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Variations of thermal conditions in the southern Adriatic from XBT measurements in the period October 2002 – June 2003

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XBT measurements along two sections in the southern Adriatic carried out from the pre-conditioning through spreading phase of the deep convection in the season 2002/03 enabled us to describe in detail the process of dense water formation. In autumn, thermal conditions revealed a prominent doming structure and cyclonic circulation in the area that strengthened the inflow of Ionian waters. In March, the vertical convection reached 600 m depth but the air-sea heat and buoyancy losses were mitigated by the horizontal advection of buoyancy. Comparison with previously collected data reveals that the temperature of the mixed water patch shows a continuous interannual increasing trend noticed in the last decade.

Key words: XBT measurements, oceanic convection, air-sea interaction, Adriatic Sea

INTRODUCTION

The Adriatic Sea, as the northernmost regional basin of the Mediterranean, is subject to strong atmospheric influence both in terms of the air-sea heat fluxes and of the freshwater input. This then impacts on the basin-wide circulation as well as the water exchange with the Ionian Sea (GAČIĆ *et al*., 1996; MANCA *et al.,* 2002). Rather prominent riverine input and winter air-sea heat losses make the Adriatic Sea an important source of freshwater as well as dense water for the entire eastern Mediterranean (CIVITARESE & GAČIĆ, 2001). The dense water is formed at the shelf of the Northern Adriatic (MALANOTTE-RIZZOLI, 1991), and in the centre of the South Adriatic Pit (ZORE-ARMANDA, 1974; OVCHINIKOV *et al*., 1987). The latter formation process is an open-ocean deep convection taking place during outbursts of cold continental air (GAČIĆ *et al*., 2002). Due to the prominent atmospheric influence, the Adriatic Sea responds promptly to year-to-year climatic variations and exchange with the eastern Mediterranean. Thus, the basin represents an indicator of variations of climatic and oceanographic conditions in the area, as well as an important driving force for the eastern Mediterranean circulation cells. Long-term monitoring of the evolution of thermohaline conditions in the area is therefore important for understanding not only the Adriatic Sea response to climatic forcing but also the functioning of the eastern Mediterranean circulation cells.

This paper reports the evolution of the thermal structure during the 2002/03 winter (convection) season in the southern Adriatic Sea as obtained from XBT measurements carried out onboard ships of opportunity. This variability is then interpreted in terms of possible forcing mechanisms and processes.

MATERIALS AND METHODS

The XBT measurements were performed, following common protocols for data acquisition, transmission and control (MANZELLA *et al.,* 2001). The XBT probe types used were Sippican T6 and Deep Blue. The T6 XBTs provided temperature profiles down to 460 m with a rated ship speed of 15 knots, while the Deep Blue maximum nominal depth is 760 m with a rated ship speed of 20 knots, although in certain cases the profiles arrived down to 900 m. Both probes had a temperature accuracy of ± 0.1°C and a resolution of 0.01°C and the profiles were measured at approximately 0.7 m intervals along the vertical. The full-resolution XBT profiles are transmitted in near-real time via cellular phone to ENEA collecting centre (La Spezia, Italy) where quality checks, including an assessment of the overall consistency of the data were performed. The measurements were carried out along two transects in the South Adriatic Pit. The data were collected along the tracks Sušac-Brindisi, crossing longitudinally the South Adriatic Pit, and Dubrovnik-Bari almost perpendicular to the first one (Fig. 1). The measurements were

