

Short-term physical and chemical variations in the bottom water of middle Adriatic depressions

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ABSTRACT: A physical and chemical dataset collected in the Jabuka (Pomo) depression area (middle Adriatic Sea) was analysed for seasonal and interannual changes in temperature, salinity, density, dissolved oxygen and nitrates. A historical dataset collected from 1980 to 1997 was extended with data from 15 oceanographic cruises conducted between 1998 and 2002 in the framework of the SINAPSI research program. The bottom water masses of the Jabuka pits are periodically renewed by Northern Adriatic Deep Water (NAdDW) at 1 to 3 yr intervals. During late winter-early spring, the new water eventually flows into the western pit and then into the central and eastern ones. During 1 yr of residence in the pits, bottom water nitrates increase 3-fold and dissolved oxygen decreases by 28 % due to mineralisation processes. Some aspects of recently observed decadal climatic anomalies in the Northern Adriatic Sea, in particular the average winter sea surface warming, are revealed by the analysed dataset. Relationships were observed between these anomalies and the Eastern Mediterranean Transient (EMT), and from this (and other indirect indications) we infer that since 1999 the Adriatic Sea has re-emerged as a major source of Eastern Mediterranean Deep Water (EMDW). These findings confirm the worth of the mesoadriatic depressions as an easily accessible recording site of interannual oceanographic variations in the Adriatic basin.

KEY WORDS: Adriatic Sea · Bottom water · Nutrients · Dissolved oxygen

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1. INTRODUCTION

The Adriatic Sea is the most continental basin of the Mediterranean Sea. It lies between the Italian peninsula and the Balkans and is elongated longitudinally, with the major axis (about 800 km length versus 200 km width) lying in a NW-SE direction. The basin shows clear morphological differences along both the longitudinal and the transversal axes, and has been divided into a northern, a central and a southern sub-basin (Artegiani et al. 1997). The northern sub-basin—spanning from the northernmost part to the 100 m bathymetric line—is characterised by an extremely shallow mean depth (about 30 m) with a very weak bathymetric gradient along the major axis, and by heavy river runoff; indeed, the Po and the other northern Italian rivers are believed to contribute about 20 % to the whole Mediterranean river runoff (Hopkins

1992). The middle Adriatic is a transition zone between northern and southern sub-basins, the latter showing some open sea conditions. This central zone spans from the 100 m contour to the Palagrūza (Pelagosa) sill (about 170 m depth), which is located on the line connecting Vieste and Split (Fig. 1). The main feature of this zone is a relatively large area lying below the Palagrūza sill (which marks the boundary between the middle and Southern Adriatic). This area exhibits 3 distinct, adjacent depressions, the Jabuka (or Pomo) pits, with maximum depths of ca. 255, 270 and 240 m, respectively (Fig. 2).

The southern sub-basin is characterised by a wide depression >1200 m in depth. Water exchange with the Mediterranean takes place through the Otranto Straits, which have an 800 m deep sill.

The main water mass entering the Adriatic basin is the Levantine Intermediate Water (LIW), which forms

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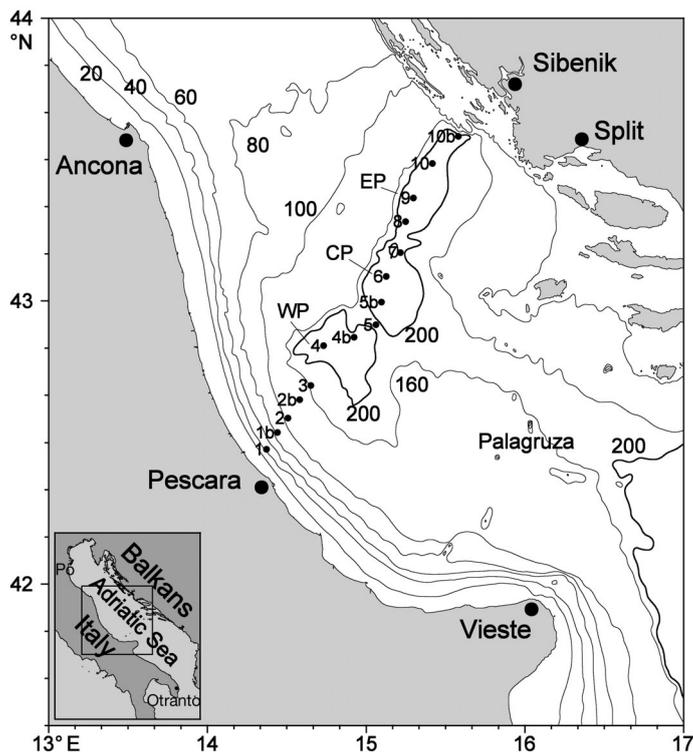


Fig. 1. Geographical position of stations in the study area. EP, CP and WP: eastern, central and western pit, respectively

in winter in the Eastern Mediterranean (Rhodes gyre; The LIWEX Group 2003). At Otranto, the LIW typically has salinity of 38.7 to 38.9 and a temperature of 14 to 15°C at depths between 200 and 400 m. The LIW and surface waters entering through Otranto Straits are transported toward the north-east, along the eastern coast, by the cyclonic general circulation of the Adriatic Sea. During their travels, these water masses undergo relevant modifications inside the basin.

