ISSN: 0001-5113
AADRAY

ACTA ADRIAT.,
56(1): 47 - 66, 2015

ORIGINAL SCIENTIFIC PAPER

Climate regime shifts and multi-decadal variability of the Adriatic Sea pelagic ecosystem

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In recent highly variable climate, a combined effect of a large-scale northern hemisphere climate and regional-scale Adriatic hydroclimate changes significantly reflected in the Adriatic Sea ecosystem. To clarify this statement we set up in connection two inter-annual systems: the air-sea interconnected system and pelagic ecosystems for the period 1961 to 2010. Within this period, significant changes occurred through 1987-1998 period, characterized by a drop of temperature, salinity and oxygen concentration in the middle Adriatic intermediate layer as consequence of a weaker ventilation of the Adriatic Sea. The pelagic ecosystem reacted to these changes. Large fluctuations in marine biota (from plankton to pelagic fish) revealed significantly different regimes before and after the late eighties. Different patterns observed through analyzed biotic parameters seem linked to modification in thermohaline circulation related to the Eastern Mediterranean Transient (EMT), whose effects prevented warmer and saltier water mass intrusions into the Adriatic Sea. These results provide evidence on connections between the shifts in the middle Adriatic pelagic ecosystem and the northern hemisphere climate via changes in regional atmospheric conditions, and highlight the importance of northern hemisphere climate changes for physical and biological regimes of the Adriatic Sea.

Key words: Mid-latitude teleconnections, Adriatic climate, regime shift, plankton, pelagic fish

INTRODUCTION

Complexity of the oceanographic states of the Adriatic Sea starts from its geographical orientation, since it is deeply embedded into the European continent and consequently regarded as a transitional zone between the influences of continental Europe and the oceanic effect of the Mediterranean Sea. As the prevailing meteorological conditions over the area are mainly controlled with external forcing *via* atmospheric teleconnection pattern, the basin-wide Adriatic thermohaline circulation (AdTHC) depends on the large-scale atmospheric oscillations. This should be emphasized since AdTHC and the environmental conditions in the sea, also change.

The Adriatic Sea has long been recognized as the sea sensitive to climate changes. The two possible states of the Adriatic Sea, the periods of stronger Mediterranean intrusions in the intermediate layer (i.e., ingressional) and periods of weaker intrusions (i.e., non-ingressional) (BUL-

JAN & ZORE-ARMANDA, 1976) have been recently explained by bimodal circulation (CIVITARESE *et al*., 2010). This is associated with the atmospheric processes on a scale larger than the Adriatic basin, i.e. with variations in air pressure in the northern hemisphere (NH) (ZORE-ARMANDA, 1969; GRBEC *et al*., 2003, SUPIĆ *et al*., 2004). Due to the recent more frequent and stronger changes in the atmosphere, the established paradigm between ingressional/non-ingressional states in the Adriatic Sea introduced by BULJAN (1953), which implies increase/decrease in salinity (and density) due to the strengthening/weakening of Levantine Intermediate Water (LIW) intrusions to the Adriatic Sea, should be revised as suggested by CIVITARESE, *et al*. (2010). Changes in nutrients and production and pelagic ecosystem are not simply a consequence of intensification of the Eastern Mediterranean water inflow in the Adriatic, since these cannot explain transient Adriatic thermohaline conditions observed in the recent decades. Establishing anti-cyclonic and cyclonic circulation in the Ionian Sea (Bimodal Oscillating System; BiOS) salinity in the southern Adriatic is oscillating between the periods of reduced and enhanced salinity. In the middle Adriatic, the thermohaline states are also oscillatory and more or less synchronous with Ionian salinity fluctuations, depending on the stronger/weaker intrusions from the Mediterranean, i.e. depending on the established cyclonic/anti-cyclonic circulation in the Ionian Sea (CIVITARESE *et al*. 2010; MATIĆ, *et. al*., 2011). The middle part of the eastern Adriatic is influenced by water intrusions from the Mediterranean (LIW and/or CW). The fluctuations of these intrusions have long ago been related to large scale pressure distribution over the NH. It is indisputable that the changes in pressure distribution over the NH and in the position of large pressure centres that define atmospheric oscillations such as the North Atlantic Oscillation (NAO), Arctic Oscillation (AO) and Mediterranean Oscillation (MO), cause changes in the thermohaline circulation of the Adriatic Sea as well as changes in phytoplankton, zooplankton and pelagic fish biomass (SANTOJANNI, *et. al*., 2006; COLL *et al.,* 2009).

Large-scale atmospheric pattern affects the marine ecosystem through regional weather pattern and ocean features. Natural modes of atmospheric variability such as the NAO, AO and MO during winter impose changes in the wind stress and heat flux on the ocean causing changes of temperature and salinity (GRBEC *et al*., 2007; MATIĆ *et al*., 2011), and biotic components (DULČIĆ *et al*., 2004, 2007; GRBEC et al., 2009; NINČEVIĆ GLADAN et al., 2009) of the Adriatic Sea ecosystem. Jumping from one stable state to another, climate system can produce a shift and establish a new regime in the marine ecosystem. According to RODIONOV & OVERLAND (2005) “in the marine environment, regimes may last for several decades and shifts often appear to be associated with changes in the climate system“. Most of the shifts in the marine ecosystem were attributed to changes in the sea temperature, salinity and circulation controlled by local atmospheric variations that are partly under the influence of large-scale teleconnections.

The objective of this paper was to explain the main environmental drivers of ecosystem variability on regional Adriatic scale. The intention of this paper is also to document synchronous changes in the atmosphere and the sea, that both interacted with marine ecosystem, from phytoplankton community to pelagic fish populations during significantly different climate regimes (1963-1986; 1987-1998) occurring in the Adriatic in the last 50 years. We wish to emphasize that only long-term series can allow such investigation especially in seas where trends and climate shifts are crucial for the ecosystem changes.

MATERIAL AND METHODS

Mid-latitude teleconnections and Adriatic climate

The dominant mid-latitude teleconnections (MLT) exert a strong influence on the cold season temperature and precipitation over the Adriatic region (Fig. 1). This is extremely important since winter season is crucial for the

