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Response of the Adriatic Sea to the atmospheric anomaly in 2003

B. Grbec[1], **I. Vilibić**[1], **A. Bajić**[2], **M. Morović**[1], **G. Bec Paklar**[1], **F. Matić**[1], **and V. Dadić**[1]

[1]Institute of Oceanography and Fisheries, Split, Croatia
[2]Meteorological and Hydrological Service, Zagreb, Croatia

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Abstract. Unusual weather conditions over the southern Europe and the Mediterranean area in 2003 significantly impacted the oceanographic properties of the Adriatic Sea. To document these changes, both in the atmosphere and the sea, anomalies from the normal climate were calculated. The winter 2003 was extremely cold, whereas the spring/summer period was extremely warm. The air temperature in June was more than 3 standard deviations above the average. On the other hand, precipitation and river runoff were extremely low between February and August. The response of the sea was remarkable, especially in surface salinity during spring and summer, with values at least one standard deviation above the average. Analysis of thermohaline properties in the middle Adriatic showed the importance of two phenomena responsible for the occurrence of exceptionally high salinity: (1) enhanced inflow of saline Levantine Intermediate Water (LIW) in the Adriatic, and (2) extremely low precipitation and river runoff, accompanied with strong evaporation. Two large-scale atmospheric indices: NAOI (North Atlantic Oscillation Index) and MOI (Mediterranean Oscillation Index), although generally correlated to the Adriatic climate, failed to describe anomalies in 2003. The air pressure gradients used for the definition of both indices significantly decreased in 2003 due to the presence of the high pressure areas over most of Europe and the northern Atlantic, and were actually responsible for the observed anomalies above and in the Adriatic.

Keywords. Oceanography: general (Climate and interannual variability) – Oceanography: physical (Air-sea interactions; Hydrography)

1 Introduction

Changes in the surface temperature in the Northern Hemisphere in the last few decades (IPCC, 2001), accompanied by changes in precipitation intensity, and the modified circulation pattern over the Northern Hemisphere are crucial factors that control the Adriatic Sea thermohaline circulation and the ecosystem on interannual to decadal time scales. Studies concerning the Adriatic Sea response to global and/or hemispheric climate changes (Marasović et al., 1998; Zore-Armanda, 1991; Grubelić et al., 2004; Supić et al., 2004) have shown that a small adjacent sea, such as the Adriatic, is an adequate site for studying mechanisms that control the mean oceanographic state and its variations.

Complex air-sea interaction processes influence the hydrobiology pattern both in the northern (Vichi et al., 2003) and southern Adriatic and are responsible for the presence of several different water types in the area (see, for example, Cushman-Roisin et al., 2001). Since the north Adriatic is a shallow sea lying entirely on the continental shelf (average depth 35 m) and is exposed to the winter cold-wind outbreaks, it is a site where shelf dense water occurs, driven by enhanced surface buoyancy loss and cold river runoff. The resulting water mass is named the north Adriatic Dense Water (NAdDW) (Zore-Armanda, 1963; Beg Paklar et al., 2001; Vilibić, 2003; Vilibić et al., 2004; Vilibić and Supić, 2005). This water is cascading towards the deep South Adriatic Pit, through the dynamics which is widely recognized to contribute to the deep water mass changes (Ivanov et al., 2004). On the other hand, deep convection takes place in the southern Adriatic (1200 m depth), leading to the formation of the South Adriatic Deep Water (SAdDW). Both dense water generation sites have been early recognized as the contributors to the eastern Mediterranean deep waters, although recently having competition in the Aegean sites of dense water formation (e.g. Theocharis et al., 2002). The third water mass characterising the Adriatic Sea hydrology is the Levantine

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Correspondence to: B. Grbec
(grbec@izor.hr)

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Intermediate Water (LIW), which is not formed locally but originates from the Levantine basin of the eastern Mediterranean (see Robinson et al., 1992). The LIW continuously enters the Adriatic in the intermediate layer but with variable intensity, depending on the position of the most frequent atmospheric pressure centres over the Northern Atlantic (Grbec et al., 1998). Surface air pressure analysis over the Mediterranean Sea showed the importance of meridional gradients for the LIW inflow in the Adriatic during the winter season, whereas the zonal gradients control the inflow in summer (Zore-Armanda, 1969).

Basin-wide Adriatic thermohaline properties are to some extent related to the large-scale atmospheric oscillations: the North Atlantic Oscillation (NAO) and the Mediterranean Oscillation (MO). NAO exerts a dominant influence on winter temperature, rainfall and storminess across most of Europe. The positive NAO reinforces the persistence and strength of westerly winds and northern Europe tends to be warmer and wetter than average, with southern Europe colder and drier. During its negative phase, NAO is characterized by weak subtropical highs and weak Icelandic lows, with weaker or less persistent westerly winds; northern Europe is colder and drier, and southern Europe is warmer and wetter than average. The NAO index measures the winter difference in sea-level pressure between the Azores and Iceland. Consequently, surface temperatures (air and sea) across wide regions, including Mediterranean, are significantly correlated to interannual NAO fluctuations (Hurrell, 1995). In the Adriatic region, a significant correlation was found between the air temperature, net heat flux and winter NAOI (North Atlantic Oscillation Index) in the northern Adriatic (Grubelić et al., 2004) and in the Mediterranean (Rixen et al., 2005, and references therein). The oscillation pattern named MO describes the dipole atmospheric behaviour over the eastern and western sub-Mediterranean basins. This dipole behaviour was first defined by Conte et al. (1989) as the differences in the standardised geopotential height anomalies between Algiers and Cairo. This dipole behaviour seems to play a dominant role in climate variability over the Mediterranean basin, being documented by a comparison of temperature, precipitation, circulation and other parameters between the Western and Eastern Mediterranean. There are other recent definitions of MO in which the authors tried to explain atmospheric dynamics over the whole Mediterranean (Palutikof, 2003; Brunetti et al., 2002). The new WeMO defined by Martin-Vide and Lopez-Bustins (2006) as the difference in sea-level pressure between the Cádiz Gulf and northern Italy, describes precipitation fluctuations over the western Mediterranean better than the NAO. The oscillation pattern defined in Grbec et al. (2002) considers the air pressure gradient between the North Atlantic (NA) and Eastern Mediterranean (EM), and is introduced due to its importance on the inflow of the highly saline Mediterranean water into the Adriatic. It has been documented that NAO and MO control the heat and water exchange processes at the air-sea interface, which explain thermohaline variations in the sea (Supić et al., 2004).

