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Mediterranean Oscillation and its relationship to salinity fluctuation in the Adriatic Sea

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To study the meteorological conditions favourable to the flow of Levantine Intermediate Water (LIW) into the Adriatic, atmospheric pressure fluctuations in the mid-northern Atlantic to the southeastern Mediterranean during 1900-1995 were analysed. The response of the Adriatic to hemispheric climatic changes described by the North Atlantic Oscillation (NAO) index was also analysed. Principal component analysis of the pressure field resulted in different modes of variability, and enabled locating the pressure areas directly related to the inflow phenomenon. These areas were generally related to the increase of salinity in the Adriatic. The analyses led to defining the term "Mediterranean Oscillation index", which refers to the difference in pressure between the mid-northern Atlantic and the southeastern Mediterranean. Salinity fluctuations in the intermediate layer of the middle Adriatic during 1947-1995, resulting from the LIW inflow, followed the year-to-year atmospheric pressure fluctuations. The atmospheric pressure field and its correlation with salinity were analysed for winter (December-March) also.

Key words: large-scale pressure difference, North Atlantic Oscillation (NAO) index, salinity, sea-level, pressure, Mediterranean oscillation

INTRODUCTION

In the early twentieth century, temperature, precipitation and fluctuations in sea-level pressure were documented for the area extending eastward to central Europe, southward to subtropical western Africa and westward to North America. This vehicle for documenting climate variability was named North Atlantic Oscillation (NAO), described by WALKER (LAMB, 1972) in the 1920s and defined by ROGERS (1984). NAO has been described as the primary climatic factor governing hemispheric-scale fluctuations, having a dominant influence on wintertime temperature across a wide region of the northern hemisphere including the Mediterranean. There are two phases of the NAO index: one positive and one negative (JONES *et al.*, 1987; MARSHALL *et al.*, 1997). The positive NAO coincides with lower temperatures over the northwest Atlantic and dry winter weather over southern Europe and the Mediterranean (HURRELL, 1995; HURRELL & VAN LOON, 1997). The NAO index increased during the last thirty years, reaching an historic maximum in the early 1990s, but besides the positive trend, there have been large decadal oscillations. Climate conditions over the northern hemisphere in the last fifty years strongly fluctuated from year to year, decade to decade and over the long term, with possible impacts on Adriatic Sea water properties. Although it is known that the NAO is important for atmospheric circulation, all the consequences of its influences on a specific area, such as the Adriatic Sea, are not currently clear.

The Adriatic, due to its orientation and since it is deeply embeded in the European continent, has specific oceanographic properties, i.e., strong spatial gradients and seasonal variations which result from the water masses formed or present in the sea. On the northernmost side, the cold and dry Bura wind causes strong cooling and mixing of the surface waters. There, the coldest Mediterranean water mass - the North Adriatic Dense Water (NAdDW) - is formed, but only during cold winters with enough episodes of strong Bura winds. Being under the influence of the freshwater Po and other rivers, this water has relatively low salinity. It spreads southward, sinks and is trapped in the Jabuka pit. If conditions are favourable for its formation, it may be transported to the southern Adriatic pit (ZORE-ARMANDA, 1963). Formation of this water mass depends on atmospheric influences and the circulation pattern (ARTEGIANI & SALUSTI, 1987; BEG PAKLAR *et al.*, 2001). In the southern Adriatic pit, the South Adriatic Deep Water (SAdDW) forms through deep-convection processes (ARTEGIANI *et al.*, 1997; VILIBIĆ & ORLIĆ, 2002). A third water mass is the Levantine Intermediate Water (LIW). The almost permanent inflow of highly saline and warmer LIW is formed mainly in the northeastern Levant in the approximately 200-600 m layer before it enters the Adriatic Sea (MALANOTTE-RIZZOLI *et al.*, 1997). LIW is a result of enhanced heat, water and buoyancy losses over the northern Levant. Inflow of the LIW into the intermediate layer of the Adriatic correlates with the pressure gradient over the length of the Adriatic (ZORE-ARMANDA, 1971, 1972). This pressure gradient affects the transport of the LIW through the Otranto Strait and as it spreads northwards in the Adriatic. The LIW, more or less, continuously enters the Adriatic in the intermediate layer but with varying intensity that depends on the position of the most frequent pressure centres over the northern Atlantic Ocean (GRBEC *et al.*, 1998).

Recently, TSIMPLIS & JOSEY (2001) showed that the NAO influences the variability of the sea level in the Mediterranean and suggested that it also plays a role in increasing the deep-water salinity of the western Mediterranean and in establishing the eastern Mediterranean transient.

Besides the aforementioned changes, the amount of dense Adriatic water in the deep waters of the eastern Mediterranean (POLLAK, 1951; ZORE-ARMANDA, 1963; OVCHINNIKOV *et al.*, 1985) seems to be less than the amount of Aegean Sea water in recent times (ROETHER *et al.*, 1996). Earlier, this phenomenon was observed by LACOMBE *et al.* (1958). These changes were associated with irregular meteorological conditions and changes in the pattern of circulation (LASCARATOS *et al.*, 1999). The consequences were the interruption of the exchange between the Ionian and Levantine basins and increased salinity in the latter (MALANOTTE-RIZZOLI *et al.*, 1999).

KLEIN *et al.* (1999) found differences in salinity of the LIW at its source between 1987 and 1995. As a consequence of reduced salinity in the LIW at its source, the salinity in the Adriatic dropped in 1995. To the contrary, in 1987 the saltier LIW layer was much thicker as it extended towards the southern Adriatic pit and caused higher salinity. Three cold winters were favourable for generating new Aegean deep water, and unusual winter wind stresses during 1988-1995 increased its southward transport (STRATFORD & HAINES, 2002).

In the middle Adriatic, salinity fluctuations in the intermediate layer follow the observed changes and suggest the possibility that changes in the pressure distribution pattern over Europe affect the intensity of the LIW inflow (GRBEC *et al.*, 2002). Therefore, it seems reasonable to relate salinity fluctuations to the modes of pressure variability over the northern hemisphere, primarily with the NAO index.

This study shows the relationship of year-to-year salinity fluctuations in the intermediate layer of the middle Adriatic to pressure distribution patterns over Europe and the different water masses in the Adriatic Sea.