Being a continental basin, the Adriatic Sea circulation and water masses are strongly influenced by atmospheric conditions, primarily winds. The main winds blowing over the Adriatic Sea are the Bora and the Sirocco. The Bora is a cold, dry wind that spills through gaps in the Dinaric Alps (the mountain range situated along the Adriatic's eastern shore), which in specific points of the Adriatic eastern coast is very intense due to katabatic effects (Poulain & Raicich 2001). In winter, the Bora causes strong heat losses in the Northern Adriatic and results in the formation of Northern Adriatic Deep Water (NAdDW). Another factor influencing NAdDW formation is water flux, mainly governed by Po river runoff, which can lower the salinity and hence density of NAdDW. NAdDW formation depends not only on buoyancy forcing (combination of heat and water surface fluxes), but also on

Po river runoff 2 mo before (Vilibic 2003), as a high freshwater input can lower the salinity of the Northern Adriatic and can possibly inhibit subsequent dense water formation. The climatological average values of temperature and salinity are $11.35 \pm 1.40^\circ\text{C}$ and 38.30 ± 0.28 , respectively, with a density anomaly $> 29.2 \text{ kg m}^{-3}$ (Artegiani et al. 1997). After its formation, NAdDW flows toward the southeast, mainly offshore of the Italian coast (Franco 1982, Artegiani & Salusti 1987, Gacic et al. 2001), increasing its temperature and salinity through lateral mixing with warmer and saltier water masses.

A peculiar water mass, the Middle Adriatic Deep Water (MAdDW), characterized by climatological average temperature of $11.62 \pm 0.75^\circ\text{C}$ and salinity 38.47 ± 0.15 with a density anomaly $> 29.2 \text{ kg m}^{-3}$ (Artegiani et al. 1997), resides throughout the year in the bottom layer of the Jabuka pits. NAdDW flowing from the Northern Adriatic eventually develops into MAdDW and settles in the Jabuka depression, provided that NAdDW density is higher than that of resident MAdDW. New NAdDW reaches the Jabuka depression area about 1 mo after its formation (Vilibić 2003), so that MAdDW renewal occurs in late winter/early spring (but not every year). Such an event generally causes a marked increment in density and oxygen concentration and a reduction in temperature and nutrients (Artegiani et al. 2001). Between renewals, bottom-water density declines owing mainly to rising bottom-water temperature and mineralisation pro-

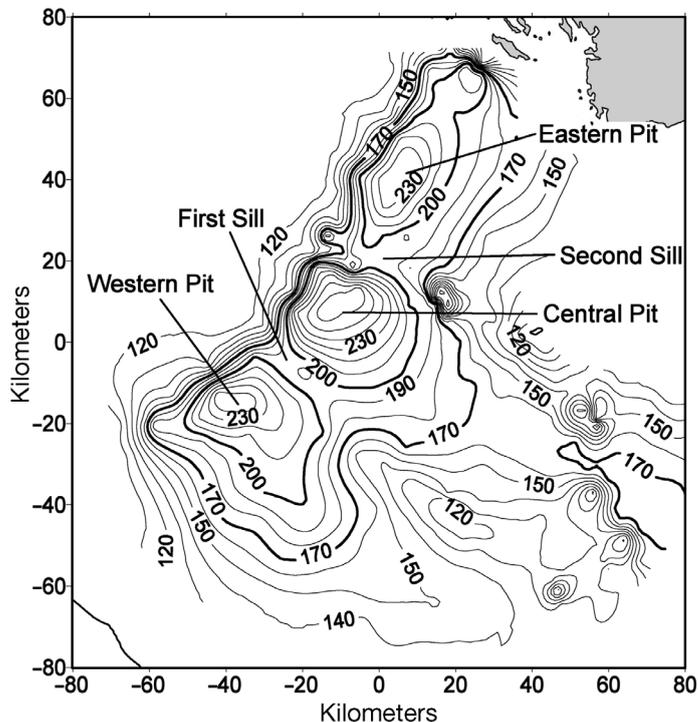


Fig. 2. Bathymetric map (high resolution) of Jabuka Pits

cesses of organic matter taking place in the bottom layer of the depressions, which accounts for dissolved oxygen consumption and the concurrent increase in dissolved nutrients (Artegiani et al. 2001).

While MAdDW stands in the Jabuka depressions throughout the year, NAdDW can be observed up to summer only (due to the shallowness of the Northern Adriatic shelf, NAdDW is progressively mixed with surface and intermediate waters). For this reason, only MAdDW (and not NAdDW) provides an integrated signal of previous winter conditions in the Northern Adriatic sub-basin; it also provides useful information on short-term climatic changes occurring in the basin.

Russo et al. (2002) found evidence from the Adriatic Sea of decadal climatic anomalies: the mean temperature of the Northern Adriatic surface waters was higher than pre-1987 levels for every season in the 1988–1999 period; salinity showed more complex variations, related to the runoff of the Po river. These changes are likely related to the Eastern Mediterranean Transient (EMT; Klein et al. 1999, Manca et al. 2003). Starting from around the end of the 1980–1990 decade, the main formation site of Eastern Mediterranean Deep Waters (EMDW) moved from the Adriatic Sea to the Aegean Sea. New bottom water masses that formed in the Aegean Sea started to enter the Ionian Sea, uplifting old Adriatic-origin deep waters and so causing a salinity reduction of LIW in the Ionian Sea, which in turn entered the Adriatic Sea once again (Klein et al. 2000). In recent years, LIW entering the Adriatic Sea has been mostly replaced by Cretan Intermediate Water (CIW, formed in the Cretan Sea), which is characterized by a slightly higher salinity. Klein et al. (2000) detected advection of this water through the Otranto Straits, and reported a salinity increase resulting from this in the Southern Adriatic, starting from 1997.

In the present paper, we firstly described the field-work undertaken in the Jabuka Pits from 1998 to 2002, providing a detailed picture of the unique process of bottom water renewal in this area. Following on from this, the extended (1980–2002) time series in the same area is analysed for indications of short-term climate variations in the Northern Adriatic Sea, which can eventually influence (or be an indicator of) Adriatic Bottom Water (ABW) production and EMDW.

