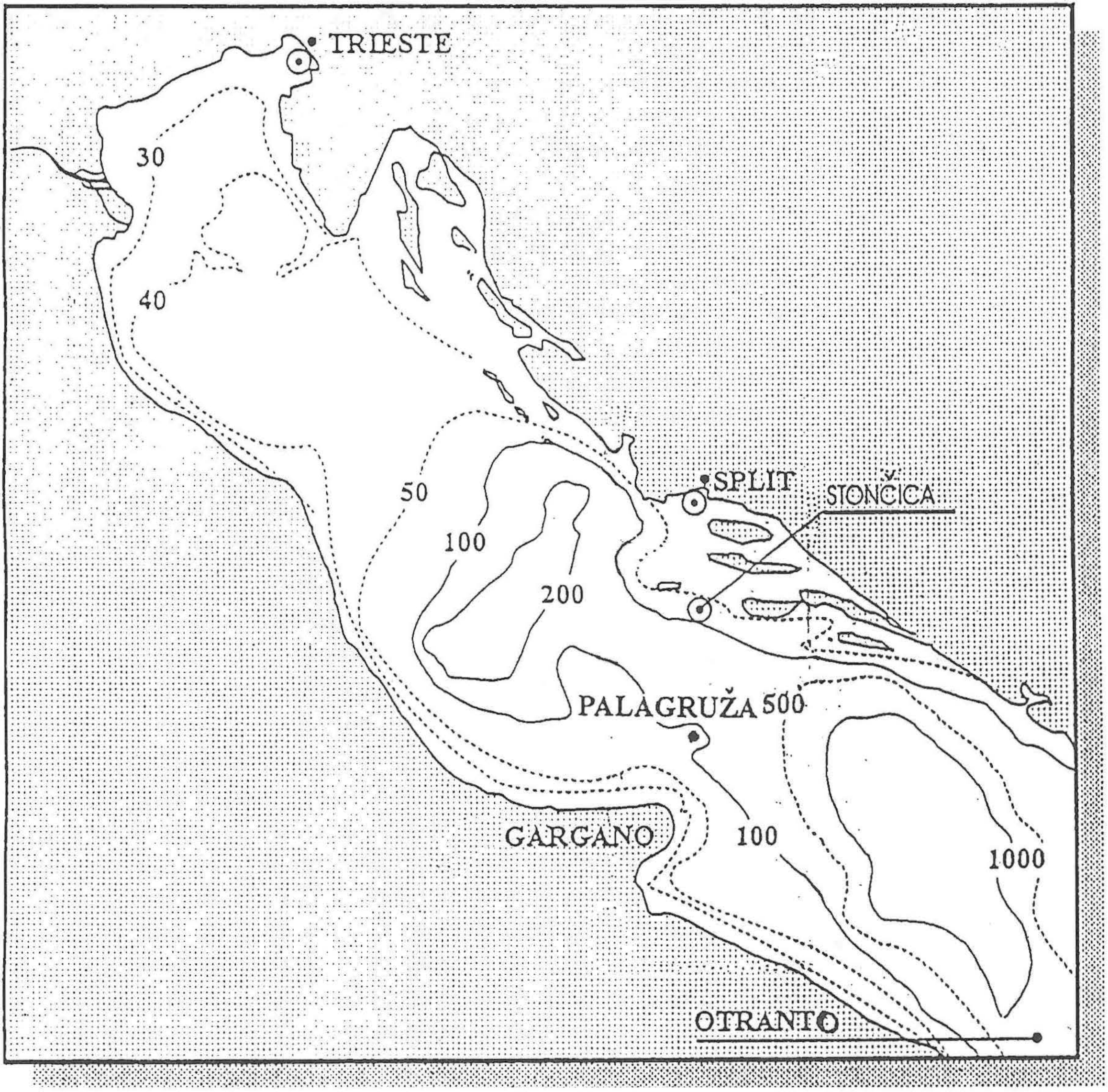
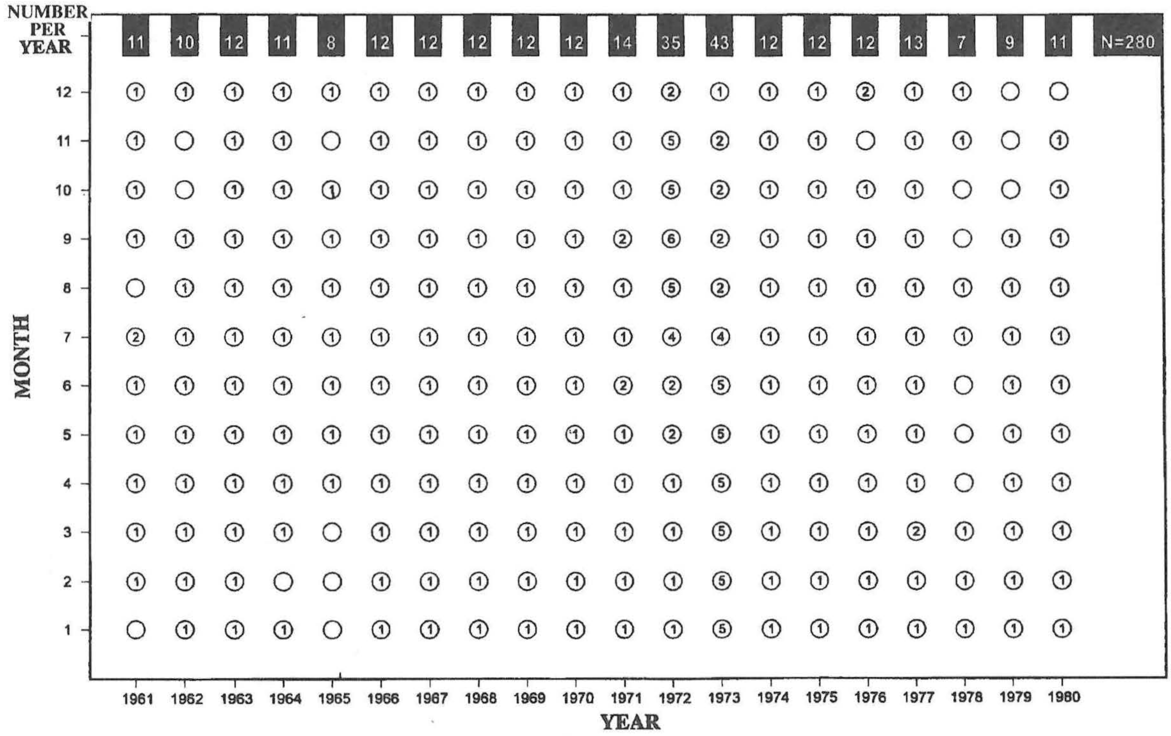