MATERIAL AND METHODS

The approach was to analyse the dependence of the LIW inflow on the NAO and the mean annual sea-level pressure over Europe by studying historical records.

North Atlantic Oscillation index

Sea-level pressure data, used to calculate the North Atlantic Oscillation (NAO) index, were taken from the website of the Climatic Research Unit of the University of East Anglia in Norwich, UK (http://www.cru.uea.ac.uk). For most analyses, the NAO index is defined as the difference in pressure between the Azores and Iceland, normalized to the 1961-1990 period (JONES *et al.*, 1997). However, since salinity changes as a result of many factors besides meteorological, it could not be normalized to the 1961-1990 period. Therefore, for the purpose of our investigation, NAO was defined as the mean annual difference in sea-level pressure between the Azores (Porta Delgada) and southwest Iceland, without normalization. The NAO index was calculated for 1900 to 1995.

Sea-level pressure field

Annual mean grid-point sea-level pressure reconstructions for 1900-1995, from European and American sources, were available on the above-mentioned web site. The data field has grid points at the intersections of every 5° of latitude and 10° of longitude and covers the entire northern hemisphere (Fig. 1a). The examined area was 30°W-40°E and 30°N-65°N. Pressure reconstructions are expressed in hPa to the nearest tenth and were adjusted to the mean sea level, with no values missing. Detailed descriptions of the data, sources and methods can be found in WILLIAMS & VAN LOON (1976), TRENBERTH & PAOLINO (1980) and JONES (1987).

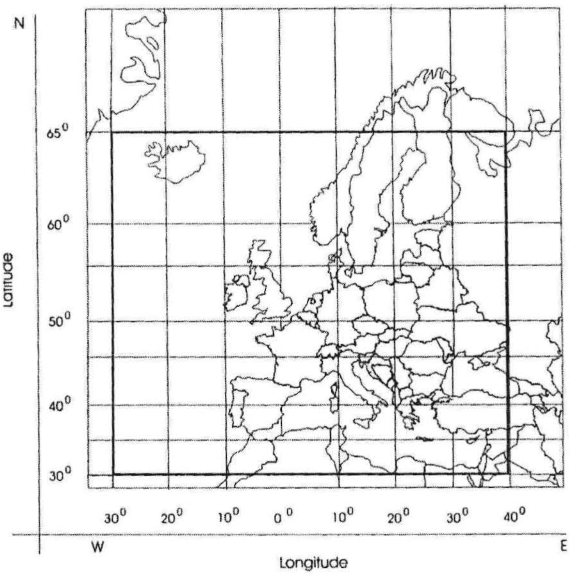


Fig. 1a. The wider European region with rectangle marked showing the location of the sea-level pressure grid-points

In our earlier paper (GRBEC *et al.*, 1998), we related pressure conditions over a wider area to the LIW inflow and it seemed that more northeastern locations of cyclones over the Northern Sea increased the pressure difference between zones, enhancing advection of saltier water from the Mediterranean into the Adriatic. Based on our previous analysis, we believed that the selected area and the resolution of the pressure field would be sufficient to quantify the influence of pressure differences on the water exchange between the Adriatic and the Mediterranean.

From the mean annual sea-level pressure data for 1900-1995, the main variability pattern was extracted from the data field of 64 grid points, using Principal Component Analysis (PC).

The analysis revealed the strong inter-annual correlation between the temporal evolution of the PC modes related to the pressure fields over the Mediterranean and Atlantic and the salinity in the Adriatic Sea. Further analysis enabled locating the areas where pressure is directly related to the inflow phenomenon, which generally causes higher salinity in the Adriatic. These analyses led to defining the Mediterranean Oscillation index (MO index) as the difference in pressure between two points in the mid-northern Atlantic and the southeastern Mediterranean.

The annual pressure data used for this analysis describe the mean annual pressure field over the area, which is relevant to the studied Mediterranean inflow process. Although the water masses LIW and NAdDW are formed only in cold dry winters, advection of the LIW to the Adriatic Sea is a process of longer duration and occurs in summer under Etesian influence (ZORE-ARMANDA, 1969; POULAIN & CUSHMAN-ROISIN, 2001) as well as in winter. It is assumed that the summer wind pushes the surface waters out of the Adriatic and the Mediterranean water (LIW) enters as a compensatory current into the intermediate layer.

PC (PREISENDORFER, 1982) was performed on the mean annual sea-level pressure field, consisting of 64 grid-points. The goals were to extract main spatial and temporal pressure modes and determine the link with salinity fluctuations. Relationships between extracted components and salinity were analysed through the correlation technique.

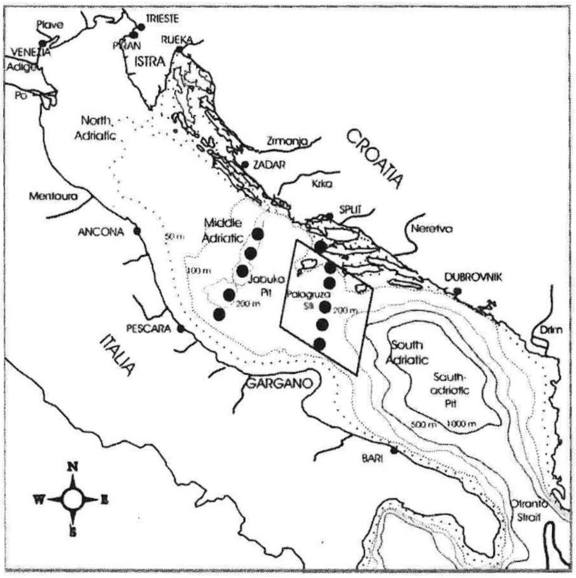


Fig. 1b The Adriatic Sea with the area marked in the Middle Adriatic used for the salinity analyses, and stations marked at the Jabuka and Palagruža transects used for identifying different water masses

Levantine Intermediate Water (salinity data)

As an indicator of the LIW inflow, the data used in this study consist of historical salinity measurements taken during 1911-1914 and from 1947 to 1998 (BULJAN and ZORE-ARMANDA, 1976; ZORE-ARMANDA *et al.*, 1991). The data were collected during cruises at a number of sta-