2. MATERIALS AND METHODS

Within the framework of the SINAPSI project, ISMAR-CNR conducted 15 oceanographic cruises in the Jabuka pits from January 1998 to August 2002, acquiring 140 CTD casts and collecting 122 seawater samples. A typical transect (Fig. 1) from the Western to

the Eastern Adriatic coast was monitored over most seasons, and comprised CTD and sampling stations through the water column used to measure physical (pressure, temperature, conductivity, fluorescence, turbidity and density) and chemical (dissolved oxygen and nutrient salts) parameters.

CTD data were collected using a SeaBird Electronics (SBE) 911-plus probe coupled to a SBE Carousel water sampler. The CTD probe was equipped with sensors measuring pressure, temperature, conductivity, fluorescence (Sea Tech Fluorimeter), turbidity (Sea Tech backscattering) and distance from the bottom (Data-sonics altimeter). Data were acquired and processed according to UNESCO (1988) standards, producing pressure-averaged data (0.5 dbar interval). Seawater was sampled at fixed depths, with a smaller number of sampling points in winter and autumn (when the water column is more homogeneous) and a larger number in spring and summer.

Water samples for nutrient salt analyses were filtered (GF/F Whatman, diameter 25 mm), stored immediately at -22°C in polyethylene vials, and analysed at the ISMAR-CNR laboratory (Ancona) using the colorimetric method (Strickland & Parsons 1972) with a Technicon TRAACS 800 autoanalyzer. Dissolved oxygen was directly analyzed on board according to Winkler (1888), and samples were immediately fixed and stored in the dark and analyzed within 24 h using the potentiometric method (Furuya & Harada 1995).

ISMAR-CNR began monitoring the central Adriatic Sea in 1980; before 1998 data were collected using similar material and methods (a detailed description can be found in Artegiani et al. 2001).

3. RESULTS

3.1. Analysis of SINAPSI data (1998–2002)

In Fig. 3 the time evolution of bottom density along the Jabuka pits transect is shown. The evident density increment in 1999 and 2002 immediately reveals that bottom water was renewed in those years. The figure also provides quite a clear indication that the new dense water came from the western side in both cases.

This fact is confirmed when looking at selected sections shown in Fig. 4. It can be seen (e.g. in April 2002) that the new dense water mass had the features of NAdDW, which forms in the Northern Adriatic during winter: i.e. very low temperature, comparatively low salinity (not shown) and high density. In February 1999 (Fig. 4a), a water mass—homogeneous from the surface to 140 m—was detected in the western pit. Bottom-water physical characteristics (relatively low density: 29.2 kg m^{-3} ; and comparatively high temperature:

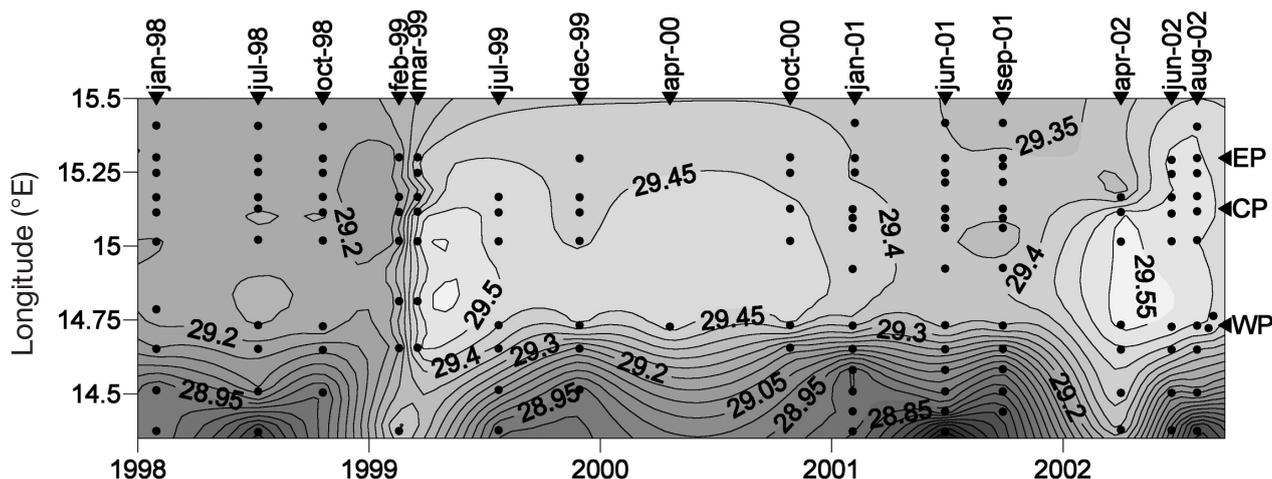


Fig. 3. Time evolution of bottom density anomaly (kg m^{-3}) from January 1998 (left) to August 2002 (right) along the transect. EP: eastern pit, CP: central pit, WP: western pit. Sampling points marked by dots

12.5°C), combined with high nitrate concentrations characteristic of bottom water, indicated that it had not been renewed. In spring, the NAdDW that had recently formed in the Northern Adriatic reached the middle sub-basin and, when denser than the water standing in the western pit, it flowed—below the 170 m bathymetric line—into the bottom of the pit (254 m). In March 1999 (not shown) the temperature and density data from the first 2 pits provided evidence that MAdDW was replaced with denser (29.5 kg m^{-3}) and colder (10.7°C) water, while the eastern pit continued to be occupied by old MAdDW. From the western pit the NAdDW flows into the central one (270 m) over the first 190 m sill, and subsequently into the eastern pit (240 m) over another 190 m sill.

In July 1999 (Fig. 4a), dense (29.5 kg m^{-3}) water was observed in the first 2 pits and at the level of the second sill (190 m) below 200 m throughout the area; the fact that dense water was also sampled at the level of the second sill suggests that analogous conditions were obtained in the eastern pit. Similar density data (29.4 to 29.5 kg m^{-3}) that were recorded in all 3 pits in December 1999 (Fig. 4b) lend substance to this hypothesis.