Fig. 1. The transect Split-Gargano in the middle Adriatic Sea. Meteorological station are denoted by •, while oceanographic stations are denoted by ◉

determined within such grid and their frequency counted from each monthly map in each year.

Salinity, as mentioned earlier, was measured once a month, while meteorological data were taken at least every three hours. In order to have comparable time series, the error must be determined due to under-sampling of the salinity data. The under-sampling problem was analyzed using the mean sea temperature from the period 1961-1980 at the coastal oceanographic station Split (Fig.1), which was the only station and the only oceanographic parameter measured at least daily on the middle Adriatic transect.

To obtain the under-sampling error, mean monthly sea temperature calculated from daily measurements (denoted by $\mathbf{T_{30}}$) were compared to data measured on the same dates the sea temperature was measured at Stončica station (denoted by $\mathbf{T_1}$). Maximum positive departure between $\mathbf{T_{30}}$ and $\mathbf{T_1}$ was 3.15 ^{0}C, while maximum negative departure was -2.80 ^{0}C. These considerable differences (Fig. 3) point to the fact that data should be filtered to ensure comparability of the data series at the annual scale. Moving average with n=12, applied to this dif-



MONTH	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	
NUMBER PER YEAR	11	10	12	11	8	12	12	12	12	12	14	35	43	12	12	12	13	7	9	11	N=280
12	①	①	①	①	①	①	①	①	①	①	①	②	①	①	①	②	①	①	○	○	
11	①	○	①	①	○	①	①	①	①	①	①	⑤	②	①	①	○	①	①	○	①	
10	①	○	①	①	①	①	①	①	①	①	①	⑤	②	①	①	①	①	○	○	①	
9	①	①	①	①	①	①	①	①	①	①	②	⑥	②	①	①	①	①	○	①	①	
8	○	①	①	①	①	①	①	①	①	①	①	⑤	②	①	①	①	①	①	①	①	
7	②	①	①	①	①	①	①	①	①	①	①	④	④	①	①	①	①	①	①	①	
6	①	①	①	①	①	①	①	①	①	①	②	②	⑤	①	①	①	①	○	①	①	
5	①	①	①	①	①	①	①	①	①	①	①	②	⑤	①	①	①	①	○	①	①	
4	①	①	①	①	①	①	①	①	①	①	①	①	⑤	①	①	①	①	○	①	①	
3	①	①	①	①	○	①	①	①	①	①	①	①	⑤	①	①	①	②	①	①	①	
2	①	①	①	○	○	①	①	①	①	①	①	①	⑤	①	①	①	①	①	①	①	
1	○	①	①	①	○	①	①	①	①	①	①	①	⑤	①	①	①	①	①	①	①	