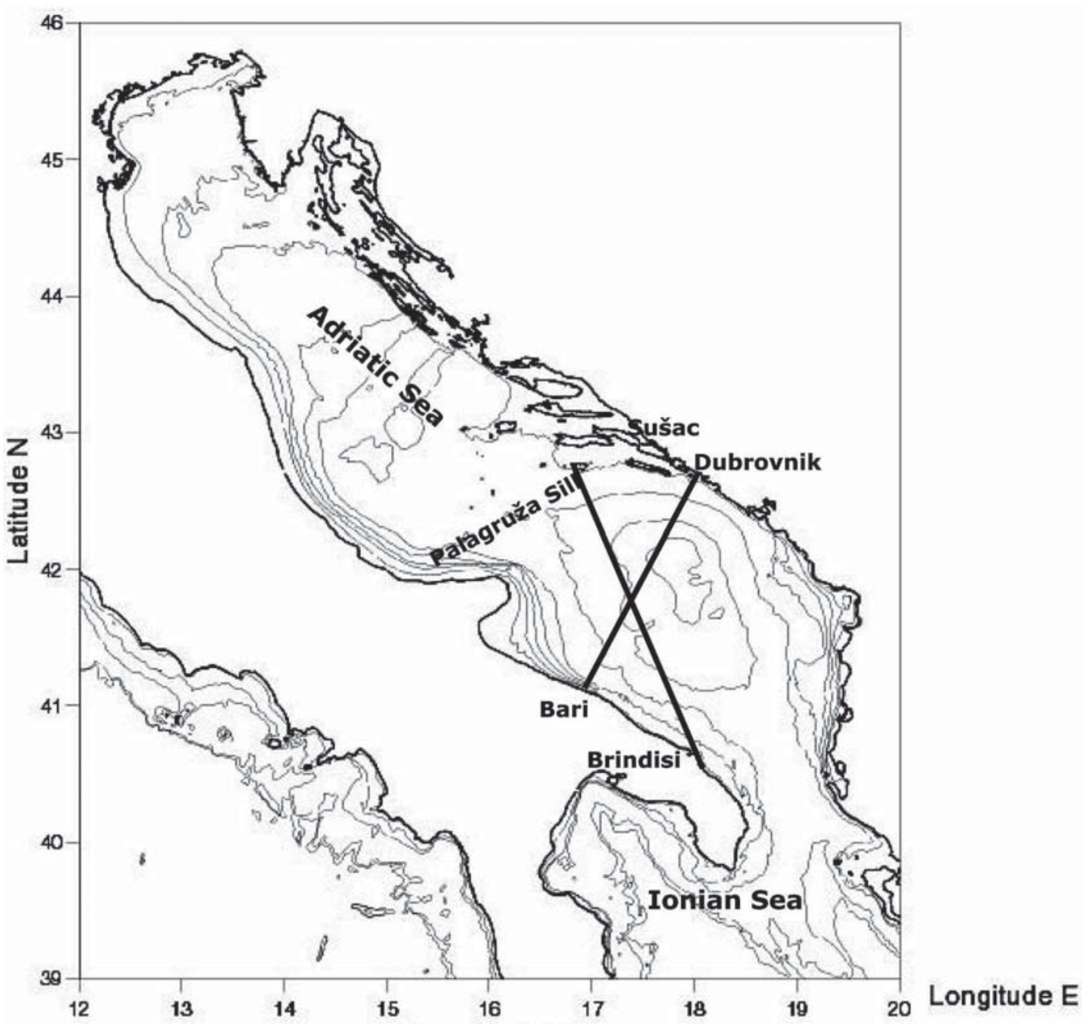

Fig. 1. Ship-of-opportunity XBT tracks in the framework of the ADRICOSM project

carried out twice a month following all three phases of dense water formation in winter 2002/03 (pre-conditioning, deep convection and spreading phase) with a spatial resolution of approximately 10 nautical miles. Data collected along the first track (the Sušac-Brindisi section) are combined with the data obtained from the Dubrovnik-Bari transect, typically two weeks apart from each other.