In 2001, MAdDW was not renewed by new NAdDW, and therefore the October 2001 maps (Fig. 4b) are a good example of conditions that rule the pits when MAdDW is not renewed: at the bottom, temperature is increased, density decreased, and, more evident, dissolved oxygen saturation percentage is low while nitrates are high because of mineralisation processes.

In April 2002 (Fig. 4c), bottom waters in the western and central pits were renewed (density: 29.6 kg m^{-3} ; temperature: 10.4°C ; oxygen: $>90\%$ saturation). Because values at the level of the second sill (190 m) were incompatible with a renewal, the dense water had presumably not yet reached the eastern pit. In June 2002 (Fig. 4c), all 3 pits contained dense water (density

29.5 kg m^{-3} , temperature 10.5°C and oxygen saturation $>90\%$). Fig. 4a–c illustrates that the dense and cold NAdDW mass entered firstly the western and then the central and eastern pit in succession, flowing over the 2 sills at 190 m. The water mass standing in the pits was probably displaced by the new water, as described by Franco (1982) for the western pit, and pushed over the Palagrüza sill to flow south.

The time diagram (Fig. 5) of bottom values measured at stations located in the 3 pits clearly shows the abrupt changes in temperature and density, the increase in dissolved oxygen and the fall in nitrates that took place at the time of the 1999 and 2002 renewals. The dissolved oxygen saturation and nitrates time diagrams also show that another renewal occurred in April 2000, but with different characteristics from 1999 and 2002. In fact, bottom density increased slightly, and the salinity time diagram reveals that the renewal occurred because of saltier NAdDW.

Between April 2000 and June 2001, when the deep water was not ostensibly renewed by water from the north, the 3 pits exhibited a 0.0501% daily consumption of dissolved oxygen saturation, as obtained from:

$$\text{O}_2\%_{\text{sat}} = \text{O}_2\%_{\text{iv}} - 0.0501t_d$$

where $\text{O}_2\%_{\text{sat}}$ is the % saturation value of dissolved oxygen after a given period of time, $\text{O}_2\%_{\text{iv}}$ is the initial dissolved oxygen value of water that has just flowed into the pits, and t_d is time in days since water inflow into the pit.

The increase in nitrates in the pits over the same period was also calculated as follows:

$$\text{NO}_3 = \text{NO}_{3\text{iv}} + 0.0085t_d$$

where NO_3 is the nitrate concentration ($\mu\text{M l}^{-1}$) in the water flowing from the pits after a given period of time and $\text{NO}_{3\text{iv}}$ is the initial value of nitrate concentration