Temporal changes in thermohaline properties, including anomalous departures during unusual atmospheric and hydrologic conditions, may have significant consequences on the ecosystem, both for the open and coastal waters. In the earlier investigations, high correlation coefficients were found between salinity in the intermediate layer and fish populations of Mackerel and Sardine (Grbec et al., 2002). However, the correlation coefficients for these two species had the opposite sign, pointing out that higher salinity was in favour of a larger Sardine catch, while lower salinity values were in favour of a Mackerel catch. Also, it is known that plankton communities are to some extent adapted to a certain salinity range. Particularly, the open sea species are more sensitive than neritic species. The phytoplankton and zooplankton species, as well (Regner, 1982), have also shown sensitivity in relation to thermohaline conditions, especially to salinity changes. In addition, advection of warmer and saltier Ionian water through the Strait of Otranto brought a number of alien warm water species into the Adriatic (Dulčić et al., 2004).

This paper attempts to achieve two goals: (1) to describe extreme atmospheric and oceanic conditions occurring in 2003 over the middle Adriatic, and (2) to analyse the influence of large-scale circulation patterns on the oceanographic properties of the Adriatic Sea. Section 2 describes the data set used in the analyses, Sect. 3 documents atmospheric and oceanic conditions that occurred in the middle Adriatic in 2003, as well as their deviation from the climatic means. Section 4 attempts to connect observed anomalies to the large-scale processes and Sect. 5 contains the conclusions.

2 Data and methods

Extensive oceanographic research was carried in the coastal area off Split, from September 2002 through September 2003, at a number of CTD stations within the framework of the ADRICOSM[1] project (http://www.izor.hr/adricosm). The position of one of the stations sampled during the ADRICOSM experiment corresponded to the historical station CJ008. The sampling has been performed bi-weekly or weekly with the CTD probe Seabird-25. These measurements will quantify the strength of the climate anomaly which occurred in 2003, by comparison to the climatic means computed from the MEDAS (Marine Environmental Data Bank of the Adriatic Sea) databank of the Institute of Oceanography and Fisheries. Mean monthly (1961–1990) temperature and salinity values through the water column were compared to the measurements in 2003 at the coastal station CJ008. In addition, open-sea changes and thermohaline anomalies were analysed by examining temperature

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[1] ADRICOSM: ADRIatic sea integrated COastal areaS and river basin Management system pilot project. Istituto Nazionale di Geofisica e Vulcanologia, Italy, and Italian Ministry for the Environment. Institute for Oceanography and Fisheries, Split, Croatia.

and salinity data collected at the permanent station CJ009, located at the Palagruža Sill. Data were acquired from both stations during the Croatian national monitoring project Jadran since 1998. The temperature and salinity time series from the stations of Pelegrin (CJ008) and Stončica (CJ009) since 1961 to 1990 were taken (Fig. 1) for the climatological analysis.

To document temperature and precipitation anomalies for the area wider than the Adriatic during the year 2003, the NCEP/NCAR surface temperature and precipitation anomaly maps for the spring-summer (MJJA), as well as for February and March, are used. The analysed area is delimited by 20 W–30 E and 30 N–70 N. Weather conditions were also investigated using the data collected at the meteorological station Split-Marjan (Fig. 1). Most of the parameters (e.g. air temperature, precipitation) were collected an hourly basis. In order to document the changes in climate in the recent period, temperature, precipitation and heat and water fluxes for the periods 1961–1990 (A) and 1976–2002 (B) were analysed. Heat and water air-sea fluxes were calculated from the available meteorological (temperature, wind, cloudiness, precipitation, humidity) and oceanographic data (sea surface temperature) for two climatological periods and are compared with the corresponding values for 2003. Heat exchange across the sea surface was computed as the sum of solar radiation, long-wave back radiation, sensible and latent heat flux. Mean monthly solar radiation flux was calculated using the Reed (1977) formula:

$$Q_s = I_C\,(1.0.62N + 0.019\,\Phi) \tag{1}$$

where I_C is a clear sky radiation, N is cloud fraction, and Φ is solar height. Clear sky radiation and solar height are calculated based on procedures described in Iqbal (1983).

For the sensible and latent heat fluxes (Q_H and Q_E) classical bulk formulae (Gill, 1982) were used:

$$Q_H = \rho_A\, c_p\, C_H \left|\vec{V}\right| (T_S - T_A,) \tag{2}$$

$$\begin{aligned} Q_E &= \rho_A\, L_E\, C_E \left|\vec{V}\right| [(e_{sat}(T_S) - r\, e_{sat}\,(T_A)]\, \frac{0.622}{p_A} \\ &= \rho_A\, L_E\, C_E \left|\vec{V}\right| [(q_S - q_A),] \end{aligned} \tag{3}$$

where ρ_A is the air density ($1.25\,\mathrm{kg\,m^{-3}}$), c_p is the specific heat capacity of the air at constant pressure ($1010\,\mathrm{Jkg^{-1}\,m^{-3}}$), L_E is the latent heat of evaporation, C_H and C_E are the turbulent exchange coefficients with values 1.0×10^{-3} and 1.5×10^{-3}, respectively, V is wind speed and q_S, q_A are the specific humidity for sea surface temperature and specific air humidity. Relative humidity and saturated vapour pressure are denoted with r and e_{sat} .

Long-wave radiation (Q_L) is calculated using the formula by May (1986):

$$Q_L = \left[\varepsilon\sigma T_S^4 (0.4 - 0.05\,\sqrt{e_{\mathrm{sat}}}) + 4\sigma T_a^3\,(T_S - T_a)\right](1 - 0.75\,N^{3.4}) \tag{4}$$

where ε is atmospheric emissivity, σ is the Stefan-Boltzmann constant, T_a and T_s the air and sea temperatures, respectively, and N is the cloud fraction.

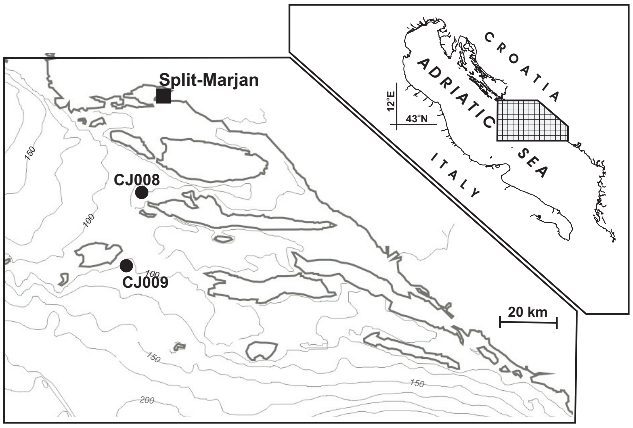

Fig. 1. Investigated area with positions of meteorological (Split-Marjan) and hydrographic (CJ008, CJ009) stations.

Water flux (W) across the air-sea interface is calculated as the difference between precipitation (P) and evaporation (E):

$$W = P - E = P - \frac{Q_E}{L_E.} \tag{5}$$

We attempted to relate the local weather changes to the large-scale circulation pattern, generally controlled by the hemispheric and regional oscillations: (1) North Atlantic Oscillation (NAO, Hurrell 1995), which is correlated to the air-sea heat exchange over the Adriatic, and (2) Mediterranean Oscillation (MO) which "measures" the LIW inflow into the middle Adriatic Sea (Grbec et al., 2003).