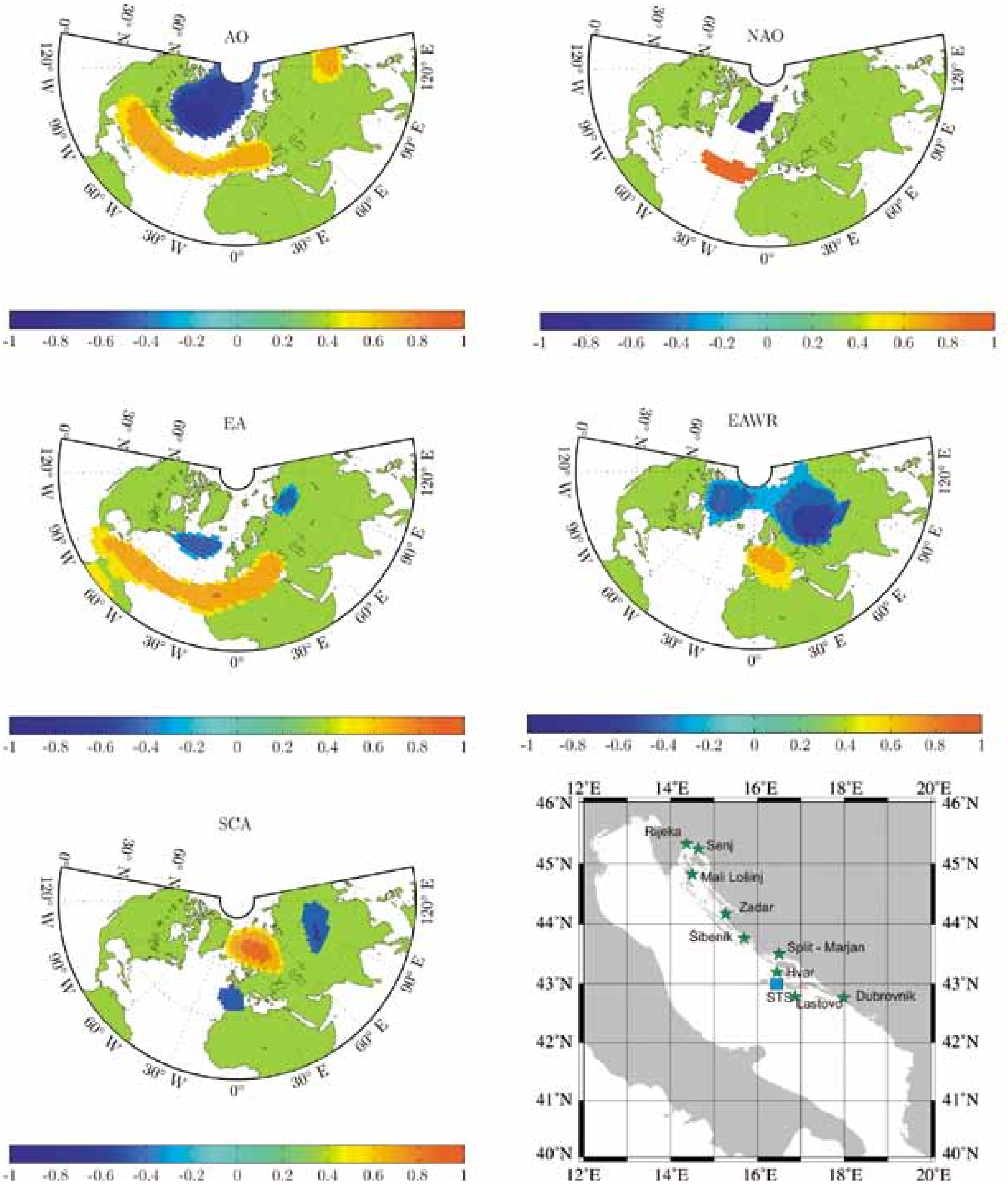

Fig. 1. MLT winter (JFM) patterns based on geographically oriented correlation coefficients between sea level pressure gridded data created using www.cpc.ncep.noaa.gov/data data sets and locations of the nine meteorological stations and one oceanographic station (□) included in this study

Adriatic thermohaline circulation, which partly controls the marine ecosystem variability. The largest mid-latitude variability refers to the role of NAO, which determines a large and robust signal on winter season in the Mediterranean region (HURRELL, 1995; RODO *et al*., 1997; XOPLAKI, *et al*., 2003). The NAO index is defined as a winter difference of normalized sea level pressure between Lisbon (Portugal) and Reykjavik (Iceland). The AO is an atmospheric circulation pattern in which the atmospheric pressure over the polar region varies in opposition with that over middle latitudes (THOMPSON & WALLACE, 1998). During the winter season (January through March) it extends upward into the stratosphere where it modulates the strength of the westerly vortex that encircles the Arctic polar cap region (THOMPSON *et al*., 2002). The NAO and AO describe similar phenomena, but giving importance to different pressure centres (THOMPSON & WALLACE, 2001). Additionally, in the eastern part of the Mediterranean region, the advection of moisture plays an important role and it seems that other large-scale patterns, like East Atlantic (EA), (KRICHAK *et al*., 2002) have a strong influence (XOPLAKI, *et al*., 2003). The EA pattern is the second prominent mode of low-frequency variability over the North Atlantic, and appears as a leading mode in all months. The EA index is defined as a north-south dipole of anomaly centers spanning the North Atlantic from east to west. The anomaly centers of the EA pattern are displaced south-eastward to the approximate nodal lines of the NAO pattern. For this reason, the EA pattern is often interpreted as a "southward shifted" NAO pattern. The positive phase of the EA pattern is associated with above average surface temperatures in Europe. It is also associated with above-average precipitation over northern Europe and Scandinavia and with below-average precipitation across southern Europe. The global/hemispheric scale teleconnection patterns, very important for Adriatic climate changes, are NAO, EA, EAWR (East Atlantic West Russia), AO and SCA (Scandinavian Oscillation) (MATIĆ, 2011).

In this paper, the Adriatic climate was studied using air temperature, precipitation, relative humidity, and wind speed. Mean winter (JFM) monthly values of the following meteorological variables were used to determine Adriatic climate proxy *via* Principal Component Analysis: air temperature, precipitation, humidity and wind speed for 9 meteorological stations along the eastern Adriatic coast (Fig. 1). The extracted principal components for the winter season were used as a proxy of the Adriatic climate. These components were put in correlation with mid-latitude oscillation indices in order to discover the possible key mechanism of ecological regimes induced by climate.

Hydroclimate and pelagic ecosystem data

The cold season is crucial for the Adriatic dynamics, controlling strengthening/ weakening of the water mass exchange through the Otranto strait (ORLIĆ, *et al*., 2007). In the stratified period, oceanic conditions in the layer below thermocline reflect possible discrepancy against the normal thermohaline circulation influenced by previous winter conditions. To examine this, the ocean data collected at the offshore station Stončica STS (43°00 N, 16°20' E) located in the central Adriatic Sea were analyzed. The depth of the station is 107 m, with detrital and slightly muddy bottom. Based on the long-term monitoring of chemical and biological parameters this area is recognized as an oligotrophic open-sea, characterized by high transparency and decreased phyto- and zooplankton abundances in comparison to the more productive coastal areas along the central Adriatic. The station is strongly influenced by the incoming Mediterranean water masses, known as the Levantine Intermediate Water. Temperature, salinity and oxygen profiles for the station Stončica were used to study hydroclimate modifications of the local environmental conditions.

Chl *a* data set from the station Stončica span from 1977 to 2010. Samples for phytoplankton biomass determination were collected monthly at standard oceanic depths, using 1.7 L Niskin bottles. Based on the proposed hypothesis that winter conditions are reflected in the thermohaline circulation in the summer period, the results are shown as integrated values from (50-75)m, that best reflects intermediate layer and Mediterranean intrusions in this area.