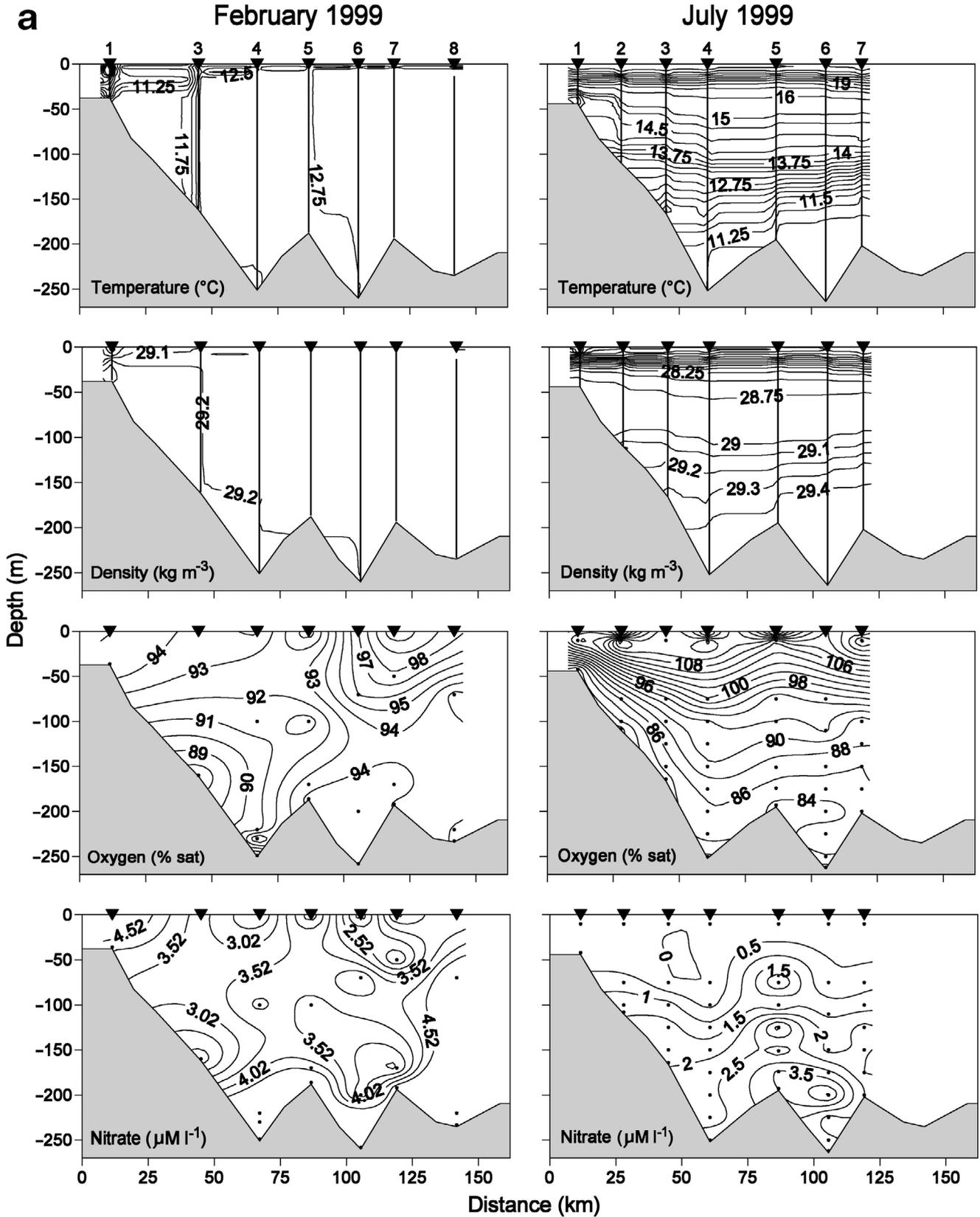


Fig. 4. Vertical distribution of temperature, density anomaly, oxygen saturation and nitrate along the transect in (a) February and July 1999, (b) December 1999 and October 2001, (c) April and June 2002. Contour interval is variable

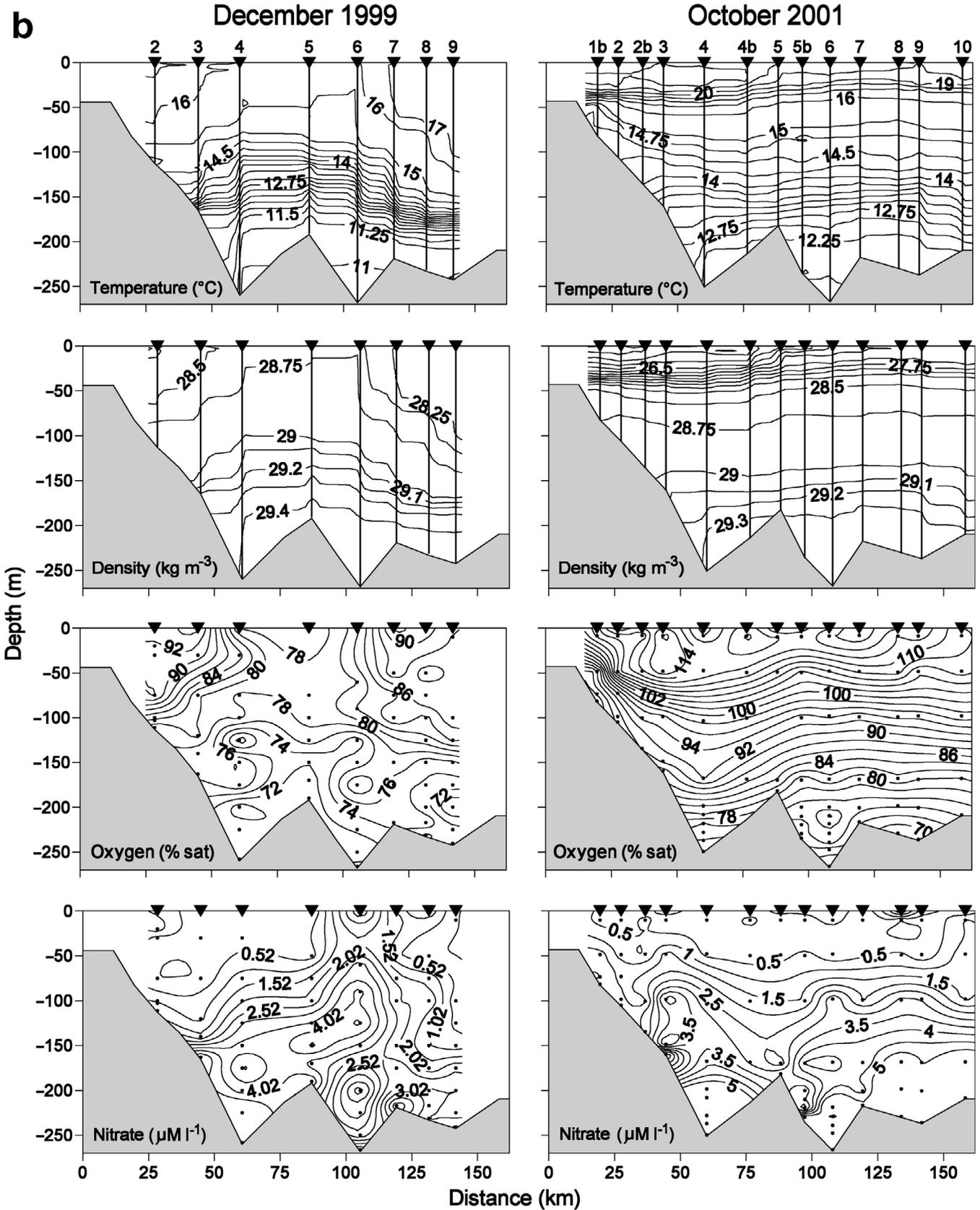


Fig. 4 (continued)