Fig. 2. Number of measurements at Stončica station in the period 1961-1980

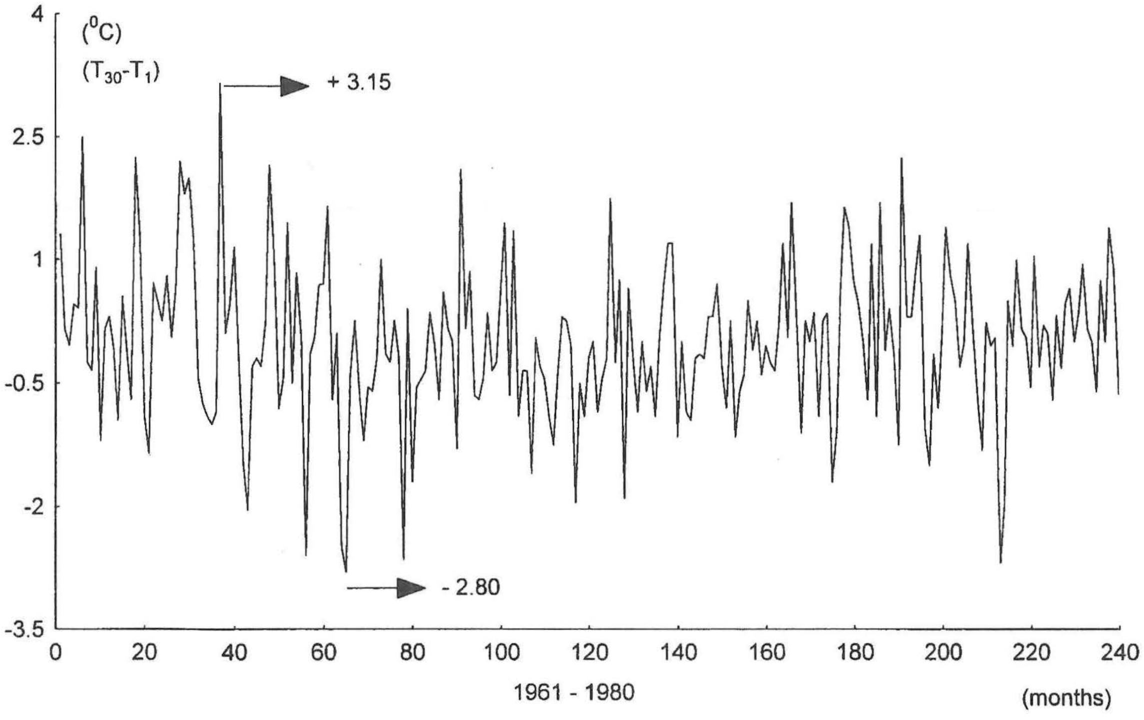


Fig. 3. The difference between mean monthly temperatures T_{30} and T_1

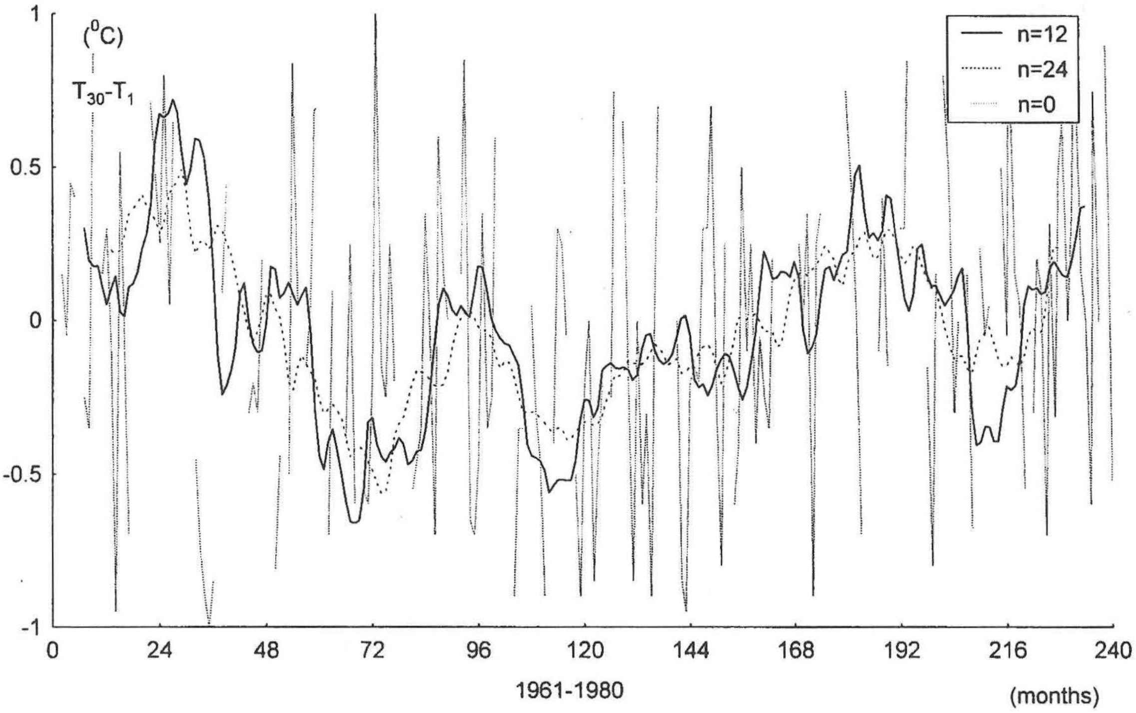


Fig. 4. Comparison of the difference (T30 - T1) (n=0) to filtered differences with moving average of n=12 and n=24 window

ferences resulted in smaller differences between the two data series. Larger filtering window diminishes differences but reduces the data set (Fig. 4) and the window n=12 seem to be an optimum choice for this data set.