Long-term zooplankton data originate from regular zooplankton sampling station Stončica since 1959, performed at approximately monthly intervals, using the Hensen net (mesh size 330 µm, 0.73 m opening diameter) towed vertically from near-bottom to the surface (100-0) m. Despite the limitations of this sampling tool, data obtained by this method are the only available long-term data set for zooplankton community. Samples were preserved by formalin fixation (2.5%), buffered with calcium carbonate. Data records include total zooplankton biomass expressed as mg m^{-3} dry weight from March 1959 to December 1994 period (with gaps) and abundance data at group level (ind. m^{-3}) available from March 1959 to March 1996 (with gaps). In this paper we have used the summer period data (JJA), since September data were sampled late in the month, which already reflects autumn conditions. The following zooplankton groups were used: Copepoda, Cladocera, Appendicularia, Thaliacea, Chaetognatha, jellyfish (Medusae/Siphonophora) as well as sardine and anchovy eggs abundance. Long term zooplankton data from station Stončica were analysed in several papers (REGNER, 1985, 1991; BARANOVIĆ *et al*., 1992; ŠOLIĆ *et al*., 1997; BERLINE *et al*., 2011). Abundance data are part of electronic archives such as COPEPOD, a global plankton database (http://www.st.nmfs.noaa.gov/plankton/).

Sardine (*Sardine pilchardus*) and anchovy (*Engraulis encrasicolus*) are commercially important fish resources in the Adriatic Sea. Small pelagic fish like sardine and anchovy are fast growing and short lived species, characterized by marked fluctuations in their respective stock sizes because of their high dependence on highly variable, environmentally driven, annual recruitment pulse. Sardine and anchovy are of major importance for Adriatic fisheries, as they account for approximately 41 % of total Adriatic marine catches (Average over the period 1970-2005, Fishstat+, FAO 2007). These two species in the Adriatic Sea are targeted with the same fishing gear, in Croatia with purse seiners, while in Italy and Slovenia pelagic trawlers are used. Hence, monthly and yearly alternations in the amount of the catches and biomass for both species are noticed. The two species are also opportunistic regarding the spawning season as sardine is spawning during the colder and anchovy during the warmer part of the year. Sardine and anchovy are common shared renewable resources. All assessments for the Adriatic Sea (GSA 17) are done within the FAO AdriaMed working group. The data used for the given assessment derive from the catch recorded for the fleets of Italy, Croatia and Slovenia, from 1975 to 2010. The biological data of the species (available since 1975 for the western and from the 2001 for the eastern side) were used to obtain the age distribution in the catches. Echo-survey abundance index was used to tune the models. The echo-surveys were carried out for both the western and eastern sides of the Adriatic from 2004 onwards. Western echo-survey abundances were split into age classes by the means of length frequency distribution coming from the western echo-survey and age-length key coming from the Italian commercial fleet. On the other hand, eastern echo-survey abundance was distributed into age classes by the means of length frequencies and age-length key coming from the Croatian commercial fleet. For sardine, the calendar year was used, by fixing the birthday date on the first of January, while for anchovy, the split year was used, by fixing the birthday date on the first of June due to the biology of this species in the Adriatic Sea. The natural mortality rate was taken as variable over age and was calculated using the Gislason's equation. The growth parameters required by this method were derived from the biological sampling of the Croatian catches. The Virtual population analysis (VPA) with Laurec-Shepherd tuning, used in this paper, respected the VPA assumption of constant catchability at age over time.

Data analysis

The Principal Component Analysis (PCA) (PREISENDORFER, 1988) was applied to determine the interannual variability of the Adriatic climate. The matrix was composed of mean winter (JFM) time series of air temperature, precipitation, relative humidity and wind speed from the nine meteorological stations along the eastern Adriatic coast. The data were structured as a matrix *M (m, n)*. Each of *m* rows describe one winter season from 1961–2007 for *n* variables consisting of four meteorological parameters for nine stations along the eastern Adriatic coast. The principal components showing eigenvalues greater than 1 (Kaiser–Guttman criterion) were used in the further analysis. The orthogonal varimax rotation of extracted principal components was applied. The obtained significant PCs were used as the Adriatic climate proxy (ACP) in the winter season. The relations between regional conditions, described by Adriatic climate proxy and thermohaline variability, described by temperature, salinity and oxygen concentrations in the stratified period together with the large-scale circulation patterns were examined through their correlations with the MLT indices.

In order to distinguish different stable periods, the Sequential t-test algorithm for regime shift detection (STARS) proposed by RODIONOV (2004) was applied on MLT indices, Adriatic climate proxies, temperature, oxygen and on the ecosystem data: phytoplankton, zooplankton, anchovy and sardine biomass data. The definitions of stable periods are based on sequential t-test analysis in which the method determines whether the next value in the investigated time series is significantly different from the previous regime mean values. If so this year is marked as a year when the new regime started. The subsequent observations are used to confirm or reject the regime shift. The hypothesis of existence of a new regime is tested using regime shift index $RSI = \sum_{i}^{i+m} \frac{x_i^*}{l\sigma_l}$ where m is number of years since the new regime starts, l is cut-off length of the regime, and s_l is standard deviation in the l-year regime. The cut-off length determines the minimum duration of a regime. The RSI represents a cumulative sum of the normalized anomalies. The differences between the mean values of a new regime and the current one are used to test the significance according to the Student's t-test. The determination of the regime is strongly dependent on the cut-off length l and probability level p of the t-test. For our time series the cut-off length is set to $l = 10$, and $p = 0.05$. The relationship of the regional conditions, described by the Adriatic climate proxy with the large-scale circulation patterns was examined through their correlations with MLT patterns both for original and de-trended time series. Process of autocorrelation removal can decrease the statistical power when slowly changing processes are important (for example in the time series with significant linear trend).

RESULTS AND DISCUSSION

Atmosphere-ocean covariability

MLT patterns over the NH were analyzed in order to compare their long-term covariability with the winter Adriatic climate and thermohaline circulation in the stratified period. Based on the winter indices in the analysed period from 1950 to 2010, MLT variability points to a few climatic turning points that separate the existence of different stable regimes. Strong drop is visible around the year 1987 in all long-term MLT pattern data, except on SCA. Cumulative sum (CumSum) of normalized deviations (Fig. 2) shows the individual values compared to the overall average. In the periods when the values of MLT indices are below the overall average (zero point for normalized values), almost all CumSums decreased. In the period when the values are above the overall average, the CumSum increased. In the year when the CumSum function has changed sign (point of inflection) from decreasing to increasing slope (or