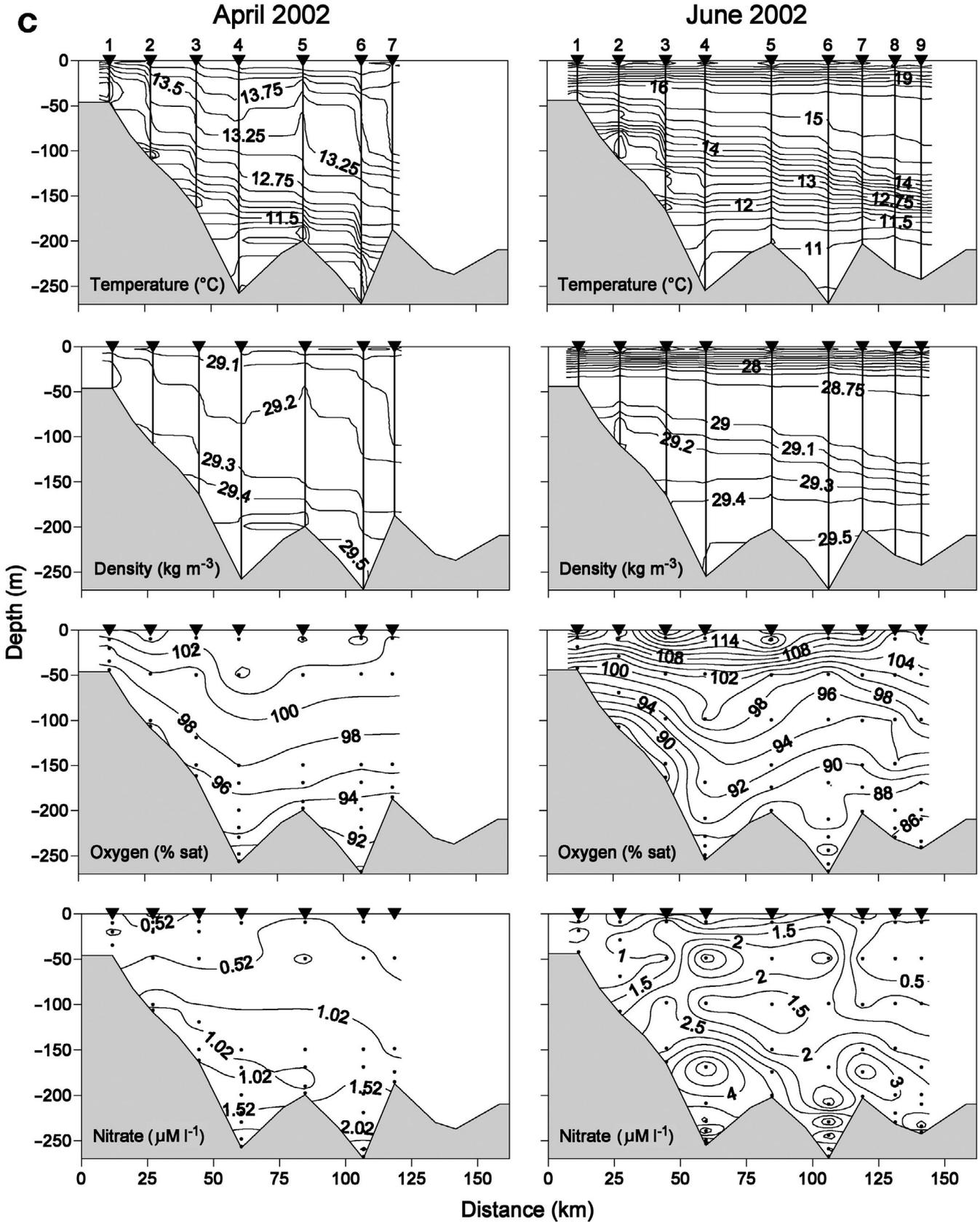


Fig. 4 (continued)

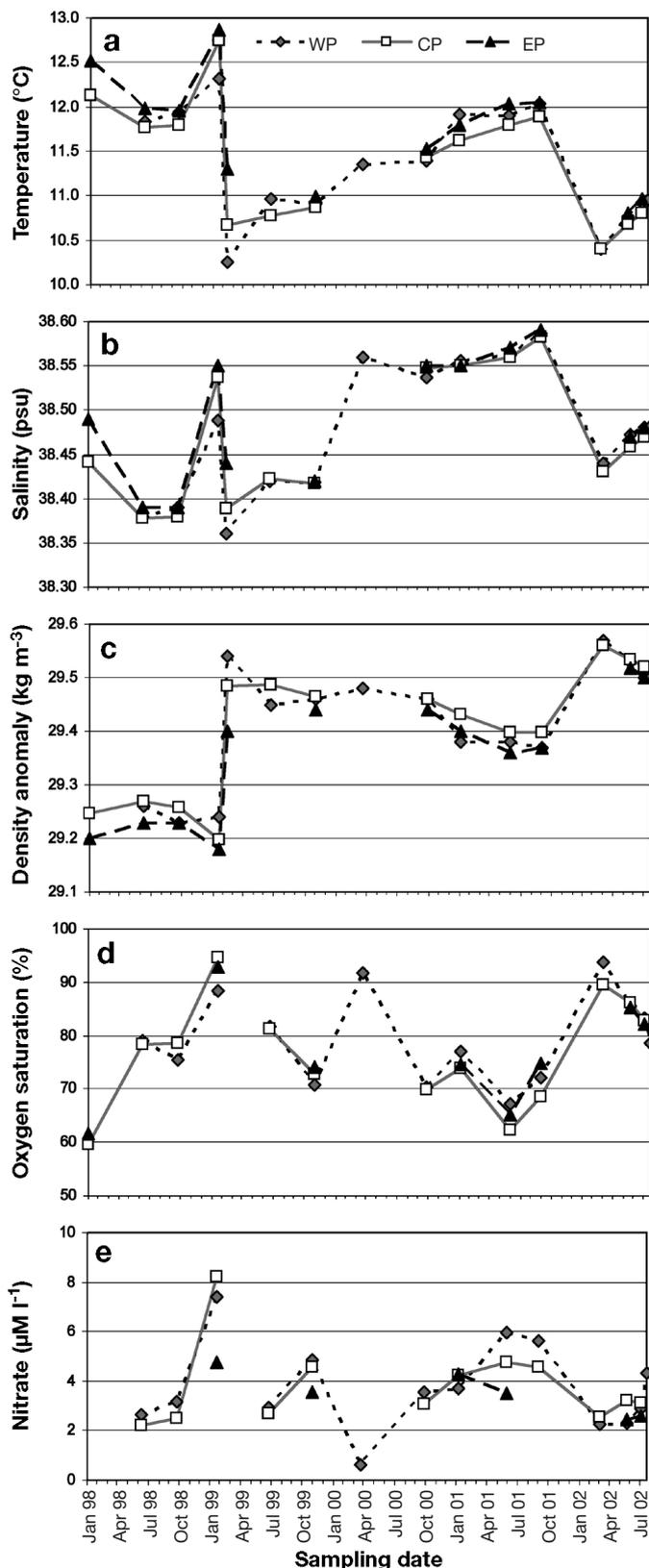


Fig. 5. Time evolution of (a) temperature, (b) salinity, (c) density anomaly, (d) oxygen saturation and (e) nitrate at bottom of pits. EP: eastern pit, CP: central pit, WP: western pit