Oceanographic measurements from the anchored ship are often called "nice weather oceanography". Indeed, when weather types are attributed to dates of measurements at Stončica station it is clear that most of the measurements were done under anti-cyclonic weather conditions (A. BAJIĆ, personal communication).

Principal component analysis technique

Salinity time series were subject to the principal component analysis (PCA) (PREISENDORFER, 1982). The PCA was performed on the correlation matrix of standardized variables (R_y). Eigenvalues (PC_r) and eigenvectors were determined, applying the varimax rotation. The significance of PC components were tested by the rule N (OVERLAND and PREISENDORFER, 1982), using Monte Carlo simulation of the random matrix of the same size as the original data matrix. From the correlation matrix R_Y, Φ and λ were determined as a solution of the matrix equation:

$$\Phi^{-1} R_Y \Phi = \lambda \tag{1}$$

$$R_Y \Phi - \lambda \Phi = 0 \tag{2}$$

Solution of the matrix equation is obtained as an infinite product of "rotations" of matrices using JACOBI's method (SPIEGEL, 1972). For the symmetric matrix R_Y accounted variance of the individual eigenvector is determined by the eigenvalue.

RESULTS AND DISCUSSION

The principal goal of this paper was to analyze long-term salinity changes in order to distinguish layers influenced by different processes. For this reason, we have first applied PCA to the salinity data for seven available depths (0, 10, 20, 30, 50, 75 and 100m). Two eigen values were found statistically significant, according to the rule N. For the reasons mentioned earlier data were filtered before they were subject to PCA. Matrix of the component loadings after varimax rotation, made to be achieved a simple structure is graphically represented in Fig.5.

On the basis of distribution of PC loadings it was possible to distinguish two layers whose variability contribute with different amount to the total variability in the salinity field. PC1 represents inter-annual fluctuations in layer from 30 down to100m and contribute 87.2% to the total variance. Second principal component, describes inter-annual fluctuations in the surface layer down to 20m and contribute 9.2% to the total variance. Therefore, at the long-term scale, PCA recognized two layers: surface and intermediate. The corresponding component scores are presented in Fig.6. Inter-annual salinity fluctuations in these two layers were explained comparing PC scores to processes that could cause changes at inter-annual scale.

In the surface layer (PC2) salinity fluctuations are under considerable influence of water flux (GRBEC and MOROVIĆ, 1997). Significant correlation coefficient (0.31) was found between PC2 and E-P, with three months lag.

Salinity fluctuations in the intermediate layer (PC1) are not affected by vertical processes and can be explained with horizontal advection of the saltier Mediterranean water. Higher salinity in the Mediterranean causes higher salinity in the middle Adriatic. As already known (ZORE-ARMANDA, 1972) the mechanism of exchange between the Adriatic and the Mediterranean can be explained by the horizontal pressure gradient between the northern and the southern Adriatic (pressure differences between Trieste and Athens).