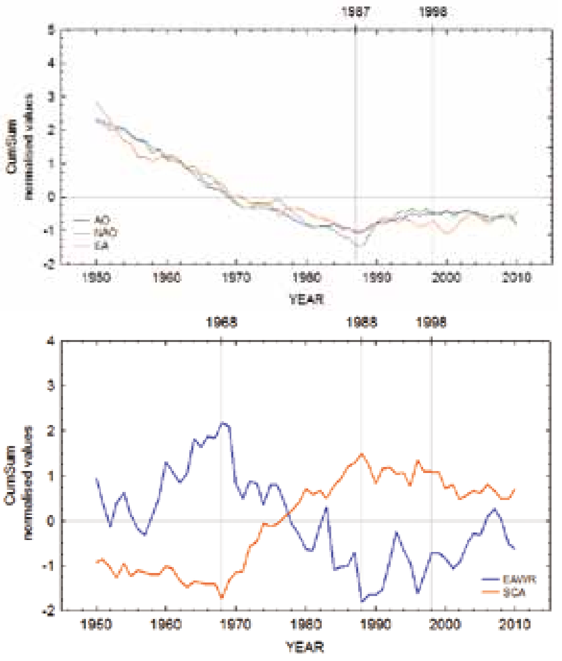

Fig. 2. CumSum of five MLT indices of AO, NAO, EA, EAWR and SCA

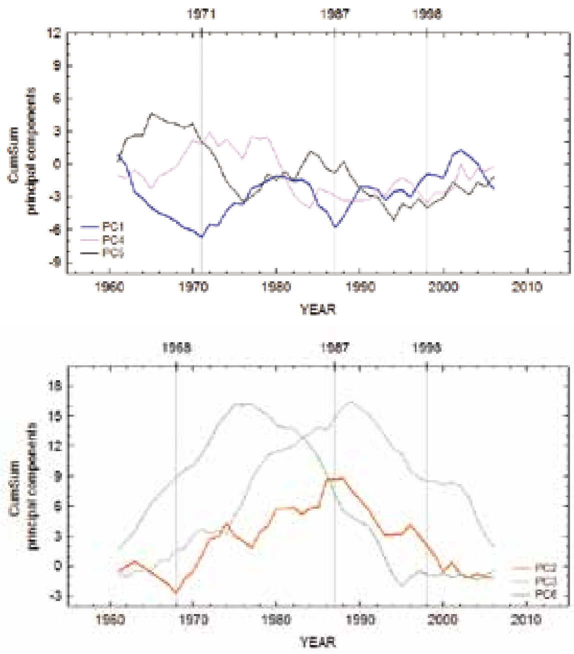

Fig. 3. CumSum of winter proxy resulting from the principal component analysis performed on meteorological data (matrix M) for nine stations along the eastern Adriatic coast

trend), the climate turning point is detected. The CumSum plots show variable but continuous decline until 1987. After 1987, the winter oscillations indices of NAO, AO, EA and EAWR have increased. Applying the STARS method on the MLT time series the two turning points (around 1987 and around 1999) bounded one stable climate regime. After performing the PCA on matrix *M,* the six significant components (eigenvalue>1) were extracted, explaining 82.7% of the total variance of the initial matrix. Extracted PC loadings separate the six different groups which contribute with different power in the total variance of meteorological variables included in the analysis. First extracted component (explained variance is 34.81%) has grouped the winter temperatures over the whole Adriatic Sea. Its temporal scores describe the air temperature variations over the Adriatic in the cold part of year. The second one, with explained variance of 28.59%, has significant loadings in the precipitation field, while the third one explained 12.9% of variance and has significant loadings in the humidity. The remaining significant principal components explain 12% of the total variance and have a significant loading in the wind variations over the Adriatic. Based on the PC analysis, the Adriatic climate proxies (ACP) were defined as temporal variations of the winter temperature (PC1) and precipitation (PC2). Wind variations over the Adriatic Sea in winter (explained by PC4, PC5 and PC6) showed strong spatial inhomogeneity. The fourth extracted component (PC4) explained interannual variability in winter wind field over the northern Adriatic, e.g. the frequency of Bora wind episodes. Next extracted wind component PC5 is related to the mean winter wind speed over the middle Adriatic, while the last significant component PC6 describes the wind variability over the areas sheltered from the Bora wind like Lastovo and Zadar. Interannual variability of wind in these areas is different from wind variability in the northern Adriatic. In the period after 1987, mean winter Bora frequency decreased from 22.42 (from the period 1981-1986) to 11.81 (in the period 1987-1998) (PANDŽIĆ & LIKSO, 2005). This phenomenon can be observed through the course of CumSum for PC4 and PC5 (Fig. 3). The crucial year 1987 has divided the two wind regimes over the Adriatic Sea. The first regime was characterized by the Bora wind in the north and Sirocco in the south Adriatic. The second regime is characterized by the Bora wind along the whole Adriatic (MATIĆ, *et al*., 2011). The CumSum plot of PC4 shows abrupt decrease of wind frequency until 1987, followed by a slow increasing period representing new stable regime until 1998. Connection between ACP and MLT is best observed on the parameters that control the temperature and precipitation conditions over the Adriatic. Correlation analysis has a significant statistical relationship between PC1 and EA, and between PC2 and SCA (Fig. 4). The positive phase of the EA pattern supports the atmospheric pressure gradient from south to north, which results in the advection of warmer air from the southern Mediterranean to the south Adriatic Sea. The correlation between the winter EA index and temperature decreases towards the south. The distribution of pressure during the positive phase of the dominant SCA controls cyclone passage in winter through the central Europe.

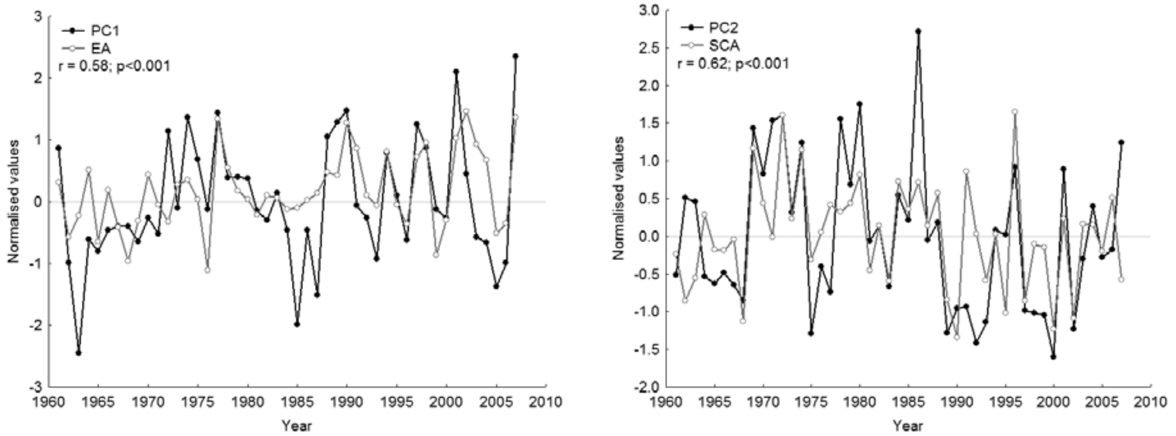

Fig. 4. Interannual variability of first extracted principal component (PC1) and EA winter index, and second extracted principal component (PC2) and winter SCA index

This explains high correlation obtained between SCA index and PC2.