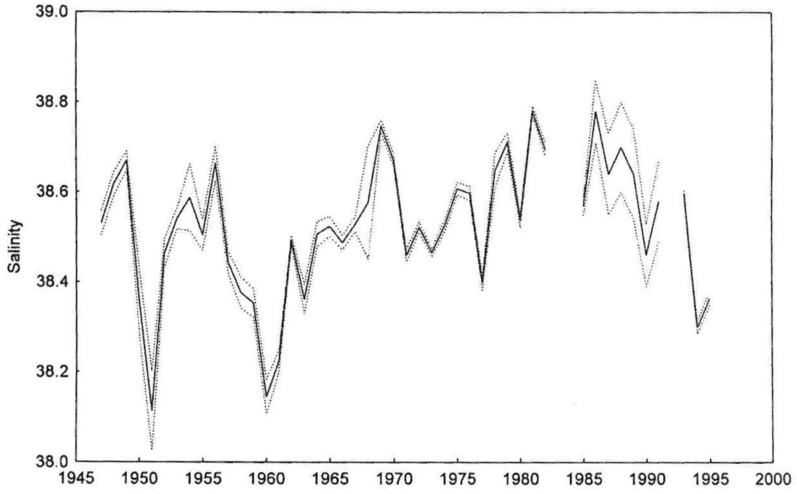


Fig. 2. The mean annual salinity in the intermediate layer of the Middle Adriatic region (see Fig. 1b) from 1945-1995. The 95% confidence limit for means is indicated

tions in the middle Adriatic. Since it was possible to detect LIW inflow in the intermediate layer of the middle Adriatic, mean annual salinity values were calculated for the layers not influenced by seasonal changes, i.e., between 50 m and 170 m at all stations in the locations shown in Fig. 1b. All the data were taken from the Institute's Marine Environmental Data Bank of the Adriatic Sea - MEDAS (DADIĆ, 1995). Mean annual salinity data are shown in Fig. 2.

Water mass distribution

To illustrate the distribution of the different water masses in different years, temperature and salinity data, measured within the framework of the Croatian National Monitoring Project, were used. During May 1998-August 1999, cruises were conducted along two transects in the middle Adriatic Sea: the Jabuka transect and transect across the Palagruža sill (Fig.1b).

The Jabuka transect consisted of five stations with the central station in the Jabuka pit; the Palagruža transect consisted of six stations. The transects and stations were selected based on previous research, to examine the inflow, outflow and presence of the different water masses.

RESULTS AND DISCUSSION

Climatic impact on inflow of Levantine Intermediate Water

Thermohaline conditions in the intermediate layer of the middle Adriatic are strongly influenced by inflows of more saline, warmer and nutrient rich water (ZORE-ARMANDA, 1963; ORLIĆ *et al.*, 1992; GRBEC & MOROVIĆ, 1997). These inflows vary strongly from year to year as a consequence of certain meteorological processes.

As a consequence of the distribution of large pressure centers over the wider Mediterranean region, the horizontal air pressure varies between the northern and the southern Adriatic, influencing the intensity of the water exchange between the Adriatic and the eastern Mediterranean. Therefore, hydroclimatic fluctuations in the middle Adriatic Sea are the result of climatic fluctuations over the northern Adriatic and over an area larger than the Adriatic itself.

As meteorological conditions throughout Europe are modulated by the NAO, we tried to discover to what extent the NAO could cause favourable conditions for both processes that are followed by increased salinity in the Adriatic. The time-series for salinity and NAO (Fig. 3)

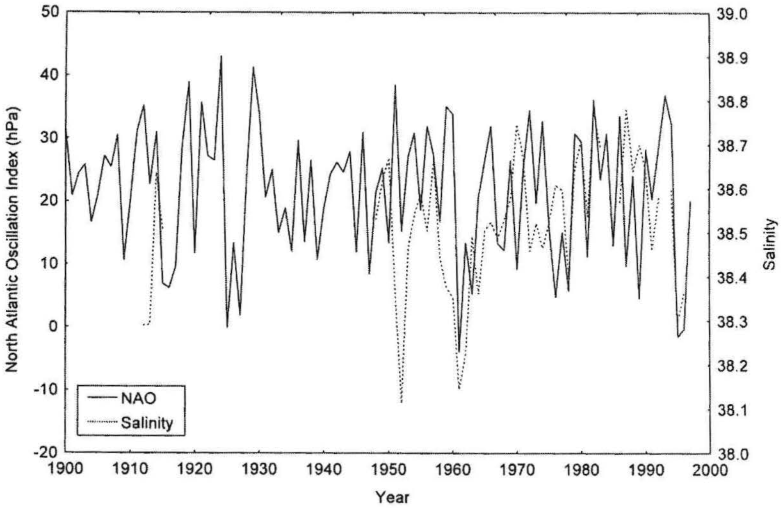


Fig. 3. Long-term salinity variations in the intermediate layer of the Middle Adriatic compared to the North Atlantic Oscillation Index

fluctuate similarly from year to year, which may indicate a relationship. Since salinity changes due to various atmospheric and hydrologic factors, a different correspondence to NAO may be observed in different periods, but no correlation was found between these parameters.

Pressure in the northern Adriatic was higher than in the southern (GRBEC, 1998), producing favorable conditions for the advection of LIW into the Adriatic. Therefore we analysed inter-annual pressure variations in an area larger than the Adriatic. The mean annual sea-level pressure field from the northern Atlantic to the southeastern Mediterranean was subject to PC analysis. Six significant components (eigen values >1) were extracted (Table 1) explaining 80% of the total variance of the pressure field. The first principal component explains 28.5% of the variability of the pressure field, indicating that this component cannot be attributed only to the mean climatological field of the whole investigated area.

Based on the PC loadings, each of the eigen values describe the pressure variation in a particular area, as indicated in Fig. 4a. Spatial distribution of the PC loadings, that extracted the maximum variability of the pressure field, shows that PC1 delimits the area of major cyclone tracks over the Atlantic and Europe. Other PC loadings delimit permanent or quasi-permanent pressure fields like PC2 or PC3 that explain the variability of the pressure over northern Europe, which is influenced by the continental Arctic air mass. The fourth significant component (PC4) explains the variability over the mid-northern Atlantic, PC5 explains the variability over the Azores high, while PC6 is related to the eastern Mediterranean low.