Net air-sea heat fluxes were calculated from the European Centre for Medium-Range Weather Forecast, Reading, UK (ECMWF) data at the air-sea interface (Q_{net}) as described by CARDIN & GAČIĆ (2003), and integrated for the southern basin, while the total heat flux $\int Q_{net} dt$ is considered in the time interval (t_1 , t_2) typically between two cruises (KOVAČEVIĆ *et al.*, 2003). The heat content change in the time interval $t_1 - t_2$ was calculated as:

$$\frac{\left[(HS)_2-(HS)_1\right]}{(t_2-t_1)}=\frac{\left[\int_{t_1}^{t_2} Q_{net} dt\right]}{(t_2-t_1)}+Q_{res} \qquad (1)$$

where the relative heat storage HS ($\mathrm{Jm^{-2}}$) in the layer between depths H_1 and H_2 with respect to a reference temperature T_0 is calculated according to HECHT (1985):

$$HS=\int_{-H_2}^{-H_1} c_p \rho \left[T-T_0\right] dz \qquad (2)$$

H_1 is the upper depth set to 5 m since the surface layer was not taken into consideration due to contamination of the signal by noise during the XBT adjustment while H_2 is a common maximum measurement depth, i.e. 760 m. The heat content change between the two subsequent XBT surveys is due essentially to the gain or loss of heat to the atmosphere (Q_{net}), to horizontal heat advection, to vertical entrainment, and to both horizontal and vertical diffusion and turbulence. ARTEGIANI *et al.* (1997) presented this balance as:

$$\frac{\partial HS}{\partial t}=Q_{net}-\nu\cdot\nabla(HS)-K_H\nabla^2(HS)+ + w\, HS\big|_{z=-H}-K_V c_p \rho\, \partial T/\partial z\big|_{z=-H} \qquad (3)$$

where K_H is the horizontal diffusion coefficient, K_V the vertical diffusion coefficient and the w vertical and v horizontal velocity components. The second and third term on the right-hand side present the horizontal advection and diffusion, while the fourth and fifth terms are associated with the vertical entrainment and diffusion, respectively. The comparison between the heat content change that was calculated from the data, and the net air-sea heat fluxes calculated as described above, gives evidence to the relative importance of the air-sea heat exchange with respect to horizontal advection, vertical entrainment and turbulent diffusion in determining the winter convection.

RESULTS

The evolution of the thermal structure from the pre-conditioning to the spreading phase in the area is described. In addition, a comparison of the winter 2002/2003 data with thermal structure evolution in the course of the four-year period (2000-2003) was made. The extent of the winter vertical mixing was then interpreted in terms of variations of the local climatic forcing (winter heat losses) at the inter-annual time-scale.

Fig. 2a and b show time-sequences of two temperature transects: Dubrovnik-Bari and Sušac-Brindisi from the pre-conditioning to the winter convection period.

At the beginning of autumn (October 2002), the XBT data clearly evidence the inflowing (warmer) water from the Ionian Sea along the eastern coast at the Dubrovnik-Bari transect (left-hand side of the graph) as depicted by the slope of isotherms. The flow of this water is also evident in a westward direction along the southern slope of the Palagruža Sill (left-hand side of the Sušac-Brindisi transect) as noted about three weeks later. This suggests that the inflowing water of Ionian origin re-circulates partly or completely around the South Adriatic