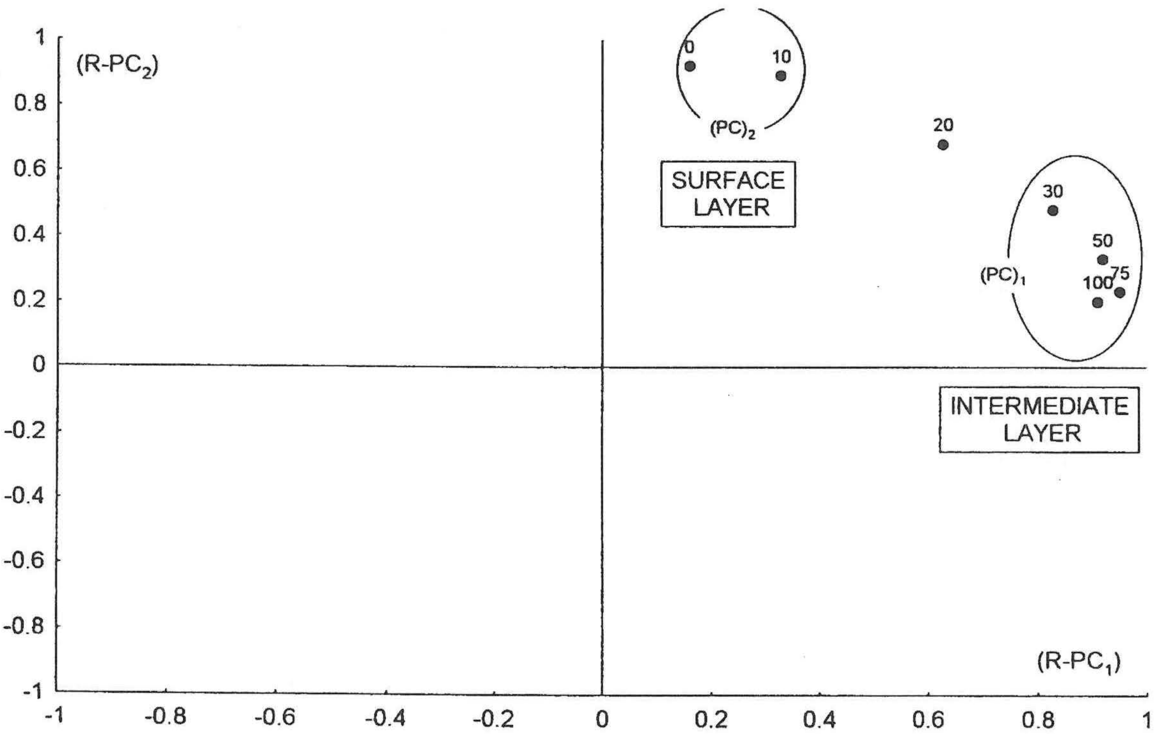


Fig. 5. Principal component loadings after varimax rotation (R-PC) in salinity field

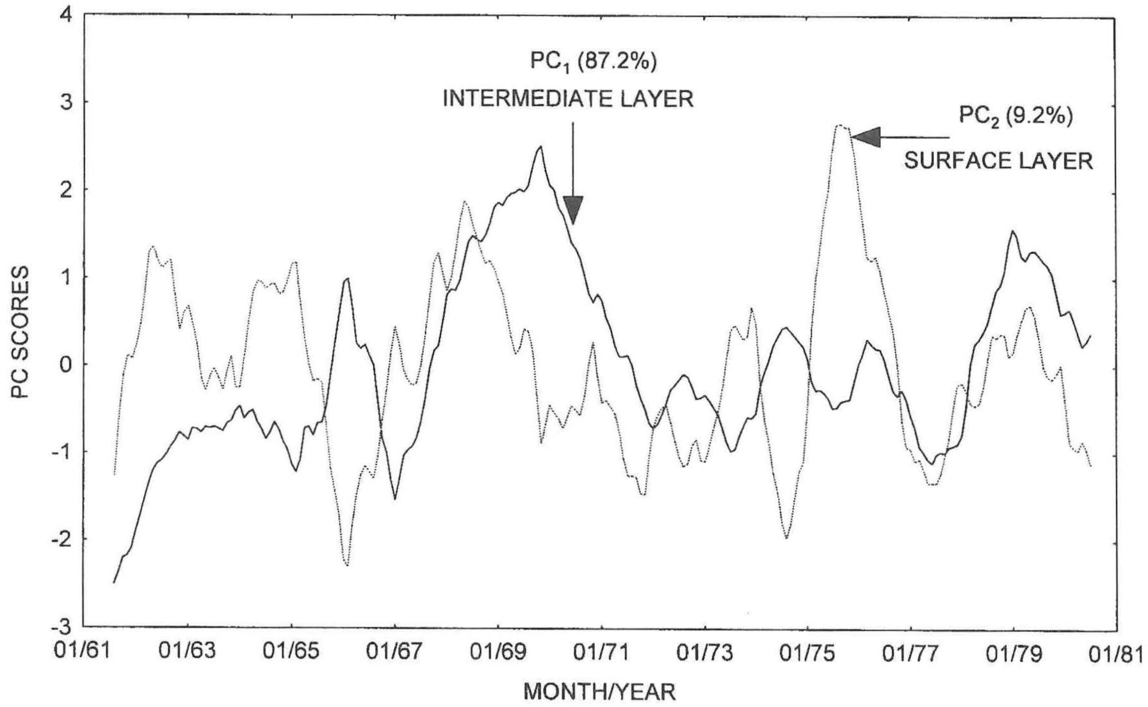


Fig. 6. First two principal component scores in salinity field

In the years with higher pressure differences, higher salinity in the intermediate layer of the middle Adriatic can be expected. Higher horizontal pressure gradient does not always correspond to higher salinity, due to a number of factors. Comparing horizontal pressure gradient with salinity fluctuations in the intermediate layer (Fig.7) two characteristic periods are evident. In the period 1961-1970 pressure gradient fluctuations are not evidently followed by salinity fluctuations. It was assumed that the Assuan dam (constructed in 1963) was one of the important causes for salinity changes in this period. Salinity in the eastern Mediterranean was increased due to the fresh water input decrease from 41 to 11 km^3 (GERGES, 1976). In the period 1971-1980, salinity fluctuations (PC1) seem to respond to pressure gradient fluctuations and correlation coefficient between them was 0.55 (significant at the 0.001 level). Apart from the higher salinity, the LIW can be detected in the intermediate layer of the middle Adriatic by higher temperature.