($\mu\text{M l}^{-1}$) in the water that has just flowed into the pits. According to this calculation, the nitrates in the pit increase after the renewal episode by ca. $3 \mu\text{M l}^{-1} \text{ yr}^{-1}$.

3.2. Analysis of the 1980–2002 time series

When analysing the 22 yr time series collected by ISMAR in the western Jabuka pit (Fig. 6: bottom density anomaly, temperature, salinity and dissolved oxygen saturation), several considerations can be drawn. In Fig. 6, 'R' indicates years when a renewal has clearly occurred, and 'x' indicates years when the western Jabuka pit bottom waters were certainly not renewed. It can be seen that renewal can occur at intervals of 1 (1982 and 1997, 1998, 1999, 2000), 2 (1982–1994 and 1984–1986) or 3 years (1993–1996).

Most of the renewals are clearly identified by a sharp increase in dissolved oxygen and density, and a simultaneous sharp decrease in temperature and salinity; however, in both 1982 and 2000 the new bottom waters were characterized by an evident increase in salinity (temperature showed an increase as well, but it was the high values of dissolved oxygen that confirmed a renewal).

Unfortunately, the Jabuka pits were poorly sampled during 1988–1992, and the 2 periods before and after this appeared to be different: temperature was higher (between 10.1 and 11.4°C) in the 1981–1986 period than in 1993–2002 period (between 10.4 and 12.3°C); salinity in the first period was high (38.4 to 38.7, dropping to 38.2 in 1986), whereas in the second period it was lower (38.3 to 38.6). Temperature showed a general increasing trend during the whole period; however, a moderately decreasing trend seemed to begin after the maximum value was reached in January 1999. Salinity during the first period showed a decreasing trend, while increasing during the second period. The combination of temperature and salinity caused a density anomaly trend that decreased up until 1998, when the absolute minimum (close to 29.2 kg m^{-3}) of the series was reached; afterwards, values partially recovered (a maximum of 29.7 kg m^{-3} was recorded in 1984).

4. DISCUSSION

During the SINAPSI study period (1998–2002), the pits evidently received new water twice, firstly in February–March 1999 and secondly in March–April 2002. A third renewal with different characteristics can be identified in April 2000.

In 1999 and 2002, the dense water mass flowing into the pits came from the western side and had the fea-