Changes of stable states in the atmosphere at hemispheric and regional scales and thermohaline variability in the middle Adriatic are synchronous. Regime shift analysis of sea temperature, salinity and oxygen for stratified period at the station Stončica in the (50-100)m layer has separated two stable periods. In the period 1987-1999 relatively low temperatures were present in the deep layers at the station Stončica. The drop of salinities in deep layers is also observed, as well as lower oxygen concentrations (Fig. 5). The same period was accompanied by a lower nutrient content (KUŠPILIĆ *et al.*, 2004). Such low temperatures, salinities and oxygen concentrations in the deep layers confirm lower advection of warmer and saltier Mediterranean waters i.e. lower ventilation of the Adriatic Sea. Such changed conditions in the period 1987-1998 point to changes in ocean climate regime. The deep layer temperature conditions in 1998 increased to the values before 1988. As highlighted in MATIĆ *et al.* (2011), the period of changed climate regime (1987-1998) was caused by the EMT, which slowed the water exchange between the Adriatic and the Mediterranean. The conditions in the South Adriatic (CARDIN *et al.*, 2011) demonstrate the role of EMT in exchange processes between the Mediterranean and the Adriatic Sea, pointing that in the period of maximum EMT influence corresponds to colder and

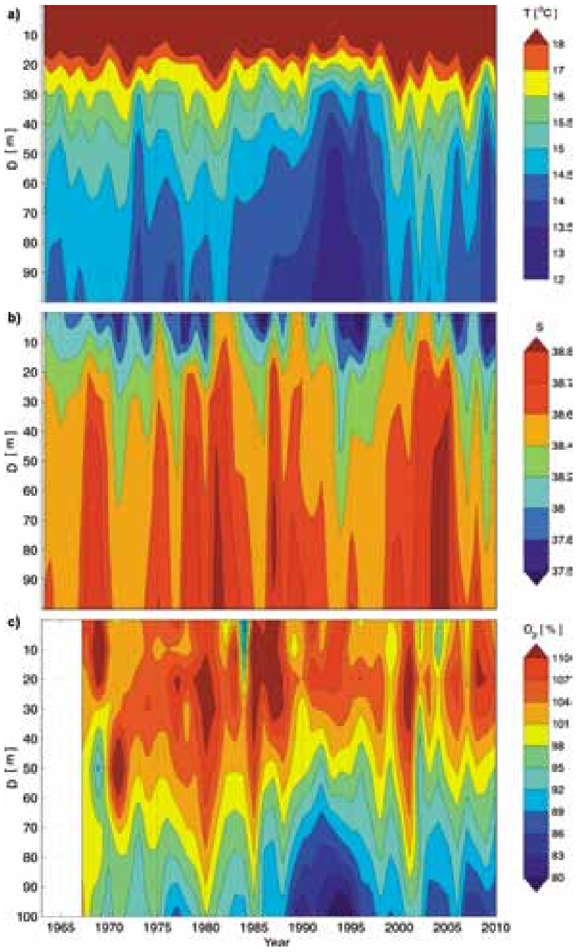

Fig. 5. Hovmöller diagram of temperature a), salinity b), and oxygen concentrations c) at Stončica station from the period 1961-2010

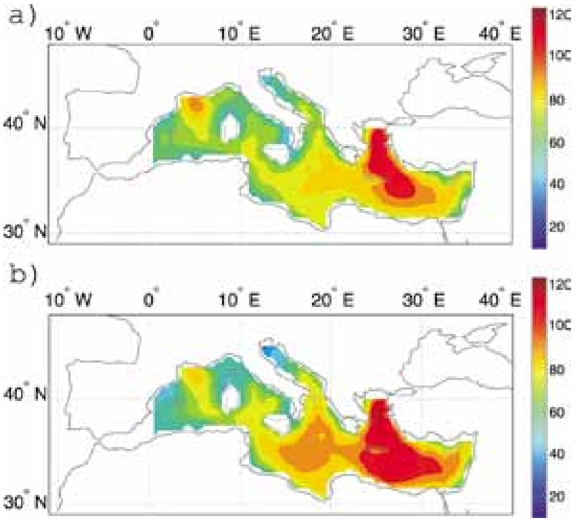

Fig. 6. Mean evaporation field for February (ERA-40 reanalysis) for the a) non EMT period (1963-1986), and b) for the EMT period (1987-1998)

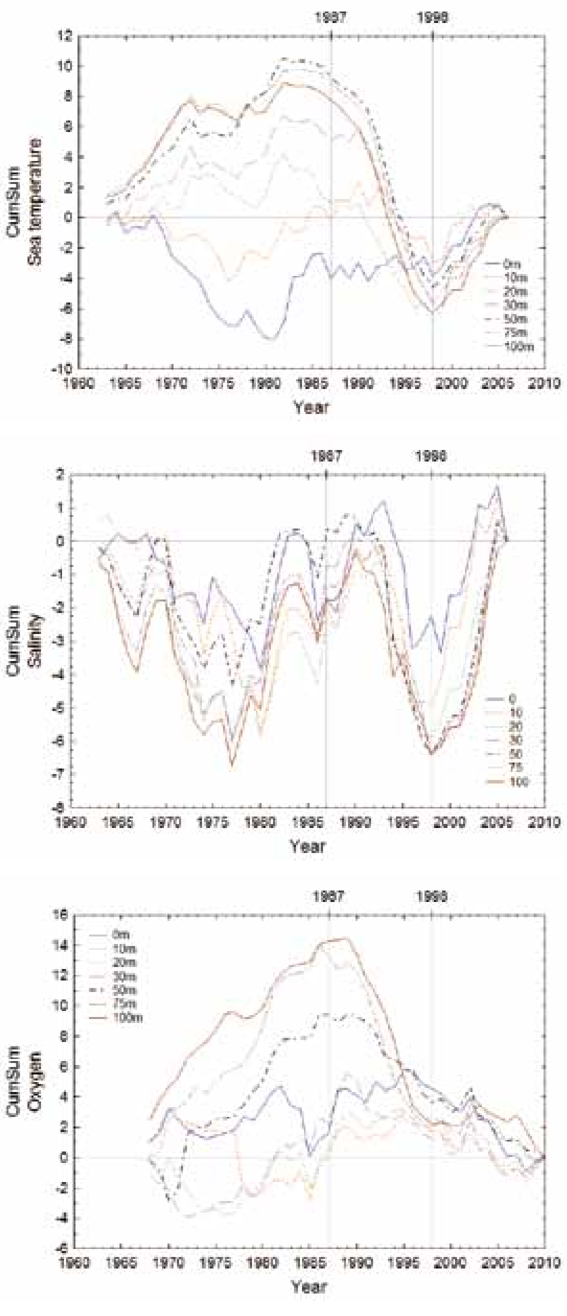

Fig. 7. CumSum plot of temperature, salinity and oxygen concentrations at the Stončica station for the standard oceanographic depths

less saline Eastern Middle Adriatic thermohaline conditions. The paper by GAČIĆ *et al.* (2011) shows, that preconditioning EMT-like events are related to internal dynamics, described by the BiOS. However, the switch of deep-water formation in the Mediterranean, from the Adriatic to the Aegean occurred only under favorable and severe winter condition in the Aegean and in the Adriatic sea. So, for more general conclusions it will be necessary to investigate atmospheric forcing in the Aegean Sea including meteorological data based on a broader area covering the Adriatic-Ionian-Aegean regions. In this very complex area the atmospheric forcing responsible for the variability of the circulation patterns during EMT winter events is linked to unusual cyclonic activities over the area. It was observed that anomalously high sensible and latent heat fluxes occurred during EMT winters, as consequences of increasing of eastern Mediterranean storms, which brought very cold air masses over the Aegean Sea (ROMANSKI *et al.* 2012). Wind stress climatology over the Mediterranean is significantly different in periods of EMT and non-EMT. The period of first climate regime (1963-1986) over wider Mediterranean area is characterized by a significantly different mean wind field than in the second climate regime (1987-1998). The conditions in the wind field after 1987 have resulted with decrease of evaporation in the North Adriatic while outbursts of polar air over the Aegean and Eastern Mediterranean caused significant evaporation increase (SAMUEL *et al.*, 1999). Evaporation over the Aegean Sea in the years of EMT formations was significantly different in comparison to non-EMT period as seen from the Fig. 6 (redrawn from MATIĆ, 2011). Although direct link between

NAO and other MLT patterns and regional atmospheric conditions over the Aegean Sea favorable for EMT formation is still a matter of investigations it is no-doubt that Aegean Sea is sensitive to both atmospheric and hydrologic forcing controlled by mid-latitude teleconnection patterns such as EAWR and potentially NAO variability (ROMANSKI *et al*. 2012).