The PC scores from the temperature field, calculated from seven vertical levels, were compared to the pressure gradient. Temperature fluctuations also show two characteristic periods. In the latter one, from 1971-1980, temperature fluctuations follow salinity fluctuations. The correlation coefficient between temperature and pressure gradient in this period was 0.68 (significant at the 0.001 level).

Since it has been shown that pressure gradient fluctuations were driving mechanism for ingressions, it is important to explain the origin of pressure fluctuations from year to year.

Horizontal pressure gradient over the Adriatic is the consequence of cyclone and anticyclone distribution over the area of wider size than the Adriatic itself. Pressure map set was divided to years with higher and lower salinity. This was done according to mean annual salinity at deep layers on the Stončica station. Salinity limit of 38.55 psu was the criteria that distinguished years of higher from those of lower salinity. Locations of lows and highs were identified on monthly maps and counted for each year. There were 13 years in each group. Mean location of highs and lows, for years with high and low salinity respectively are

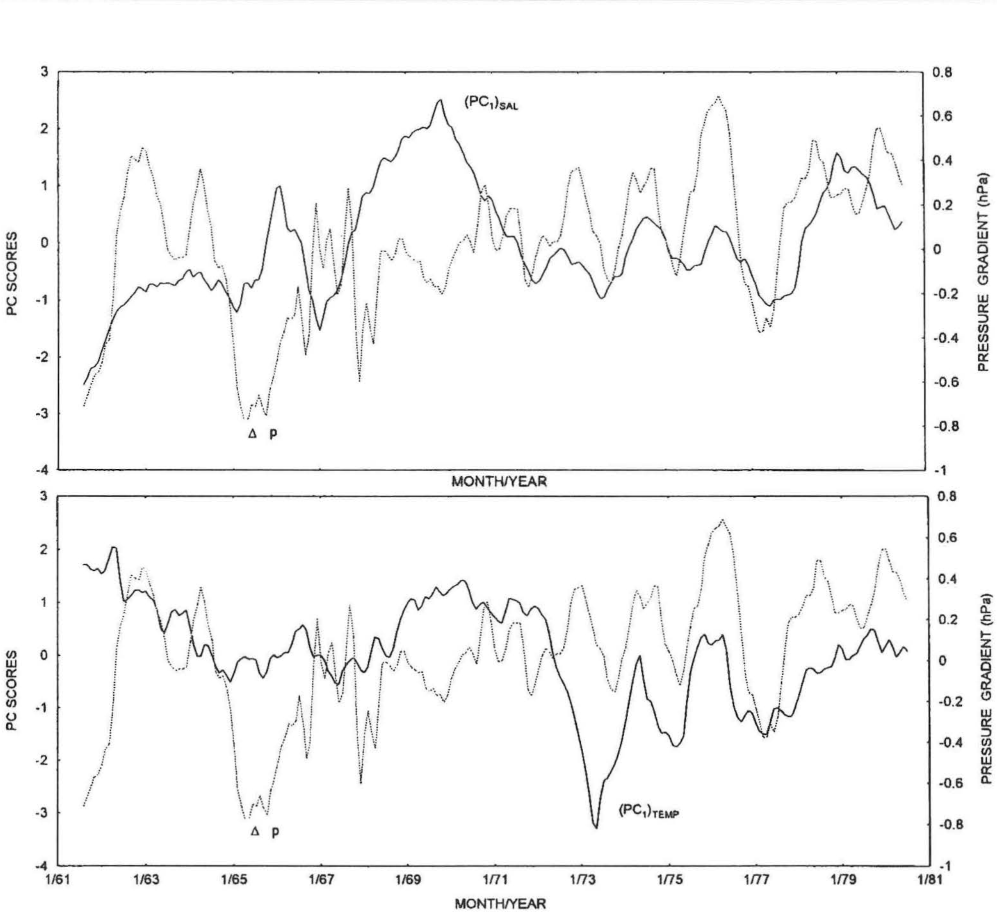


Fig. 7. Time series of air pressure horizontal gradient and principal component scores obtained from salinity and temperature field