For the purpose of our investigation the NAO index (NAOI) is defined as a winter (DJFM) difference of normalized sea level pressure between Lisbon, Portugal and Reykjavik, Iceland from http://www.cgd.ucar.edu/cas/jhurrell/. The correlation of NAOI and local meteorological conditions at Split-Marjan station is investigated for the period between 1961 and 2003. Based on earlier works (Grbec et al., 2002; Supić et al., 2004), the MO index is defined as the result of Principal Component Analysis (PCA), applied to the mean annual pressure data distribution for the Northern Hemisphere within the area 30 W–40 E and 30–65 N for the period 1948–2003. A high correlation between MOI and the Adriatic salinity is a result of the distribution of permanent pressure centres (the Azores high, the Iceland low and the Southeast Mediterranean low), which reinforce LIW inflow due to pressure and/or associated winds over the area.

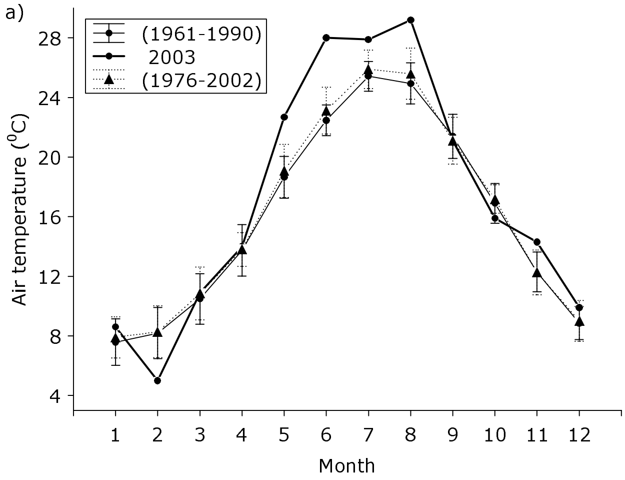

Fig. 2a. Annual cycle of monthly mean air temperature at Split-Marjan for the periods 1961–1990 and 1976–2002 and for the year 2003. Vertical bars represent interannual standard deviations for particular month.

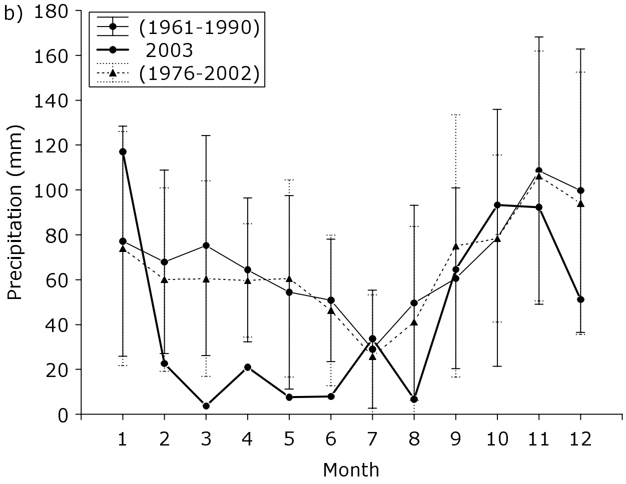

Fig. 2b. Annual cycle of monthly mean precipitation at Split-Marjan for the periods 1961–1990 and 1976–2002 and for the year 2003. Vertical bars represent interannual standard deviations for particular month.

3 Local climate and transient characteristics

3.1 Atmospheric conditions

Annual cycles of mean monthly air temperature and precipitation for the climatic period 1961–1990 (A) and 1976–2002 (B) (Figs. 2a and b) provides insight into the local climate characteristics. It is evident that period B has, on average, 0.5°C higher summer temperatures, whereas there was no difference between winter temperatures (Fig. 2a). The year 2003 was extreme in comparison to both periods. The precipitation regime is of a maritime type, with more precipitation in the cold than in the warm part of the year (Fig. 2b). The mean annual precipitation amount is 825 mm/year for period A and 723 mm/year for period B at the Split-Marjan station, located at the 124 m height. Less than 16% of the annual precipitation amount is measured in summer, and more than 30% in autumn. The rainy season occurs due to strong cyclonic activity in the Mediterranean and Adriatic region, with frequent front passages along the Adriatic. Due to typical cyclone paths, the precipitation has the highest variability (largest standard deviations) from October to December, and the lowest in June and July.

The weather during the year 2003 started with normal air temperatures in January (Fig. 2a). However, February was characterized with a strong, dry and cold bora wind (Furlan, 1977; Belušić et al., 2004) that occurred rather frequently, decreasing temperature and humidity in the area as low as 1.5 standard deviations below the average. On the other hand, temperatures considerably above the normal were recorded in the whole period between May and August, exceeding average values in June for more than 5 standard deviations relative to period A and for 3 standard deviations relative to period B. The major precipitation anomaly (relative to both periods) occurred between February and August, when almost no precipitation was recorded in the area (sea Fig. 2b), with the exception of July when the average was increased due to mesoscale systems and storms. Therefore, one may expect rather anomalous behaviour of the sea, as both atmospheric effects (increased temperature and decreased precipitation) result in a salinity increase and moreover were coupled with low river runoff.

Climate anomaly charts for 2003 from NCEP-NCAR analyses relative to the 1968–1996 values are given in Figs. 3a and b. Very low air temperatures were recorded in February, much lower than the 1968–1996 average. The heat wave started in spring with high positive anomalies for the Adriatic, which became even higher in the summer period. The 2003 have been ranked as the warmest summer ever recorded in the region.

Precipitation conditions were also extreme in 2003, with almost all the hemisphere being extremely dry in spring and summer, due to the dominant and lasting influence of high atmospheric pressure field. The driest month was March 2003, with a monthly precipitation amount considerably less than the average monthly value. This anomaly was observed in the whole Adriatic, from its northern part (Lyons et al., 2006) to the south (Morović et al., 2006). Over Italy, unusual winter and spring-summer atmospheric-sea conditions also occurred (Celio et al., 2006). Air-sea fluxes followed weather conditions over the area (Fig. 4). Large heat losses occurred in the winter period, with extreme values in February. The departure from the mean was about $-100\,\mathrm{Wm}^{-2}$ (1.5 standard deviations). The opposite situation occurred in summer 2003 when the heat gain was significantly higher than average, exceeding one standard deviation above the mean in