RSI analysis defined the two shifts: in 1987 and 1998. CumSum of normalized sea temperature, salinity, and oxygen in the analyzed period divided surface from deeper layers (Fig. 7). This point to the fact that interannual changes in these layers are influenced by different processes. Evidently, the climate shift in the atmosphere is reflected only in the deep layers. This is caused by circulation process in the stratified period when lateral movements are significant (GRBEC & MOROVIĆ, 1997). The surface layers, which are under direct atmospheric input, are not discussed here.

Because of its large spatial covariability, climate variables such as temperature, wind and pressure pattern can have strong teleconnections within widely separated ocean basins (OVERLAND, *et al*., 2010). This is a main reason of a strong synchrony between atmosphere-ocean system in which extremes of crucial variable (or variables) can cause shifting from one stable state to another. Conversely, in the biotic marine environment such covariability is more complex. Land-locked Adriatic Sea is considered a basin sensitive to climate changes, and biogeochemical covariability in its marine environment can be visible, which opens the possibility to find causality between climate variables and ecosystem response on regional scale.

Pelagic ecosystem response

Plankton

The response of the marine ecosystem shows a switch from negative to positive anomalies in summer phytoplankton biomass after 1987 (Fig. 8). Chl *a* CumSum shows a steep increase from approximately 1987 until 1999, after that period the values drop, then start rising again around 2006, attaining more stable dynamics afterwards. The biomass drop in the period 2000-2005 corresponds to the course of the processes over the NH and cold winter temperature (see Figs. 3 and 4). Documented increases in phytoplankton biomass in NH marine basins and lakes were successfully linked to the NAO change in phase at the end of 1980s, causing a more or less synchronous shift in the phytoplankton community from a traditional dominance of diatoms to flagellates and dinoflagellates (ALHEIT *et al*., 2005; ALHEIT & BAKUN, 2009). A significant relationship between the NAO and phytoplankton biomass has been detected through the

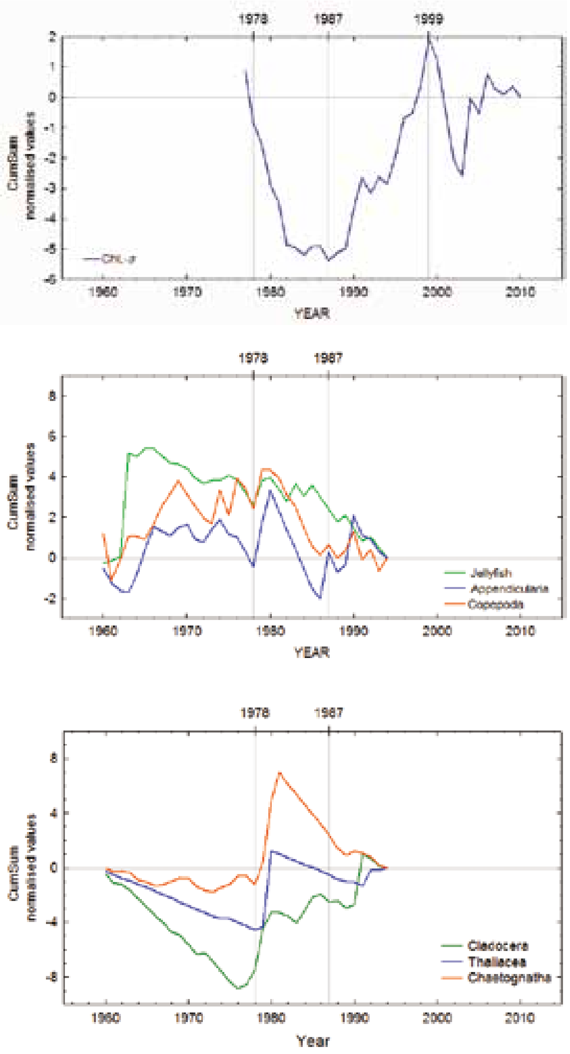

Fig. 8. CumSum for Chl a concentrations, CumSum of summer values for jellyfish, appendicularian and copepod abundances, and CumSum of summer values for cladocera, thaliacea and chaetognatha

correlation of chl *a* during spring maximum in April and February (NINČEVIĆ GLADAN *et al.*, 2009). An increase of phytoplankton abundance, particularly dinoflagellate densities, in the period from the mid-1980s to the mid-1990s coincided with years characterized by a high NAO index. GRBEC *et al.* (2009) attributed the significant decrease in primary production in the 1987-1998 period to the influence of the EMT which established a new circulation regime, preventing the LIW intrusions into the Adriatic Sea. The recorded phytoplankton shift at the station Stončica occurred in the intermediate layer (50-75)m during summer stratified conditions and coincided with low intrusion of Levantine water and presence of old water characterized by lower temperature, salinity and oxygen. Earlier studies have shown that the investigated area is characterized by high abundances of cyanobacteria during the stratification period, particularly *Synechococcus* spp. in the 50-75 m layer (NINČEVIĆ *et al.*, 2002). Since fairly high abundance of *Synechococcus* spp. has been generally associated with lower salinity and/or lower temperature environments (PARTENSKY *et al.*, 1999), the increase in chl *a* concentrations in summer period could be attributed to the onset of environmental conditions favorable for *Synechococcus* spp. growth. The inconsistency between biomass and production can be understood through different response of different species that shows complexity of the pelagic ecosystem.

After a steady decline starting from 1960, summer mesozooplankton abundance experienced a major increase in 1979-1980. After 1980, however, the values declined again, reaching the lowest point in 1987. From 1987 onwards, the increasing trend continued until 1992, which marks the end of the zooplankton series. A steady increase was also evident in summer mesozooplankton biomass data around 1987 (see Fig. 10). Decomposition of the time series into taxonomic groups and subsequent correlation analysis of the cumulative sums showed reversed trends for both total mesozooplankton abundance and biomass with copepods, jellyfish and appendicularians and matching positive trends with cladocerans, thaliaceans and chaetognaths. Copepod and appendicularian summer values behaved irregularly until 1980, when they dropped abruptly and decreased more or less regularly since then, while jellyfish decreased steadily from the late 1960s (Fig. 8). Conversely, cladoceran summer values showed a major increase in 1979-1980, and again after 1987, while summer abundances of both thaliaceans and chaetognaths displayed a significant increase in the 1980, and roughly followed each other in the period 1980-1990, after which they showed the opposing trends.