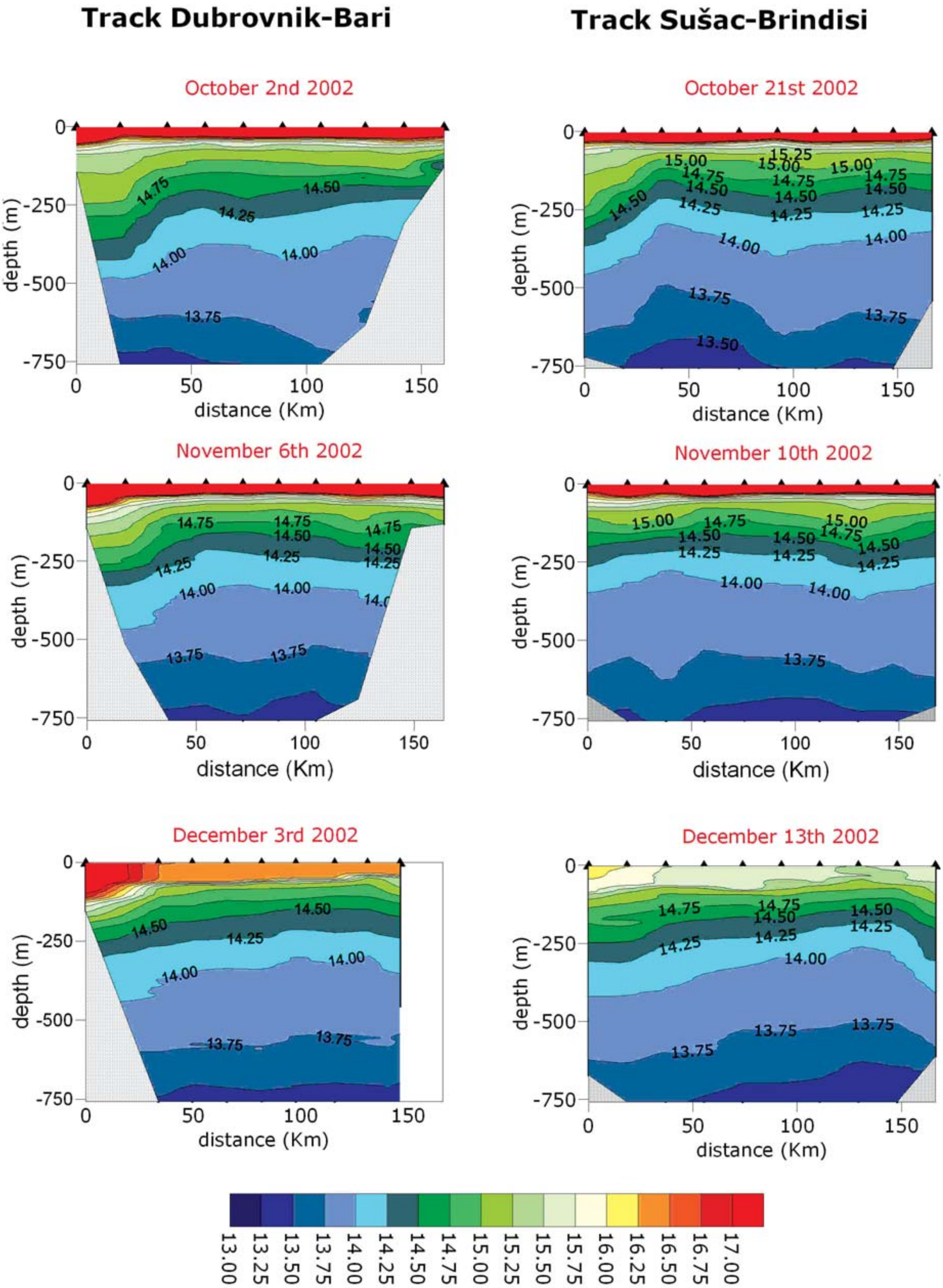

Fig. 2.a Sequence of temperature transects from October through December 2002 along Dubrovnik-Bari (left) and Sušac-Brindisi sections (right). Eastern coast (Dubrovnik) is on the left-side of the graphs and the northern part of the Sušac-Brindisi transect is shown on the left part of the graphs