Time variability of the PCs is shown on Fig. 4b. The highest correlation coefficients are found between PC4 and PC6, and salinity (Table 2). Both PCs show strong interdecadal variability. The PC6 shows a decreasing trend, but not after 1947, therefore the correlation with salinity is due to the correspondence with interdecadal variability. Although the highest variability is over the Europe and the Mediterranean (PC1), it is not linked to inter-annual salinity fluctuations in the Adriatic. The significant correlation coefficient between salinity and time evolution of PC4 suggests that the area under the influence of PC4 covers the oceanographic polar front zone, which plays an important role in temperature conditions over central Europe (ROSSOV & KISLYAKOV, 1969). The intensive penetration of such air in the central Mediterranean is followed by more intensive cyclonic activity and, as a consequence, the formation of colder and denser water in the northern Adriatic. Another important fact, already discussed by ZORE-ARMANDA (1972), is the relationship between the amount of ice over the northern Atlantic and Adriatic salinity.

Table 1. Eigen values and explained variance of the first 6 significant principal components, extracted from the PC analysis of the annual sea-level pressure field in the period 1900-1995. The significance of the six factors was tested by the asymtotic eigen values analysis by PREISENDORFER (1982), based on hundreds random number calculations. (for â=1.5, (x, â)=0.90 can be attributed to all eigen values >2.29)

PC	Eigen values	Explained variance %
1	18.21	28.45
2	11.38	17.78
3	8.84	13.81
4	5.84	9.13
5	4.30	6.72
6	2.41	3.76
Total explained variance		79.66

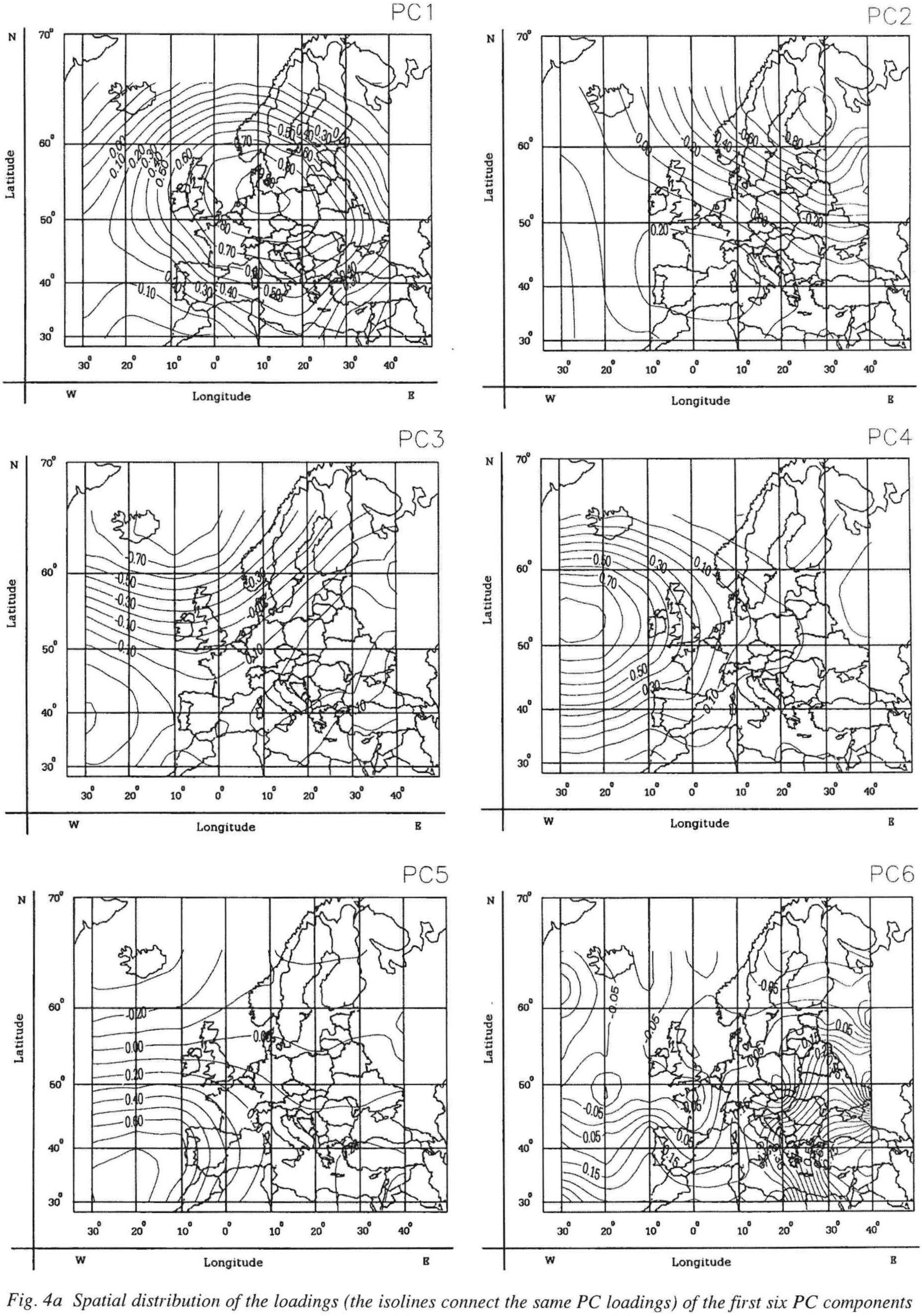


Fig. 4a Spatial distribution of the loadings (the isolines connect the same PC loadings) of the first six PC components extracted from the sea level pressure field