Several studies highlighted the changes in the middle Adriatic plankton abundances and production that occurred at the beginning of the 1980s, and were attributed to the intrusion of Mediterranean water (BARANOVIĆ *et al.*, 1992; MARASOVIĆ *et al.*, 1995, 1999, 2005; ŠOLIĆ *et al.*, 1997; GRBEC *et al.*, 2009). The change of the NAO in the late 1980s was also reflected in all trophic levels in the pelagial of the North Sea, the central Baltic Sea (ALHEIT & BAKUN, 2009), northwestern Mediterranean (MOLINERO *et al.*, 2005) and Adriatic Sea (CONVERSI *et al.*, 2009, 2010; GRBEC *et al.*, 2009). CONVERSI *et al.* (2009) identified the substantial increase in copepod abundance, and shift towards the smaller species in the copepod population structure in the northern Adriatic Gulf of Trieste centered around 1987, proposing circulation changes and system warming as the environmental drivers for those changes. This increasing trend in the copepod abundances was not evident in our data, but that could be related to the significant undersampling of small copepods with the 330 µm mesh size net, which were presumably most affected in that period (CONVERSI *et al.*, 2009).

Pelagic fish

Since 1975, sardine and anchovy stocks assessments have revealed strong fluctuations in biomass (Fig. 9). Biomass of sardine in the Adriatic Sea (obtained by VPA) reached its maximal value in 1984. After that, sharp decline was noticed until 1999 when the lowest biomass level was obtained. Within the observed collapse, there were few years of stability, from

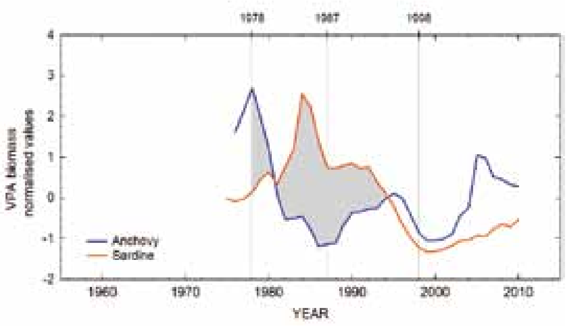

Fig. 9. Normalized VPA of anchovy and sardine biomass in the Adriatic Sea

1987 to 1992. From 1999 onwards, a slight but permanent increase of sardine stock biomass was noticed till the end of investigated period. Anchovy biomass on the other hand, attained its maximum value in 1978. Subsequently, anchovy biomass level started dropping until 1985, when a minimal biomass value was reached. From 1985 onward, recovery of the stock that lasted till 1995 was noticed. Afterwards, anchovy stock collapsed again until 2000, when recovery started again. Alternations between observed sardine and anchovy biomass proved to be statistically significant; negative correlation was established. Opposite biomass contractions among those two species have also been reported earlier in other geographical areas (LLUCH-BELDA *et al*., 1992; BARANGE *et al*., 1999; SCHWARTZLOSE *et al*., 1999; LYNNE *et al*., 2004; TAKASUKA *et al*., 2007; BARANGE *et al*., 2009). Factors that most likely account for mentioned fluctuations were changes in food availability mediated through changes in environmental conditions and variations in fishing effort. Significant positive correlations obtained between anchovy biomass and copepods abundance ($r=0.57$; $p<0.05$), as well as between anchovy biomass and abundance of anchovy eggs ($r=0.64$; $p<0.01$) contributed to aforementioned hypothesis. There was no positive correlation between sardine biomass and zooplankton, because all zooplankton components were sampled during summer, which is not main feeding season for sardine (GARRIDO *et al*., 2008). Starting from 1994, opposite behavior of sardine biomass has changed to simultaneous trend with anchovy. This might be associated with a drop in temperature and salinity in the Adriatic Sea (see Figs 5 and 7). Those changes in temperature and salinity were not favorable for sardine, which according to previous researches (AL-JUFAILI, 2007; BENSON & TRITES, 2002; ALHEIT & BAKUN, 2009) positively correlate with warm regimes and higher salinity (PUCHER-PETKOVIĆ *et al*., 1971; KARLOVAC *et al*, 1974). Hence, with observed declines in temperature and salinity, drop in the sardine biomass was most likely to appear. After excluding autoregressive effect correlation dropped.

However, observed pelagic fish biomass fluctuations were not recorded in costal fish communities, indicating that the biological consequences of the regime shift observed in the period 1987-1999 in the intermediate layer of middle Adriatic Sea were confined to the open sea areas. Besides generally occupying the shallower waters which are principally influenced by direct atmospheric variability, in comparison with pelagic fish that are directly connected to the phytoplankton and zooplankton biomass fluctuations, majority of demersal fishes inhabiting coastal communities feed on different prey groups and manifest opportunistic behavior which puts them in an independent category regarding trophic ecology. Moreover, demersal fishes have longer life span which does not depend on single successful recruitment, whereas in pelagic populations based on one or two annual classes (e.g. sardine and anchovy) (JENNINGS *et al*., 2007), a single poor recruitment event in conjunction with the high fishing effort may cause population collapse. Obviously, direct and visible changes are faster and more easily observable within consumers occupying lower trophic levels or specialists feeding on just one prey group (KING, 2007).

In addition, some changes in pelagic fish population could be influenced by overexploitation and pollution (LOTZE *et. al.,* 2011), and increasing number of new species in the Adriatic Sea (DULČIĆ & DRAGIČEVIĆ, 2011) that all suggest possible changes in stages of the marine ecosystem important for the biomass. The knowledge of these interactions contribute to understanding the mechanisms of changes in the pelagic ecosystems.

CONCLUSIONS

MLT patterns over the NH covary with the winter Adriatic climate and thermohaline circulation in the stratified period, pointing to climatic turning points around 1987 and 1998 that separate relatively stable climate regimes: 1) before 1987 with more frequent Bora wind in the north and Sirocco in the south Adriatic, and 2) after 1987, characterized by the lower frequency of Bora wind present along the whole Adriatic. In the marine environment, the period 1987-1998 was characterized by lower deep layer temperatures, drop of salinity, oxygen and nutrients, confirming lower ventilation of the Adriatic Sea, caused by EMT.