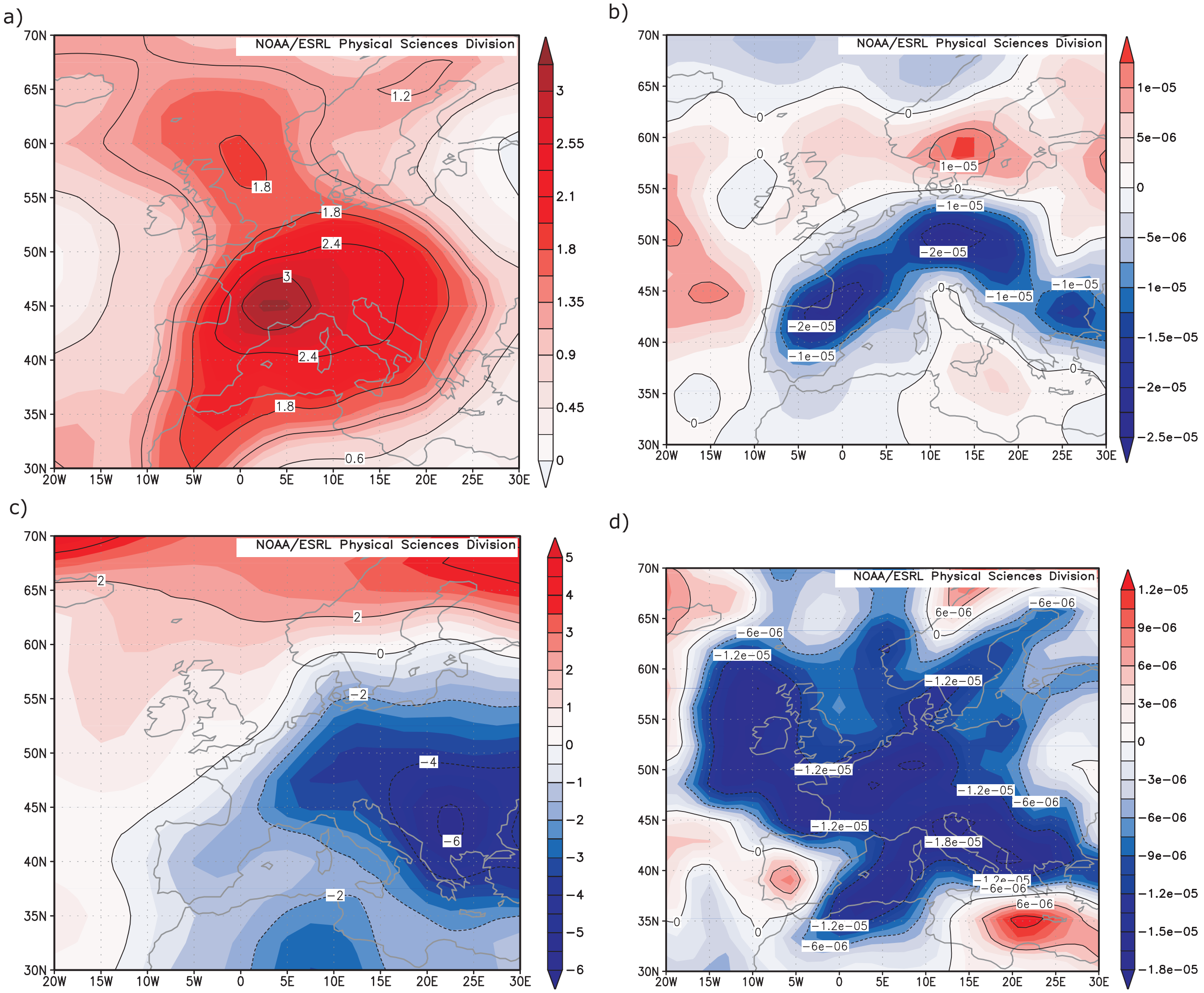

Fig. 3. Spatial distribution of 2003 spring-summer (MJJA) air temperature **(a)** and precipitation anomalies **(b)** relative to 1968–1996 and the anomalies of the most extreme months in 2003; February for low temperature **(c)**, March for low precipitation **(d)**. Images were provided by the NOAA-CIRES (taken from Climate Diagnostics branch, Boulder, Colorado http://www.cdc.noaa.gov/.

May and June. Water flux was even more anomalous, especially between February and June. The strong winds (Grbec et al., 2006) enhanced water losses from the sea during February, whereas in the heating season evaporation increased due to high temperatures. Since almost no precipitation was recorded, $E-P$ values were about 4 times higher than the average, exceeding 1 standard deviation between February and April 2003. It should be added that, due to the low precipitation over the Adriatic, river runoff was extremely low and the river deltas were intruded by the coastal seawater (ADRICOSM Final Science Report, Group of authors, 2005).

3.2 Oceanic response

Water temperature and salinity anomalies were studied for the stations CJ008 and CJ009 and are presented in Figs. 5 and 6. A temperature increase can be observed for both stations in the surface layer following the processes at the air-sea interface and highlighting August as an extremely warm month. The response of the sea to the atmospheric input in 2003 was even more extreme in the salinity field. The coastal waters, which are usually stretched over the surface in the coastal area, were confined to the coast and river deltas, enabling the intrusion of saline open-sea water closer to the coast. The salinity anomalies are seen at both stations, where a strong departure from the climatological values occurred in

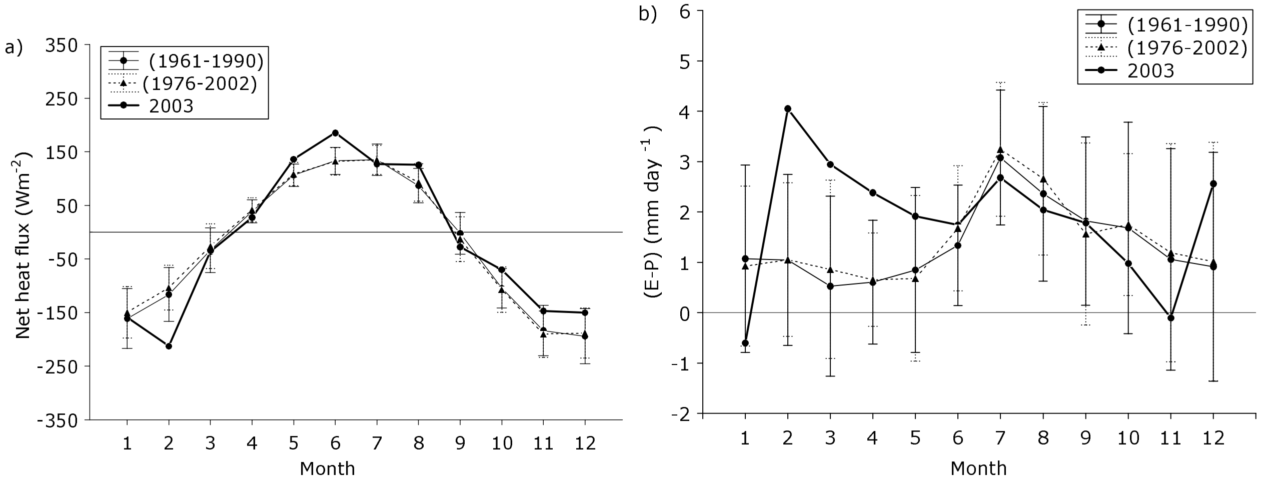

Fig. 4. Monthly mean **(a)** net heat and **(b)** water flux (evaporation – precipitation) computed at Split-Marjan for the periods 1961–1990 and 1976–2002 and for the year 2003. Vertical bars represent interannual standard deviations for particular month.