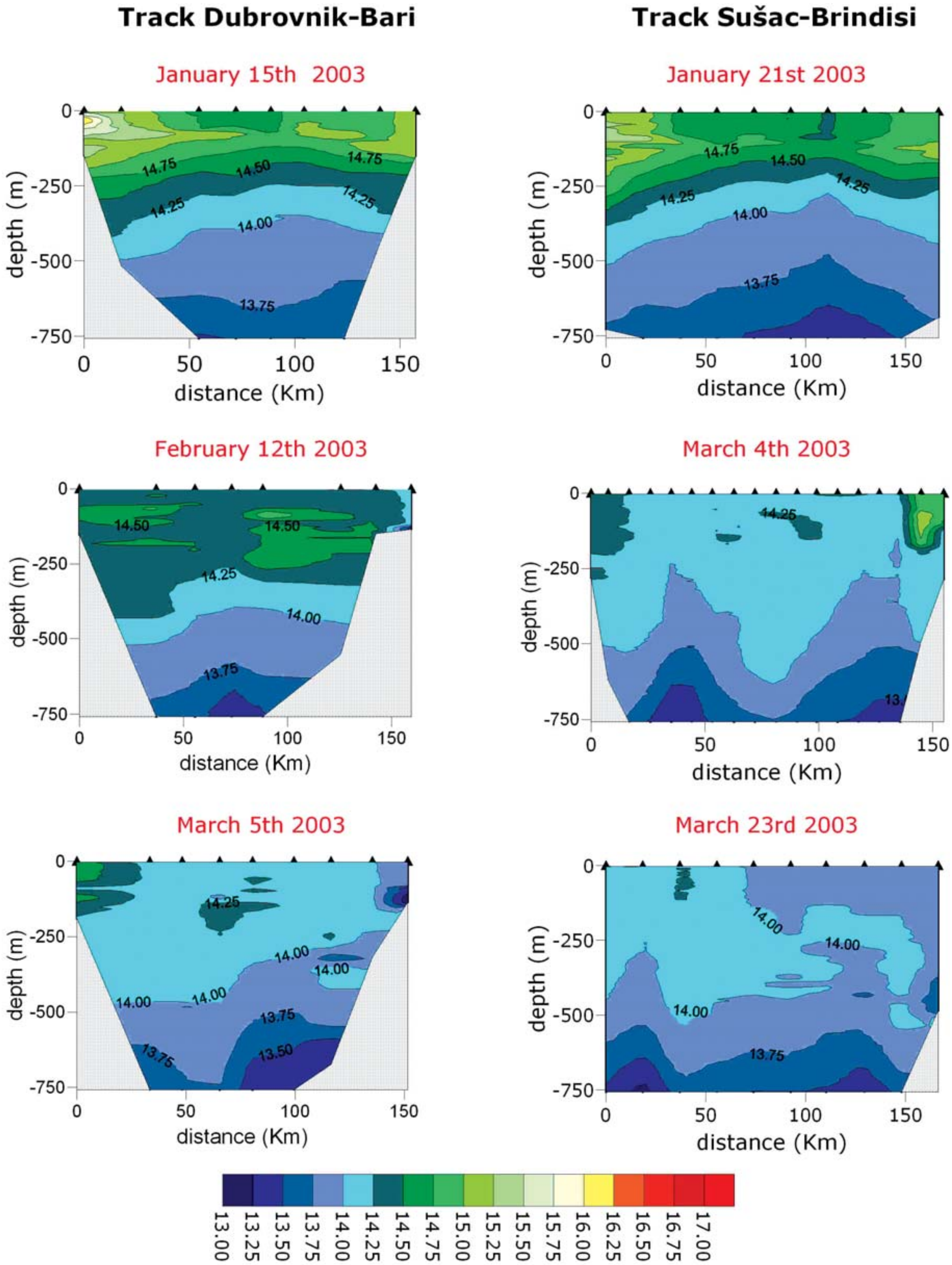

Fig. 2.b Sequence of temperature transects from January through March 2003 along Dubrovnik-Bari (left) and Sušac-Brindisi (right) transects

Pit. The inflow of the Ionian/Mediterranean waters into the Southern Adriatic Pit is also rather intense during November with a weakening of the re-circulation at the Palagruža Sill. These data corroborate the results of some previous studies documenting that the inflow from the eastern Mediterranean reaches its maximum in autumn (KLEIN *et al*., 2004; MANCA *et al*., 2003). In December 2002 the basin clearly showed the inflow of warm waters (left-hand side of the Dubrovnik-Bari transect) and the relatively weak re-circulation in the area of the Palagruža Sill (left-hand side of the graph showing the Sušac-Brindisi track). Important differences between the two transects in December in the surface layer temperatures down to about 60 m (on average by about 0.8°C) were present since the Dubrovnik-Bari XBT measurements were carried out about ten days before those at the Sušac-Brindisi transect. These differences were due to the strong heat-loss event (Fig. 3) associated with almost one week of bora wind blowing between the two cruises. This wind-induced mixing in the upper layer led to significant erosion of the seasonal thermocline (Fig. 4), which produced a heat content decrease in the first 60 m of about 55 Wm^{-2}. Integrating over the entire portion of the water column subject to temperature changes between the two cruises (up to 300 m depth), the heat content decreased to a lesser extent, i.e. by about 30 Wm^{-2}. The average surface heat loss in the area between the two cruises was estimated to be about 228 Wm^{-2}. Therefore, it results that the surface heat loss was about seven times larger than the heat content decrease over the water column as obtained using eq. (1). This suggests that the advection of heat, i.e. the intrusion of warm waters of Ionian origin into the Southern Adriatic Gyre in the upper layer, played a significant role in mitigating the sea-surface heat loss effects (MANCA *et al*., 2002; CARDIN *et al*., 1999; CARDIN & GAČIĆ, 2003).