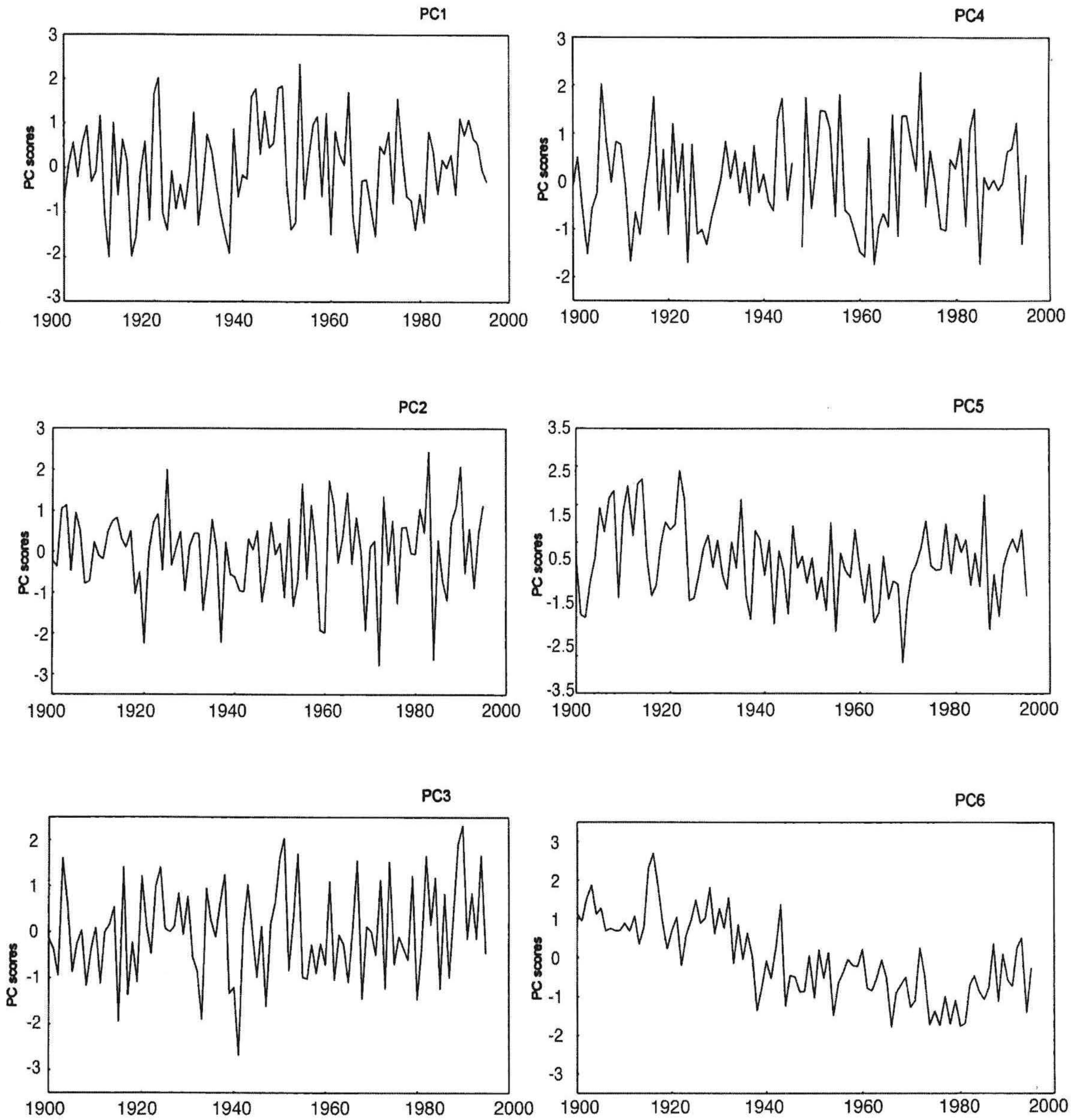
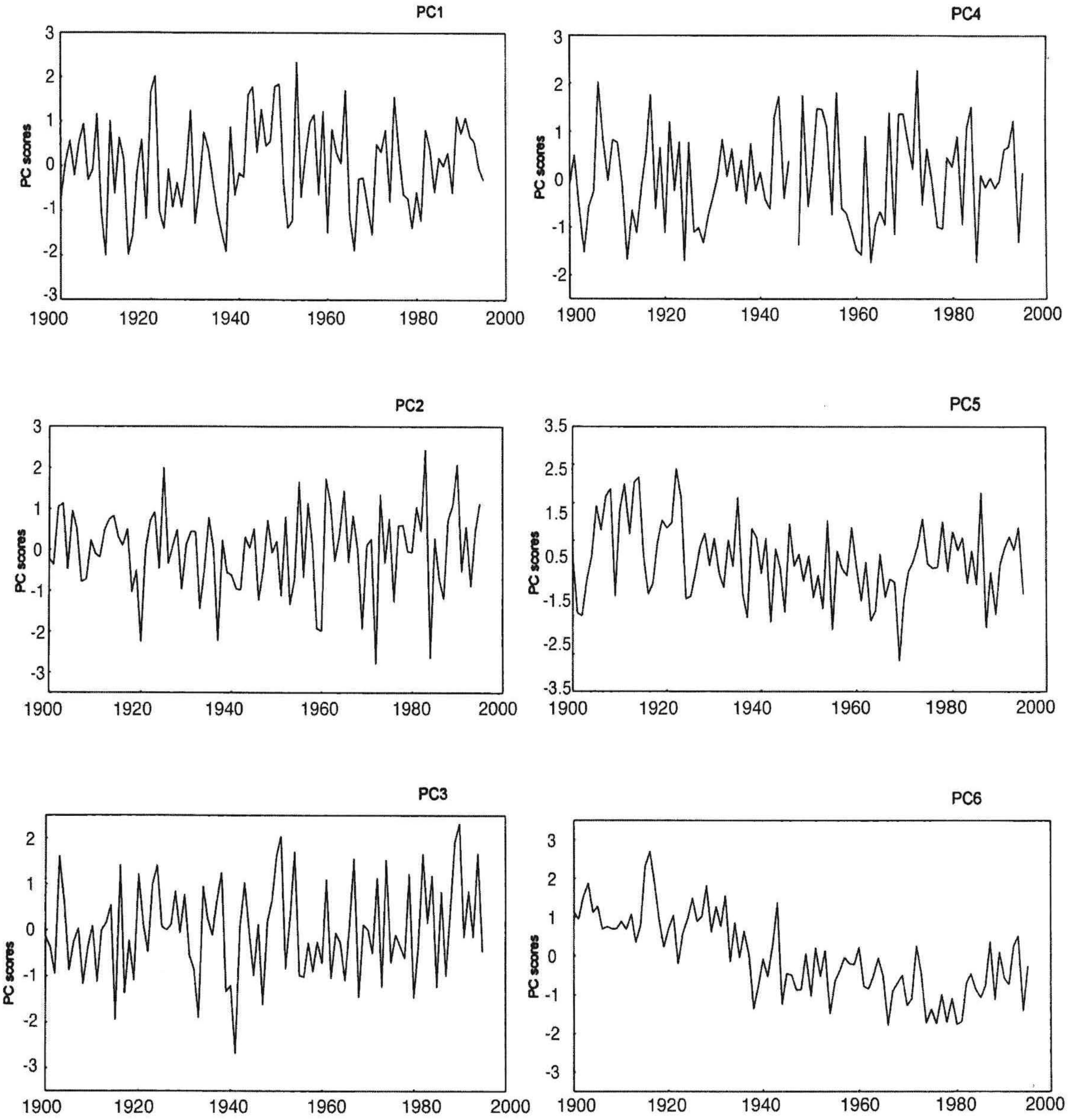