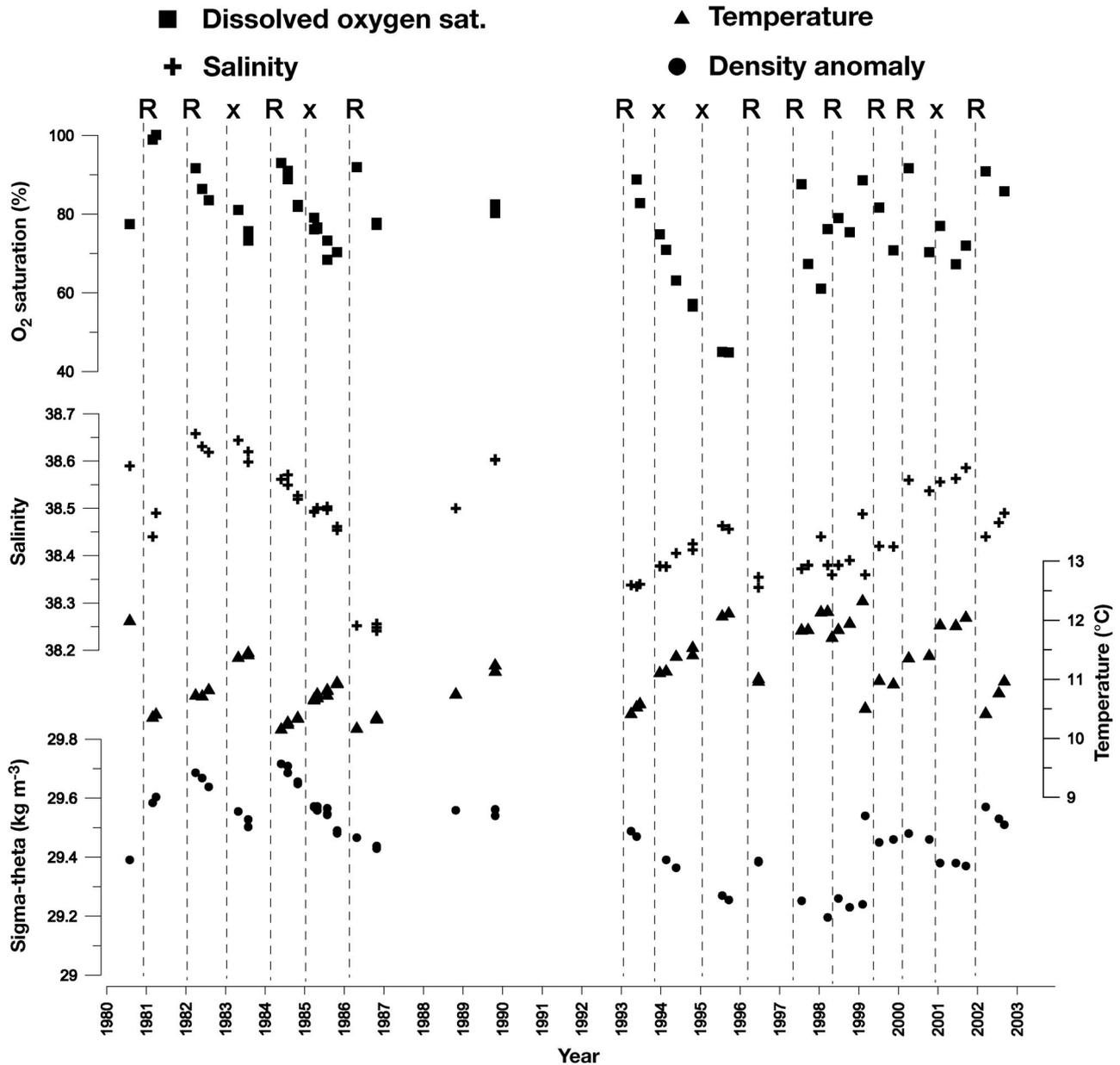


Fig. 6. Time evolution of temperature, salinity, density anomaly (sigma-theta) and oxygen saturation at the bottom of western Jabuka pit. Samples taken in January of each year. R: renewal, x: no renewal

tures (very low temperature, comparatively low salinity and high density) of NAdDW, which forms in the Northern Adriatic in the winter. This water mass reaches the middle sub-basin about 1 mo after its generation (Vilibić 2003) and, when denser than the water standing in the western pit, flows into the bottom of the pit (254 m), filling it up to the 150–170 m isobath level. From the western pit it flows into the central pit (270 m) over the first 190 m sill and subsequently into the eastern pit (240 m) over another 190 m sill (Fig. 2). The old MAdDW and part of the new NAdDW can enter the Southern Adriatic Basin. If the NAdDW that reaches

the Middle Adriatic is less dense than the resident MAdDW, it is not able to occupy the deepest part of the depressions and it continues to flow southward along the western side of the basin towards the southern sub-basin.

In 2000 (when unfortunately only the western pit was sampled), MAdDW renewal was not evidenced by an abrupt change in temperature and density, but rather by a change in salinity; the dissolved oxygen increase and the simultaneous decrease nitrates (Fig. 5) was indicative of new water in the western pit. Temperature slightly increased, but density increased too,

due to higher salinity. Observations collected in the Northern Adriatic basin confirm that the dense and salty NAdDW of 2000 was roughly 1.0°C warmer and 0.1 kg m⁻³ less dense than 2002 NAdDW (Russo et al. 2005), these differences are about the same as those between the 2000 and 2002 bottom water characteristics of western Jabuka pit.

A similar renewal episode occurred in 1982, when new warmer and saltier waters replaced the cold and fresh bottom waters that arrived in 1981. Therefore, it can be stated that renewals can occur without cooling in the presence of higher salinity of the new dense water.

Extending the analysis to the 1980–2002 period, it can be seen that, starting from the period 1987–1992, bottom temperature shows a clear increasing trend (progressively higher minima and higher maxima) up to January 1999; this is in agreement with the seasonal average sea surface temperature increase of the period 1988–1999 compared to the previous years observed for the Northern Adriatic by Russo et al. (2002). During the last decade of the last century, while the temperature of the NAdDW that was renewing Jabuka pit bottom waters was increasing, its density was decreasing: a density minimum was reached in 1998. The bottom density minima obtained in the pits during 1994–1998 are in agreement with the density minimum of ABW from the Southern Adriatic (Manca et al. 2003) and the lowering of LIW salinity in the Ionian and Adriatic Seas during the 1990s (a consequence of EMT occurrence).

Starting from 1999, the trend decreasing density in the middle Adriatic depressions reversed: temperature decreased (but still remained higher than pre-1987 values) and, above all, salinity increased. The salinity increase can be ascribed to the major ingression of high salinity Cretan surface and intermediate waters into the Adriatic Sea in 1999 (Klein et al. 2000); accordingly, a relevant salinity increase was observed in the Northern Adriatic Sea starting from 1999 (Russo et al. 2005). The bottom density increase in the middle Adriatic depressions, detected as of 1999, is an indication that ABW production was re-initiated, as found by Manca et al. (2003) on the basis of data collected from the Ionian Sea in 1999.

5. CONCLUSIONS

In the course of the 1998–2002 period, the Jabuka pits underwent 2 complete water renewals, one in February–March 1999 and the other in March–April 2002. Denser and colder water from the north (NAdDW) firstly entered the western pit and then the central and eastern pits over the two 190 m sills that separate them

before flowing south over the Palagrüza sill (170 m). In April 2000 there was evidence of a renewal due a warmer but denser NAdDW (owing to its higher salinity); a similar episode occurred in 1982, supporting this interpretation.

Dissolved oxygen saturation of the water mass standing in the 3 pits showed a negative trend from ~90 to 65% between April 2000 and June 2001, representing a total decrease of 28%.

Over the same period, nitrates increased 5-fold from ca. 1 µM l⁻¹ to ca. 4.8 µM⁻¹; this indicates that the MAdDW flowing south over the Palagrüza sill after a year or more in the pits brings a considerably greater concentration of nitrates into the southern sub-basin than the NAdDW flowing directly into it.

Bottom temperature and salinity in the middle Adriatic depressions show trends that are in agreement with decadal climatic changes evidenced from the Northern Adriatic Sea and with recent variations in the eastern Mediterranean water masses. These facts confirm that the middle Adriatic depressions are an optimal site from where to monitor, at a seasonal scale, an integrated signal of Northern Adriatic Sea water mass variations; furthermore, information obtained from this site can also be relevant to the whole Adriatic and Eastern Mediterranean.

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