the spring 2003, both in the surface and bottom layer (Figs. 5 and 6). A major departure from the climatological values can be observed in May and June at the surface, when surface salinity, according to climatology, has a minimum, due to a spring maximum in river runoff (Raicich, 1996). As no river maximum occurred in spring 2003, due to low precipitation in the region, the surface salinity was constantly increasing till October, to about 38.8. Such a high value is even higher than the average LIW salinity in the open south and middle Adriatic Sea obtained from the climatological studies (Zore, 1963; Grbec and Morović, 1997; Vilibić and Orlić 2001, 2002). Bottom salinity at CJ008 (Fig. 5) has been also higher than the average after March 2003, but not so anomalous as in the surface layer. The same is valid for the station CJ009. The maximum has been reached in October, when haline homogeneity occurred over most of the area.

Since the bottom salinity during summer at CJ008 and CJ009 is driven mostly by intermediate open-ocean advection, it may be concluded that the open Adriatic waters were more saline than usually, as a consequence of a larger inflow of the LIW into the Adriatic. Actually, increased inflow of the warmer and saltier water from the Ionian Sea was confirmed by direct CTD and current measurements performed in winter 2002/2003 and spring 2003, as described in Orlić et al. (2006). Maximum values obtained in the East Adriatic Current during May are interpreted as a consequence of strong wintertime cooling and a lagged response of the Adriatic-Ionian basin-wide thermohaline circulation (Orlić et al., 2006).

Conclusively, exceptionally high salinity in the middle Adriatic coastal area was caused by (1) extremely low precipitation and river runoff, accompanied by strong evaporation, which increased the salt content in the surface layer, and (2) by a spreading of the open-sea waters toward the coast, which was characterized by salinity higher than the long-term average.

Anomalous characteristics of the year 2003 in the open Adriatic Sea can also be seen from the comparison of the time series of the vertical temperature and salinity profiles measured at station CJ009 in 2003, versus the climatological values (Fig. 7). The well-known impact (e.g. Buljan and Zore-Armanda, 1976) of the heat gain to the surface layer temperature, and thermocline destruction during autumn may be easily resolved from Fig. 7a. Also, the impact of the East Adriatic rivers to the surface layer can be nicely seen in the springtime, subsequently triggering the baroclinic intrusion of the bottom saline waters towards the coast in late summer/autumn (Fig. 7a). During spring and summer 2003, the sea surface gained a large amount of heat, concentrated it in a narrow surface layer (up to 10 m), due to low winds, and reduced vertical mixing (Fig. 7b). Therefore, a lower-than-average temperature may be found in the subsurface layer (10–20 m) till August, when a massive heat transfer was pushed towards the deeper waters (Fig. 7b). A positive temperature anomaly (larger that 1°C) can be seen in September–October 2003 in the whole water column, emphasising the amount of the heat stored in the narrow surface layer during spring and summer, and being widened in autumn through the vertical mixing processes. A positive salinity anomaly, with values larger than 0.15, can be seen along the water column, being particularly strong in the surface layer during springtime.

4 Connection to large-scale processes

In order to put the atmospheric anomaly of 2003 in the context of large-scale atmosphere dynamics, the mean winter

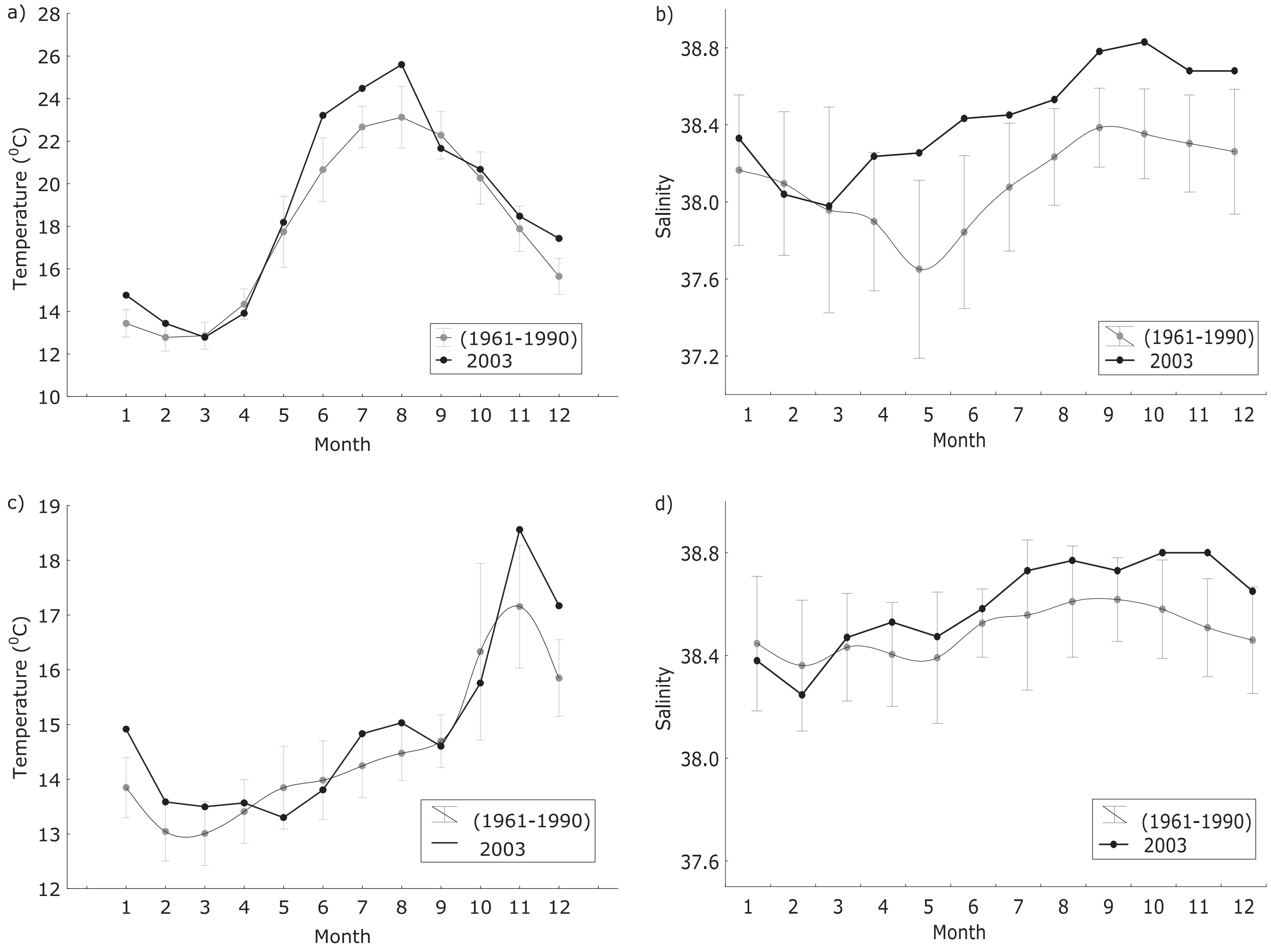

Fig. 5. Monthly mean surface temperature **(a)** and salinity **(b)**, and bottom temperature **(c)** and salinity **(d)** at the station CJ008 for the period 1961–1990 and for 2003.