Fig. 4 b. Temporal evolution of scores of the first six PC components extracted from the sea level pressure field

Table 2. Results of the correlation analysis between the first 6 significant extracted principal component scores of the annual pressure field in the period 1900 -1995 and salinity in the intermediary layer of the Middle Adriatic. (denotes correlation coefficient significant at 0.001 level)*

Correlation coefficient	Annual salinity
PC1	0.11
PC2	-0.01
PC3	-0.01
PC4	0.36*
PC5	0.01
PC6	-0.24



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Correlation coefficient	Annual salinity
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PC2	-0.01
PC3	-0.01
PC4	0.36*
PC5	0.01
PC6	-0.24

Table 3. Results of the correlation analysis between the annual salinity in the intermediary layer of the Middle Adriatic and difference of the PC4 and PC6 components from the PC analysis of the pressure field in the period 1900-1995, the MOI (pressure difference between the gridpoints in the Mid North Atlantic and the Southeastern Mediterranean) and NAO for the same period. (denotes correlation coefficient significant at 0.001 level)*

Correlation coefficient	Annual salinity	Number of data	Significance level
PC4-PC6	0.43*	48	0.001
MOI	0.38*	48	0.001
NAO	-0.07	48	

The highest PC loading of PC4 covers the area around the grid-point 50°N-30°W while the highest loading of PC6 is around 30°N-40°E. The pressure distribution over these two areas was related to the inflow mechanism. The conditions that coincide with the intensified inflow of LIW into the Adriatic were different between the two extracted components. The highest correlation coefficient was between the difference of PC4-PC6 and salinity (Table 3). Therefore we believe that not only the difference of the PCs, but also the pressure difference between the areas with the highest PC loadings, may be related to salinity fluctuations. The pressure differences between these two areas significantly correlate with salinity for 1947-1995.

To explain the inflow in terms of differences in pressure between the mid-northern Atlantic and southeastern Mediterranean, we defined pressure oscillation across the Mediterranean and Adriatic as "Mediterranean Oscillation (MO)", which can be quantified by the pressure difference named the MO index. This is analogous to the already established Mediterranean Oscillation for the 500 mb geopotential level between the western and eastern Mediterranean (CONTE *et al.*, 1998). The area in the mid-northern Atlantic is regulated from permanent pressure centres - the Azores high and the Iceland low, while the area in the southeast Mediterranean is probably under the influence of the permanent southeast Mediterranean low.

Salinity and the MO index do not equally correspond throughout the period (Fig. 5). At

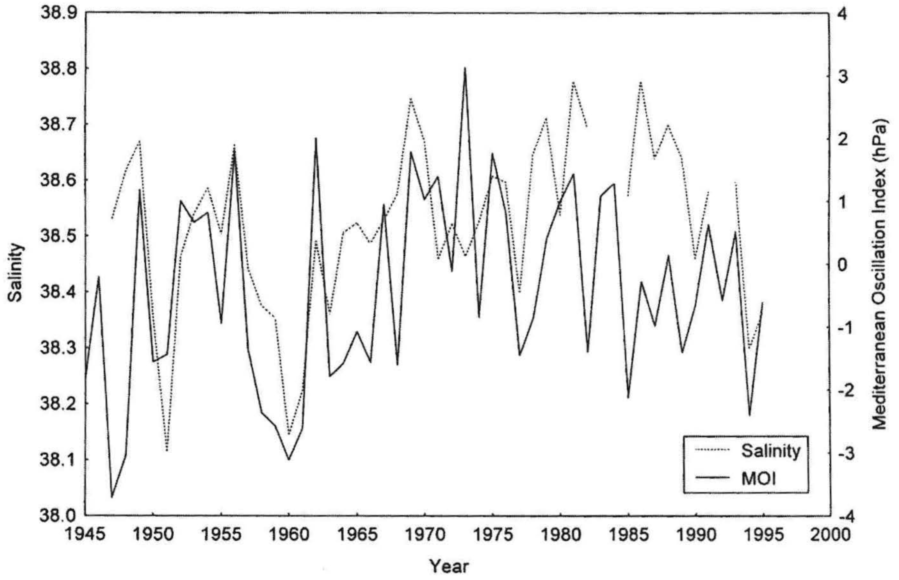

Fig. 5. The long-term salinity variations in the intermediate layer of the Middle Adriatic compared to the Mediterranean Oscillation index defined through this analysis

Table 4. Results of the correlation analysis between the annual salinity in the intermediary layer of the Middle Adriatic and difference of the PC4 and PC6 components from the PC analysis of the winter (DJFM) pressure field in the period 1900-1995, the MOI (pressure difference between the gridpoints in the Mid North Atlantic and the

Correlation coefficient	Annual salinity	DJFM salinity	Number of data	Significance level
PC4-PC6	-0.23	-0.31	48	0.001
MOI (DJFM)	0.19	0.08	48	0.001
NAO(DJFM)	-0.10	-0.09	48	

the beginning and end of the studied period, the two factors corresponded better than between 1964 and 1973.

The increase of salinity in the eastern Mediterranean during this period, and consequently in the intermediate layer of the middle Adriatic, was influenced by changes in the fresh water budget after construction of the Aswan Dam in 1964 (GERGES, 1976) because the gradual reduction of the Nile inflow into the eastern Mediterranean lasted several years. The salinity during this period varied from year to year due to meteorological influences but tended to increase due to the reduced input of fresh water.