Atmospheric winter conditions, together with thermohaline circulation are recognized as the forcing parameters for the biological ecosystem, which responded more or less synchronously in all its components (Fig. 10). Recorded shift of phytoplankton biomass can be attributed to low intrusion of the Levantine water during EMT. Conditions of old, unstirred water seem to favor the cyanobacteria *Synechococcus* spp. growth, which usually appears in the intermediate layer during stratified conditions. A steady increase in summer zooplankton biomass after 1987 could be the reflection of the established underlying physical ecosystem changes. In the time series, sardine and anchovy usually had opposing trends. The fact that small pelagic fish constitute an important part of big pelagic fish diet (such as tunas, including also small tuna species) and demersal fish (such as hake that usually follow anchovy as its preferred prey), could possibly contribute to the lack of their alternations that occurred after 1994. We suppose that the EMT, established in 1987, was responsible for the alternation collapse. Our

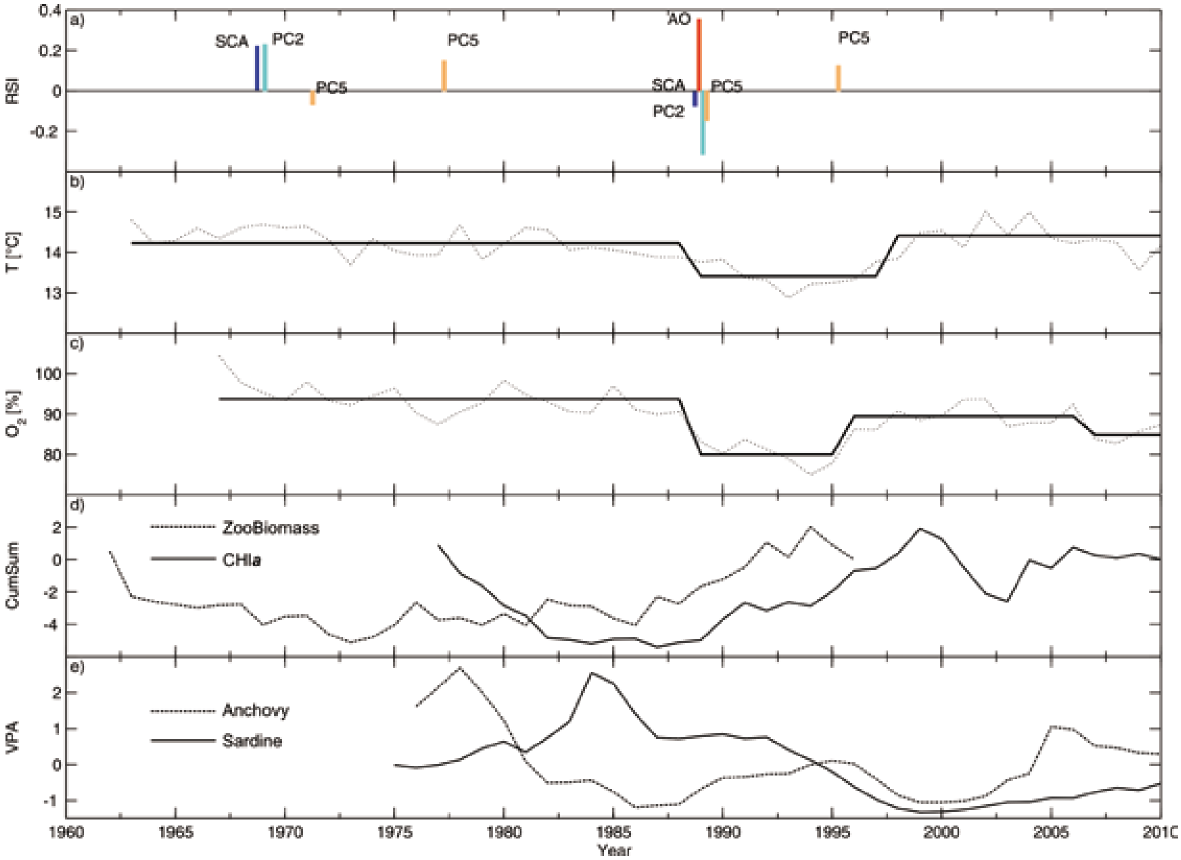

Fig. 10. RSI values for MLT indices and for Adriatic climate proxies a), temporal variations of sea temperature b) and oxygen c) with solid line representing mean states; CumSum of Chl a and zooplankton biomass d) and alternations of normalized anchovy and sardine ratio

future research will focus on investigating how climate drives trophic food web under distinctly different environmental conditions.

ACKNOWLEDGEMENTS

This research was supported by the Croatian Ministry of Science, Education and Sports through grants: No 001-0013077-1118, No 001-0013077-0845, No 001-0013077-0532, No 001-0013077-0844, and through SECCHI project (http://www.izor.hr/web/guest/secchi). The authors are grateful to the ADRIAMED Working Group for their help in collecting the data. The authors are grateful to Gordana BEG PAKLAR (Institute of Oceanography and Fisheries, Split, Croatia) for a critical review of the paper.

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List of acronyms

ACP	- Adriatic Climate Proxy
AdTHC	- Adriatic ThermoHaline Circulation
AO	- Arctic Oscillation
BiOS	- Bimodal Oscillating System
CumSum	- Cumulative sum
CW	- Cretan Water
EA	- East Atlantic
EAWR	- East Atlantic - West Russia
EMT	- Eastern Mediterranean Transient
ERA-40	- ECMWF 40 Year Reanalysis
FAO	- Food and Agriculture Organization
GSA	- Geographical Sub Area
JFM	- January, February, March
JJA	- June, July, August
LIW	- Levantine Intermediate Water
MLT	- Mid-Latitude Teleconnection
MO	- Mediterranean Oscillation
NAO	- North Atlantic Oscillation
NH	- Northern Hemisphere
PCA	- Principal Component Analysis
RSI	- Regime Shift Index
SCA	- Scandinavian Oscillation
STARS	- Sequential t-test algorithm for regime shift detection
VPA	- Virtual population analysis

Klimatski skokovi i više-dekadna promjenjivost pelagičkog ekosustava Jadrana

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SAŽETAK

U vrijeme sve izrazitije promjene klime ekosustav Jadranskog mora pod značajnim je utjecajem atmosferskih promjena koje se događaju na sjevernoj hemisferi te na regionalnoj skali Jadrana. U svrhu objašnjenja međuovisnosti ekosustava Jadrana i atmosferskih procesa na različitim prostornim skalama (od hemisferske do regionalne) analizirana je višegodišnja (1961.-2010.) promjenjivost sustava atmosfera-more i pelagičkog ekosustava. Unutar promatranog vremenskog razdoblja najznačajnija promjena dogodila se između 1987. i 1998. u intermedijalnom sloju srednjeg Jadrana i bila je obilježena padom temperature mora i saliniteta te kisika kao posljedica slabijeg ventiliranja Jadrana. Istovremeno su u ekosustavu pelagijala Jadranskog mora primijećene velike fluktuacije u biomasi morskih organizama (od fitoplanktona do plave ribe). Izdvojena su signifikantno različita stanja ekosustava Jadrana prije i poslije kasnih osamdesetih godina prošlog stoljeća. Uzrok ovim različitim stanjima ekosustava dijelom se može povezati sa modificiranom termohalinom cirkulacijom Jadrana koja je pod utjecajem EMT (Eastern Mediterranean Transient) sprječavala ulazak toplije i slanije vode u Jadransko more, uzrokujući na taj način uočene promjene u ekosustavu. Ovi rezultati dokazuju povezanost između skokova u pelagičkom ekosustavu na području srednjeg Jadrana i klime na sjevernoj hemisferi putem promjena u regionalnim vremenskim uvjetima te ističu važnost utjecaja klimatskih promjena i skokova na fizikalna i biološka stanja Jadranskog mora.

Ključne riječi: telekonekcija srednjih zemljopisnih širina, klima Jadrana, klimatska stanja, plankton, pelagična riba