heat exchange at the air-sea boundary, obtained by meteorological and SST data at Split-Marjan station, have been examined for the period between 1961 and 2003 (Fig. 8), and correlated to the NAO index. The correlation coefficient between the winter NAOI and the winter air temperature is 0.31 (43 pairs), significant at $p<0.05$ level, while the correlation with net heat flux is 0.42 (43 pairs), significant at $p<0.05$ level. Despite of the year-to-year rapid changes in both winter NAOI and heat flux, the changes are highly correlated on a decadal scale – the higher the winter NAOI, the higher the heat flux and vice versa (Fig. 8a). The link to the surface waters of the Adriatic Sea is given by the NAO influence through surface air-sea fluxes (heat and water fluxes), which are highly correlated to the air temperature and precipitation (Tsimplis and Josey, 2000).

Contrary to the surface, whose properties depend on the boundary exchange processes, intermediate layers are presumably driven by advection, which, according to Zore-Armanda (1969), is controlled by the air pressure distribution partially represented by MOI. Figure 8b comprises the series of annual MOI and the mean intermediate salinity (mean values in the 50–150 m depths) in the middle Adriatic. The correlation between MOI and intermediate salinity is 0.33 when all the data (55 pairs) are used (at $p<0.05$ significance level). However, a high correlation is predominantly the result of MO forcing from 1948 to 1977 ($r=0.65$; 30 pairs; $p<0.001$), since the correlation between MOI and salinity from 1978 to 2003 is lower. A somewhat higher correlation coefficient (0.51) is obtained if the time differences of MOI (MOI in the current year – MOI in the preceding year) are correlated to the time differences in intermediate salinity (for 53 pairs significant at $p<0.05$), since the enclosed sea, such as the Adriatic and the Eastern Mediterranean, can preserve its intermediate and deep temperature and salinity during a few years, and therefore these characteristics are not formed in particular year, but in a few preceding years. The residence

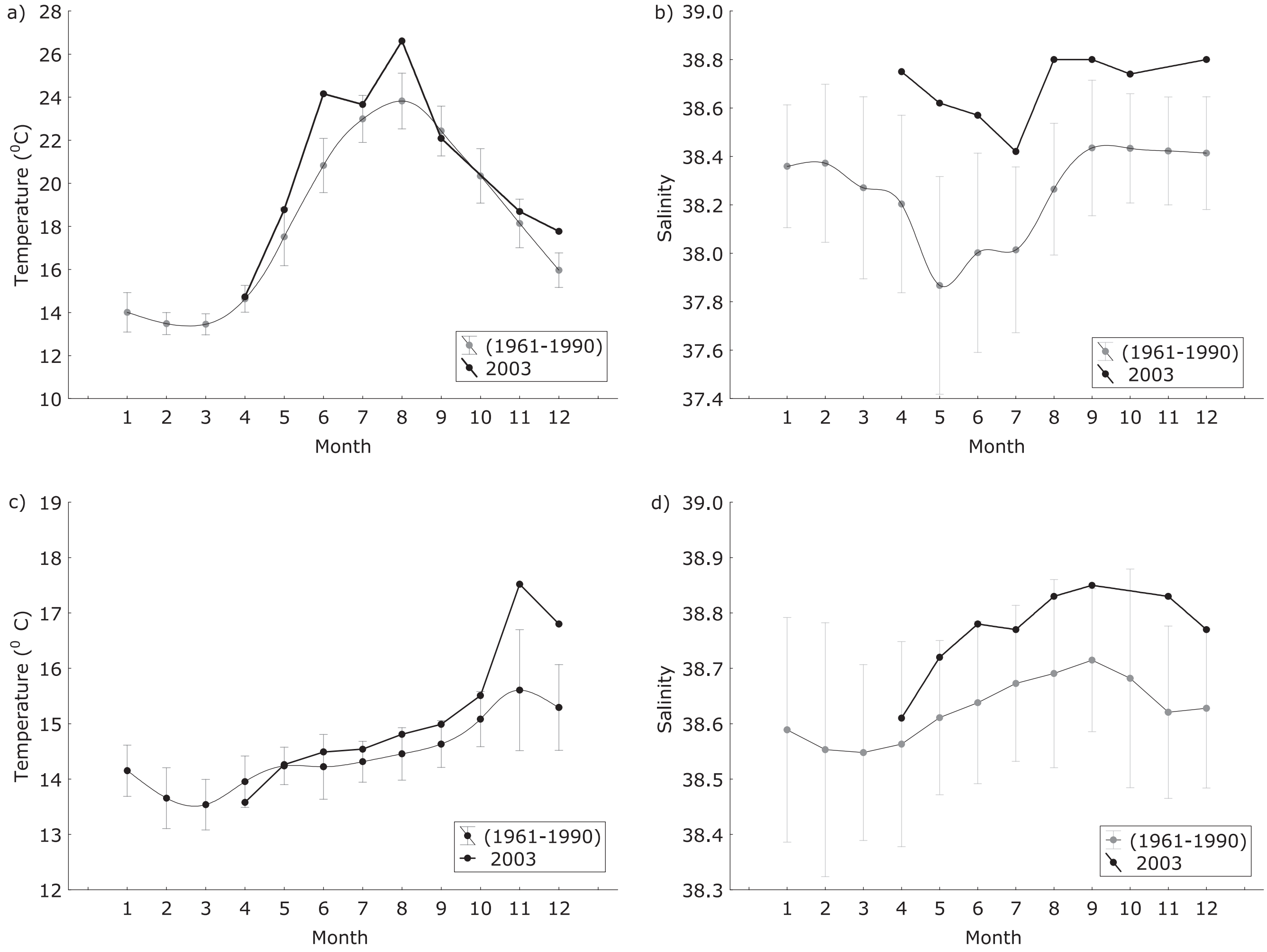

Fig. 6. Monthly mean surface temperature **(a)** and salinity **(b)**, and bottom temperature **(c)** and salinity **(d)** at the station CJ009 for the period 1961–1990 and for 2003.

time of the deep Adriatic water is estimated to be about 2–3 years (Vilibić and Orlić, 2002). Therefore, the change in salinity in the middle Adriatic is predominantly driven by the advection of LIW, which was presumably formed some years before (Supić et al., 2004).