PC analysis was also performed for the winter pressure field (December-March). There was no correlation between the winter NAO and salinity, while the correlation of the principal components of the winter pressure field with salinity was much lower (Table 4).

Climatic impact on water mass distribution

Considerable year-to-year variability of the MO index, as well as variations of overall meteorological conditions that caused cold or mild winters, resulted in formation of different water masses in the Adriatic in different years.

The appearance of NAdDW in the northern Adriatic and LIW in the middle Adriatic can be evidenced in hydrographical data from the Jabuka pit and Palagruža transects collected May 1998-August 1999, which indicate that the two phenomena are related. The situation in May 1998 was different than in May 1999 in both the surface and the bottom layer. Surface conditions are a consequence of direct atmospheric influence. In the middle Adriatic, NAdDW was absent in both transects during 1998. In the Jabuka transect (Fig. 6), it appeared in February 1999 and remained there until May 1999 while in the Palagruža transect (Fig. 7), it appeared later (in April 1999) and remained there in May 1999. Unfortunately, measurements were not frequent enough to follow when the formation of NAdDW occurs, although we can follow the spread of the NAdDW from the Jabuka to the Palagruža transect.

In 1998, at Palagruža, the more southerly transect, both LIW and SAdDW were detected while no LIW was detected in the more northerly Jabuka transect. In 1999, both were present at Palagruža through February; by April 1999, LIW reached Jabuka.

During the period May 1998-May 1999, the dense (cold) NAdDW appeared in the Jabuka pit and later in the Palagruža sill, and LIW progressed from the southern Palagruža sill to the northern Jabuka transect. The absence of lighter middle Adriatic water also shows that, during this period, the inflow of Mediterranean water prevailed.

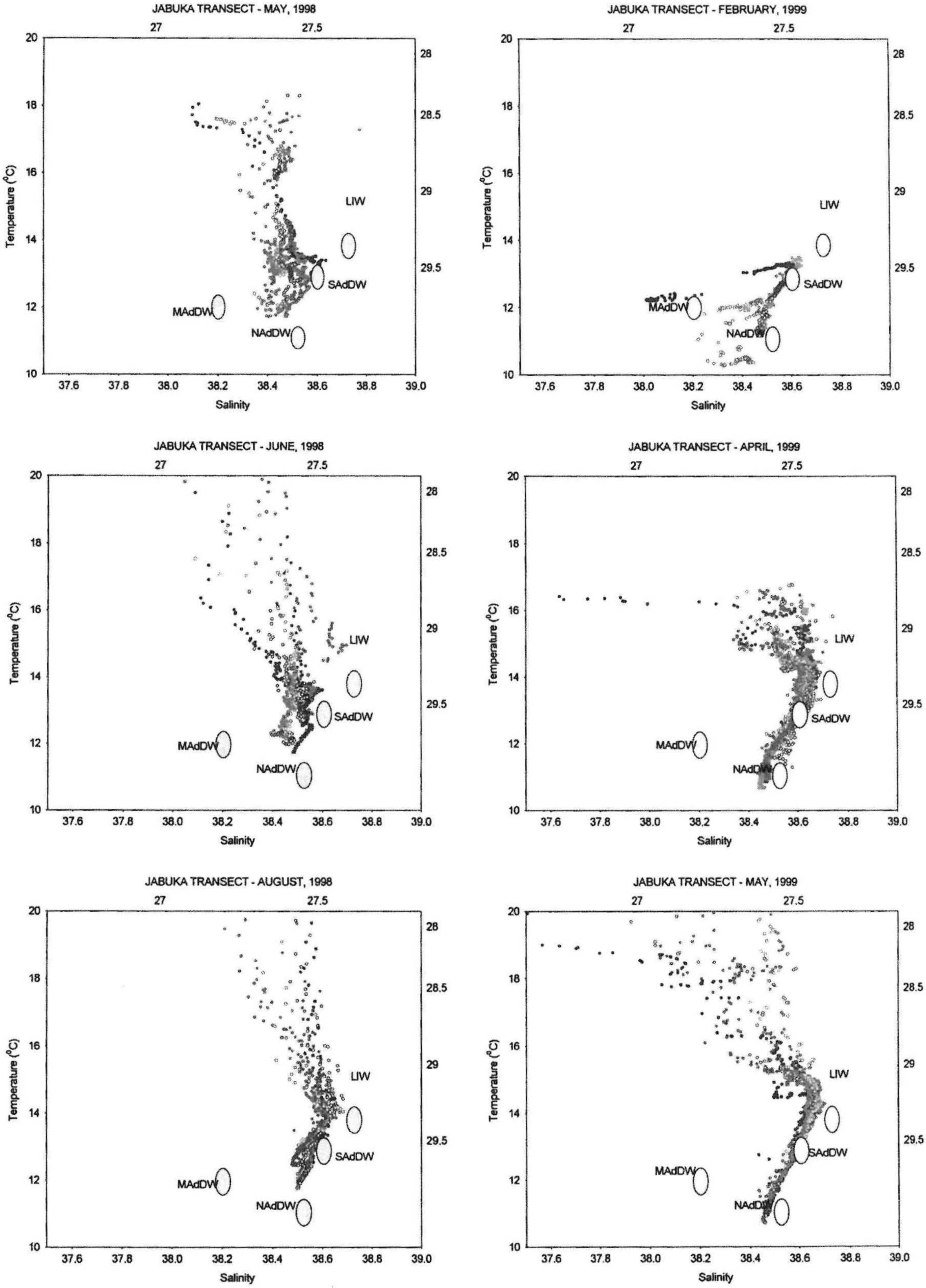

Fig. 6. T-S diagram for the Jabuka transect for the period 1998-1999. The circles indicate the water masses defined by ZORE-ARMANDA (1963)