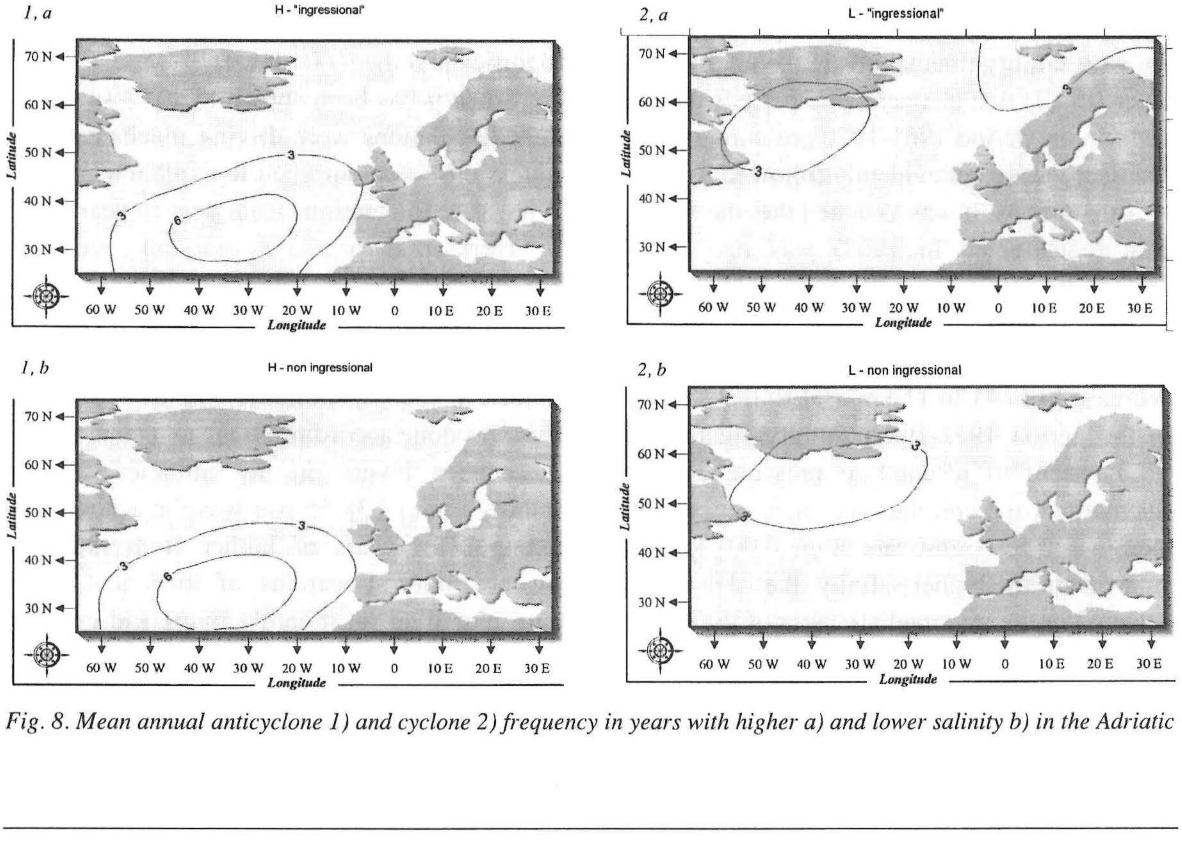


Fig. 8. Mean annual anticyclone 1) and cyclone 2) frequency in years with higher a) and lower salinity b) in the Adriatic

presented in Fig. 8. The analysis of mean pressure maps, show difference in the highest and the lowest pressure center location. The difference between two features is evident: in years with higher salinity in the Adriatic, Azores high is shifted to the North-East and additional low pressure center appears further north-east which corresponds to a pole-ward shift of the major cyclone tracks. Pole-ward displacement of cyclones over the Atlantic was observed for the latter period by KÖNIG *et al.* (1993). This pole-ward (northeastward) shift may influence zonal pressure gradients, which probably strengthen water exchange between the Adriatic and the Mediterranean. Years of lower salinity are characterized by mostly meridional air-pressure gradient direction.

CONCLUSIONS

Analysis in the salinity field showed that PCA was successfully applied to these data, revealing two layers whose salinity properties change due to different processes. In the surface layer, salinity changes due to water flux influence. In the intermediate layer salinity is under considerable influence of horizontal advection. Salinity change in the intermediate layer is highly correlated to horizontal pressure gradient between northern and southern Adriatic.

Salinity fluctuations in the intermediate layer are not affected by vertical processes and can be explained with horizontal advection of the saltier Mediterranean water.

Comparing horizontal pressure gradient with salinity fluctuations in the intermediate layer two characteristic periods are evident: the period 1961-1970 when pressure gradient fluctuations are not evidently followed by salinity fluctuations and the latter period (1971-1980) when salinity was highly correlated to the pressure gradient fluctuations.

Advection mechanism appears to be related to the distribution of the large-scale (from Atlantic to Europe) low and high pressure centers. It seems that more northeastward location of cyclones increases zonal pressure gradients, which enhance saltier water advection from the Mediterranean into the Adriatic.

REFERENCES:

BULJAN, M. 1953. Fluctuations of salinity in the Adriatic. Izv. Rep. Rib.-biol. Exped. "Hvar", 2: 1-64.