It is seen in Fig. 8b that there are periods with a low correspondence between MOI and the salinity changes, which point to the importance of other processes. The sharp rise in salinity since 1997 may be a result of recent changes in Levantine and Aegean intermediate water characteristic (Manca et al., 2004).

Although significant correlations between the Adriatic Sea properties and two large-scale atmospheric indices do exist on a long-term scale, they failed to explain anomalous behaviour in 2003. The definition of both indices, NAOI and MOI, is based on air pressure gradients. Mean winter air pressure anomalies obtained from NCEP-NCAR analysis indicate a decrease in the meridional gradient used for the definition of NAO (Fig. 9), namely the northern part of the Atlantic, usually occupied with a low pressure, has a strong positive anomaly. Large heat losses in the Adriatic in winter 2003, therefore, cannot be ascribed to the intensive cyclonic activity, which is related to NAO, but rather to the influence of a Siberian anticyclone, as can be noticed in the mean winter air pressure field (Fig. 9).

The zonal air pressure gradient, according to Zore-Armanda (1969), is responsible for the summer inflow of LIW in the intermediate layers of the Adriatic, and this process results in the positive correlation between the zonal gradient and the intermediate salinity, as can be seen from Fig. 8b. Although in 2003 salinity and MOI were in phase, such a low MOI could hardly justify such a high salinity. A relatively low value of MOI resulted from spatial and temporal changes in the circulation patterns over Europe (Fig. 9). The Atlantic area, normally occupied with high pressure in the year 2003, has a negative anomaly, while the eastern

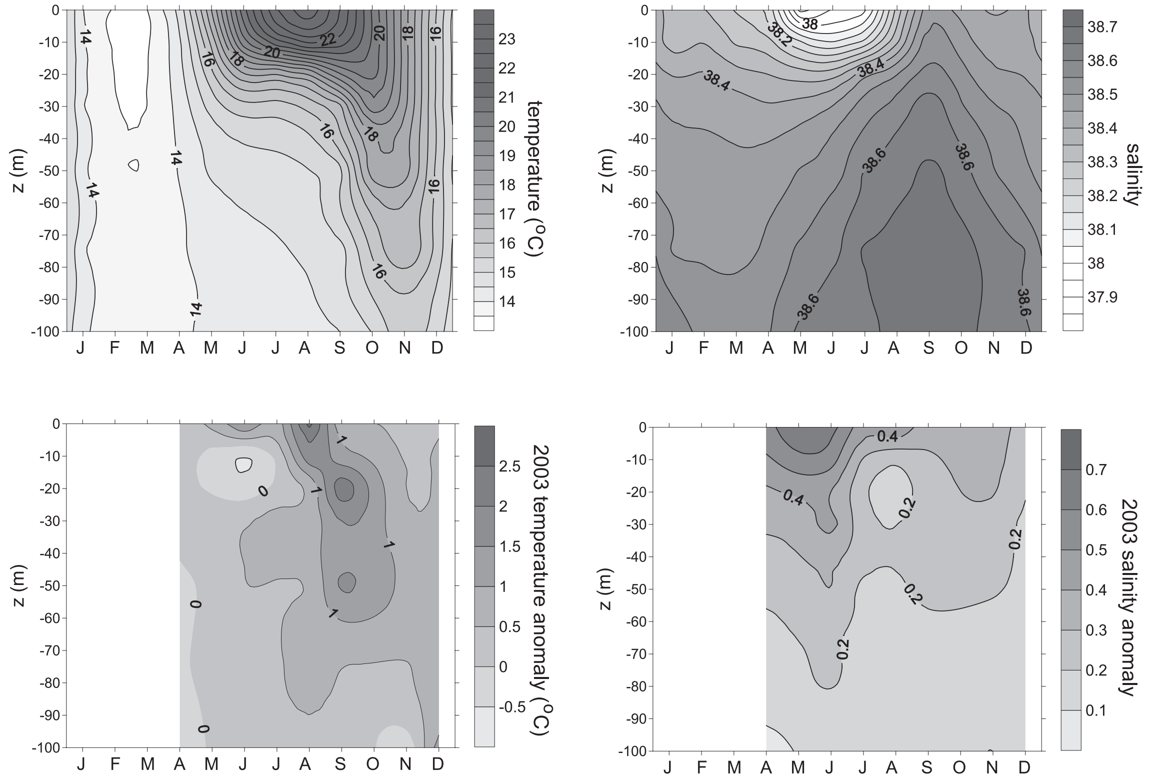

Fig. 7. Annual cycle of average temperature and salinity at the CJ009 station for the period 1962–1994 (upper panels), and the difference between 2003 values and the averages (bottom panels).

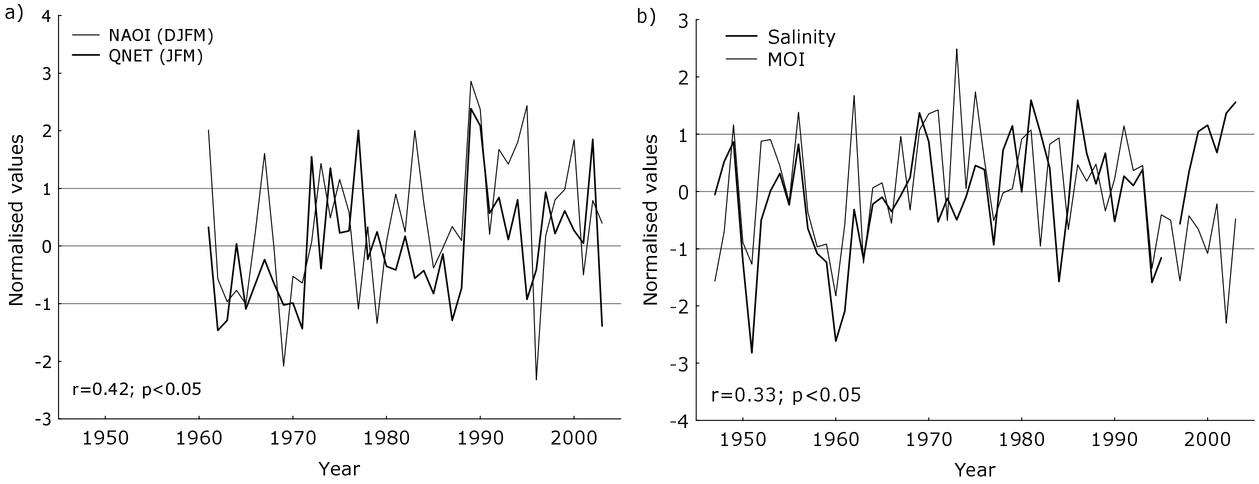

Fig. 8. Time series of normalized mean winter heat flux at Split-Marjan and NAOI for the 1961–2003 period **(a)** and time series of normalized annual mean salinity at CJ009 station and MOI for the 1948–2003 period **(b)**.