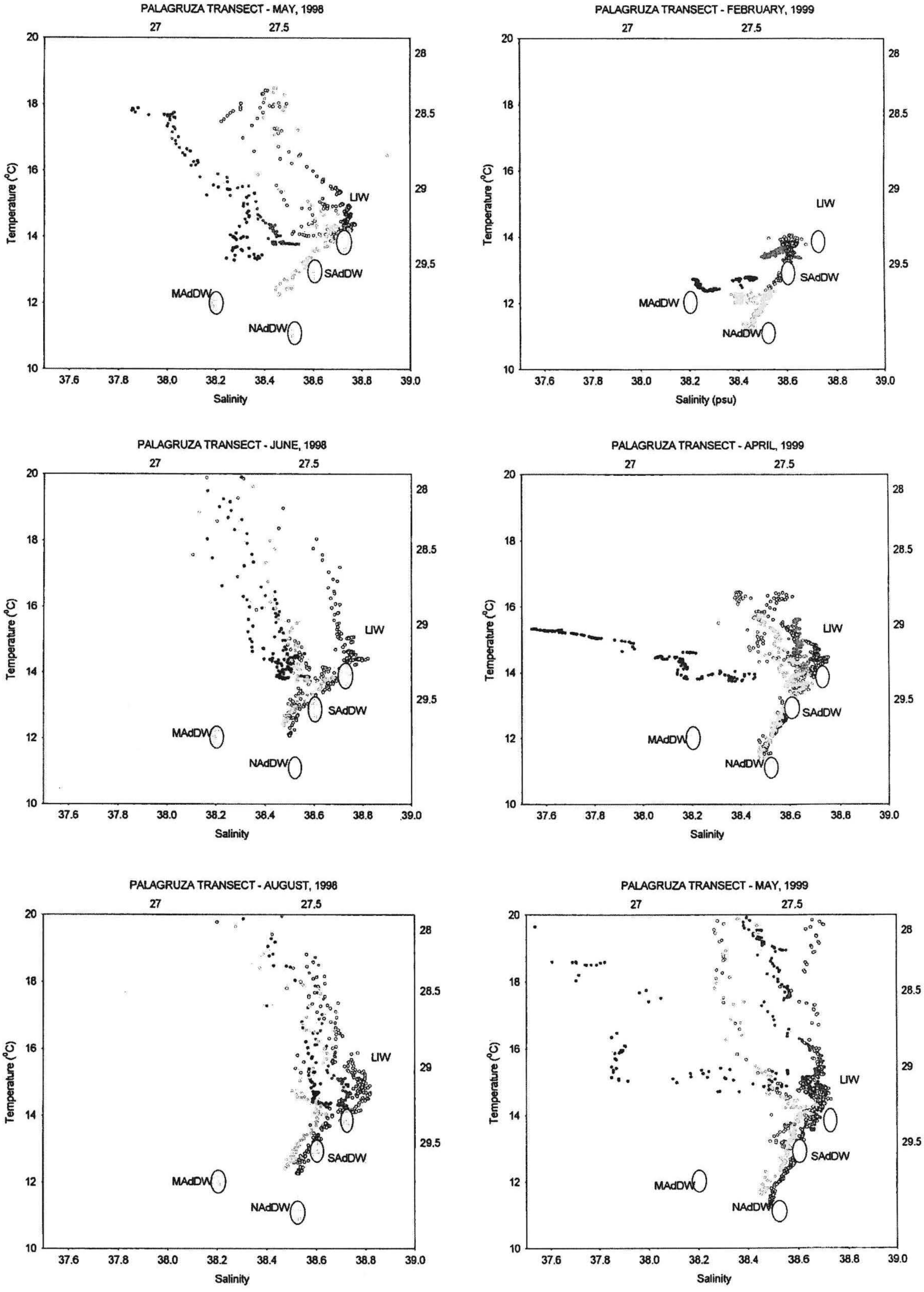

Fig. 7. *T-S diagram for the Palagruža transect from May, 1998 to August, 1999. The circles indicate water masses defined by ZORE-ARMANDA (1963)*

CONCLUSIONS

Large differences of pressure between semipermanent pressure fields in the mid-northern Atlantic and southeast Mediterranean are related to stronger water inflow from the Mediterranean to the Adriatic.

The impact of climatic conditions on the year-to-year fluctuations of thermohaline properties of the Adriatic Sea was analysed for 1900-1998, using new data. The relationship between the atmospheric pressure distribution over the Mediterranean Sea and salinity fluctuations was investigated. Patterns obtained by Principal Component analysis of the differences in pressure between the mid-northern Atlantic and the southeastern Mediterranean correlated with the mean yearly time-series of salinity in the intermediate layer of the middle Adriatic, and was used to describe the fluctuations in inflow intensity of the saltier LIW across the Strait of Otranto into the Adriatic.

The relationship between the North Atlantic Oscillation (NAO) and salinity variation in the intermediate layer of the middle Adriatic, in spite of some similarities, was not clear.

Principal Component (PC) analysis was applied to the large-scale pressure field and enabled definition of the Mediterranean Oscillation (MO) index as the difference in pressure between the mid-northern Atlantic and the southeast Mediterranean. It was shown that the MO index is related to the intensity of the LIW flow into the Adriatic. The inflow is stronger when the pressure is relatively higher over the mid-northern Atlantic. Low correlation between PC components of the winter pressure field favours the assumption that winter action is only a part of the inflow mechanism.

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Mediteranska oscilacija u odnosu na fluktuacije slanosti u Jadranskom moru

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SAŽETAK

Analizirane su godišnje vrijednosti kolebanja tlaka zraka za područje od sjeveroistočnog Atlantika do jugoistočnog Sredozemlja za razdoblje od 1900-1995 g. kako bi se odredila meteorološka stanja koja su povoljna za ulazak istočno mediteranske intermedijarne vode (LIW) u Jadran. Analizirana je i reakcija na klimatske promjene hemisfere definirane pomoću NAO indeksa. Analiza glavnih komponenti (PC) polja tlaka dala je različite modele promjena i omogućila lociranje područja tlaka direktno vezanog za istočno mediteranski ulazak vode u Jadran, koji se očituje u porastu slanosti. To je omogućilo definiranje Mediteranske oscilacije (MO) kao razlike tlaka zraka između područja sjeveroistočnog Atlantika i jugoistočnog Mediterana. Kolebanja i slanost intermedijarnog sloja u srednjem Jadranu od 1947-1995 kao posljedica ulaza LIW vode u Jadran, slijede godišnje promjene tlaka zraka. Analiza atmosferskog tlaka u odnosu na slanost provedena je i za zimske mjesece (prosinac-ožujak).

Ključne riječi: razlika tlaka zraka na velikoj skali, NAO, slanost, tlak zraka na morskoj razini, Mediteranska oscilacija