BULJAN, M. and M. ZORE-ARMANDA. 1976. Oceanographical properties of the Adriatic Sea. Oceanogr. Mar. Biol. Ann. Rev., 14: 11-98.

BULJAN, M. and M. ZORE-ARMANDA. 1979. Hydrographic properties of the Adriatic Sea in the period from 1965 through 1970. Acta Adriat., 20: 1-368.

DEUTSCHER WETTERDIENST ZENTRALAMT. 1956-1980. Die Grosswetterlagen Europas. Offenbach.

GERGES, M.A. 1976. The damming of the Nile River and its effect on the hydrographic condition and circulation pattern on south-eastern Mediterranean and Sues Channel, Acta Adriat., 18: 179-191.

GRBEC, B. and M. MOROVIĆ. 1997. Seasonal thermohaline fluctuations in the middle Adriatic Sea. Il Nuovo cimento, 20: 561-576.

KÖNIG, W., R. SAUSEN and F. SIELMANN. 1993. Objective identification of Cyclones in GCM Simulations. J. of Climate, 6: 2217-2231.

LAMB, H.H. 1972. Climate, Present, Past and Future, Vol.1. Mathuen, London, 613 pp.

MAKJANIĆ, B. 1978. Dinamička meteorologija. Sveučilište u Zagrebu. Zagreb, 189 pp.

MORCOS, S. 1972. Sources of the Mediterranean Intermediate Water in the Levantine Sea. In A.L. Gordon. Studies in physical oceanography, 2. Gordon & Breach Science Publishers, New York:185-206.

NAMIAS, J. 1963. Large-scale air-sea interactions over the north Pacific from summer 1962 trough the subsequent winter. J. Geophys. Res., 68: 6171-6186.

OVERLAND, J.E. and R.W. PREISENDORFER. 1982. A significance test for principal component applied to a cyclone climatology. Mon. Weath. Rev., 101: 1-4.

PREISENDORFER, R.W., 1982. Principal Component Analysis in Meteorology and Oceanography. Elsevier. Amsterdam, 425. pp.

ROUSSENOV, V., E. STANEV, A. VINCENZO and N. PINARDI. 1995. A seasonal model of the Mediterranean Sea general circulation. J. Geophys.Res., 100: 13 515-13 538.

SPIEGEL, F. 1972. Probability and statistics. Shaum's outline series. Mc Graw-Hill, Newyork, 321pp.

TZIPPERMAN, N. and P. MALLANOTTE-RIZZOLI. 1991. The climatological seasonal circulation of the Mediterranean Sea. J. Mar. Res., 49: 411-434.

ZORE-ARMANDA, M. 1963. Les masses d'eau de la mer Adriatique. Acta Adriat., 10: 1-94.

ZORE-ARMANDA, M. 1969a. Temperature relations in the Adriatic Sea. Acta Adriat., 13: 1-50.

ZORE-ARMANDA, M. 1969b. Watter exchange between the Adriatic and the Eastern Mediterranean. Deep-Sea Res., 16: 171-178.

ZORE-ARMANDA, M. 1969c. Origine possible des fluctuations de la salinité de l'eau de la mer Adriatique. Rapp. Comm. int. Mer Médit., 19: 719-722.

ZORE-ARMANDA, M. 1972. Response of the Mediterranean to the oceanographic /meteorological conditions of the Northern Atlantic. Rapp. Comm. int. Mer Médit., 21: 203-205.

ZORE-ARMANDA, M. 1974. Formation of eastern Mediterranean deep water in the Adriatic. Coll. Internat. C.N.R.S. 215: 127-133.

ZORE-ARMANDA, M. and M. BONE. 1987. The effect of bottom topography on the current system of the open Adriatic Sea. Boll. Oceanol. Teor. Appl. 5: 3-18.

ZORE-ARMANDA, M., M. BONE, V. DADIĆ, M. MOROVIĆ, D. RATKOVIĆ, L. STOJANOSKI, and I. VUKADIN. 1991. Hydrographic properties of the Adriatic Sea in the period from 1971 through 1983. Acta Adriat., 31: 5-547.

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Novi pogledi na dugoročne promjene saliniteta u Jadranskom moru

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SAŽETAK

Kako bi se objasnile fluktuacije saliniteta na otvorenom srednjem Jadranu, nizovi podataka s postaje Stončica su podvrguti analizi glavnih komponenata. Rezultati su uspoređeni s meteorološkim faktorima. Osnovni rezultati pokazuju da su fluktuacije u površinskom sloju (0-20m) u dobroj korelaciji s fluksom vode, dok one u srednjem sloju (30-100m) slijede promjene gradijenta tlaka zraka između sjevernog i južnog Jadrana, koji je pokazatelj intenziteta advekcije vode iz Sredozemlja. Da bi se objasnio mehanizam advekcije dodatno je analizirano polje tlaka šireg područja (70W-40E i 20N-80N) uzevši u obzir učestalost pojave ciklona i anticiklona.