Mediterranean, where a low pressure resides in summer, has a positive anomaly (Fig. 9). Both anomalies result in a decreased zonal gradient. Therefore, increased inflow of the saltier and warmer water mass through the Otranto Strait in spring/summer 2003 was not induced by air pressure zonal gradients but rather by a thermal influence in winter, as explained by Orlić et al. (2006). Extremely low winter temperatures enhanced dense water generation in the Adriatic and consequently reinforced the exchange of the water with the Ionian Sea, with a few months delay (Orlić et al., 2006).

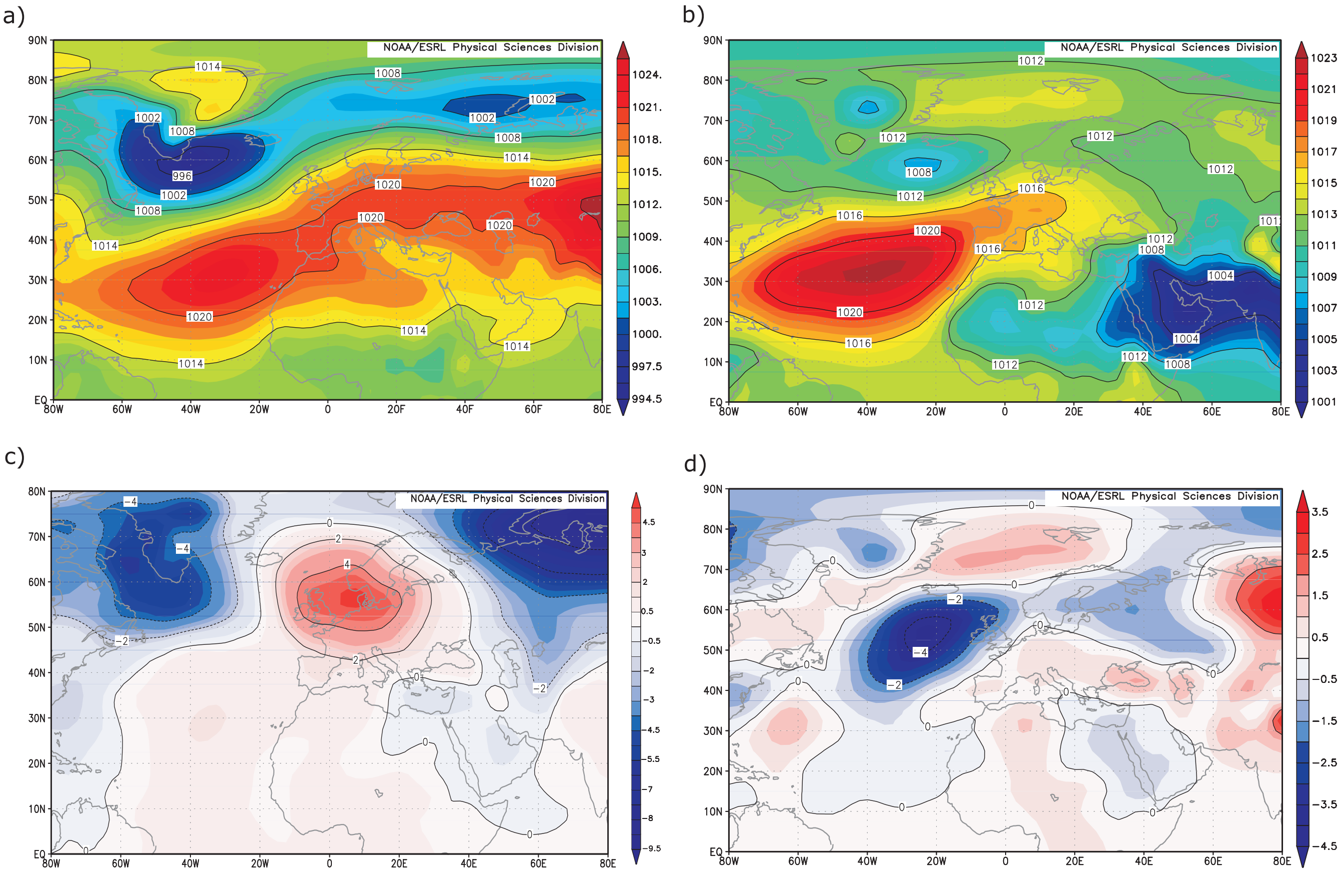

Fig. 9. Spatial distribution of sea level pressure (SLP) for 2003 **(a)** JFM period **(b)** MJJA period and SLP anomalies relative to 1968–1996 for **(c)** JFM period and (b) MJJA period Images were provided by the NOAA-CIRES (taken from Climate Diagnostics branch, Boulder, Colorado http://www.cdc.noaa.gov/.

5 Conclusions

The climate anomaly of the year 2003, which occurred over most of Europe, has strongly influenced the Adriatic air and sea properties, both in coastal and open sea regions. Confirmation for this is given through the analysis based on long meteorological and oceanographic data series (more than 50 years) from the middle Adriatic eastern areas. The anomaly was recorded both in heat and water fluxes at the air-sea interface and was driven by the anomaly in air temperature and precipitation. Just to emphasise the strength of this anomaly, let us state that in June 2003, the air temperature was about 3 standard deviations above the average, whereas precipitation was constantly below average for at least 1 standard deviation between February and June. Strong cooling in the winter season and heating afterwards resulted in high baroclinicity, concentrating the heat in the upper 10 m of the sea, being transferred towards the deeper layers in late summer/autumn through the vertical mixing and turbulence. Strong bora in February and low precipitation, as well as high temperatures during spring and summer, resulted in high evaporation, which increased surface salinity. The bottom salinity has also been above the average, due to the inflow of saltier-than-average water from the south and/or Mediterranean into the Adriatic. Winter dense water formation triggered basin-wide (Adriatic-Ionian) circulation and enhanced delayed LIW inflow in May (Orlić et al., 2006). The salinity increase was particularly anomalous in the coastal waters, due to the lack of freshwater inputs.

Although the Adriatic Sea conditions are certainly driven by regional and large-scale processes (NAO and MO), the 2003 case deviate to a bit from the general behaviour. Two large-scale atmospheric indices, NAOI and MOI, although generally correlated to the Adriatic climate, failed to describe the anomalies in 2003. The air pressure gradients used for the definition of both indices significantly decreased in 2003, due to the presence of the high pressure areas over most of Europe and the northern Atlantic, and were actually responsible for the observed anomalies above and in the Adriatic.

As a result of the extreme conditions in the year 2003, with high summer temperatures and strong northward inflow, a number of warm water species in the Adriatic during 2003 increased by three times in comparison to the previous years (Dulčić et al., 2004). Since the recent climate changes are in favour of extreme conditions (Beniston and Stephenson, 2004), their impact on the Adriatic ecosystem is expected to increase in the future. These extreme events indicate a need to continuously monitor and further understand regional and large-scale processes, not only for the thermohaline properties and circulation pattern but also for the ecosystem conditions of the small, semi-enclosed sea, such as the Adriatic.

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