The January 2003 transects showed the initial phase of the vertical convection reaching about 150 m depth and taking place in the centre of the gyre (see the dome-shape structure of isotherms at both transects and the surface mixed water patch in the centre). However, the heat content in the surface layer was relatively

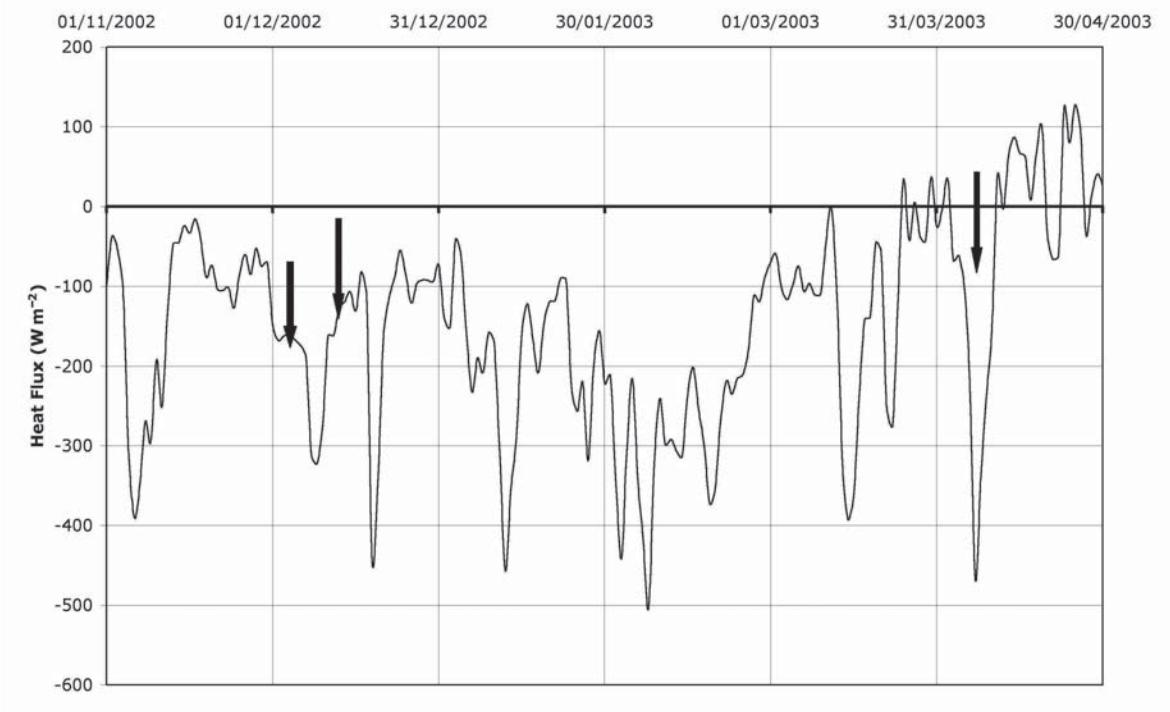

Fig. 3. Daily average heat fluxes from November 2002 through April 2003. Times of the cruises mentioned in the text are denoted by arrows. Negative values of heat fluxes indicate sea surface losses from the sea to the atmosphere

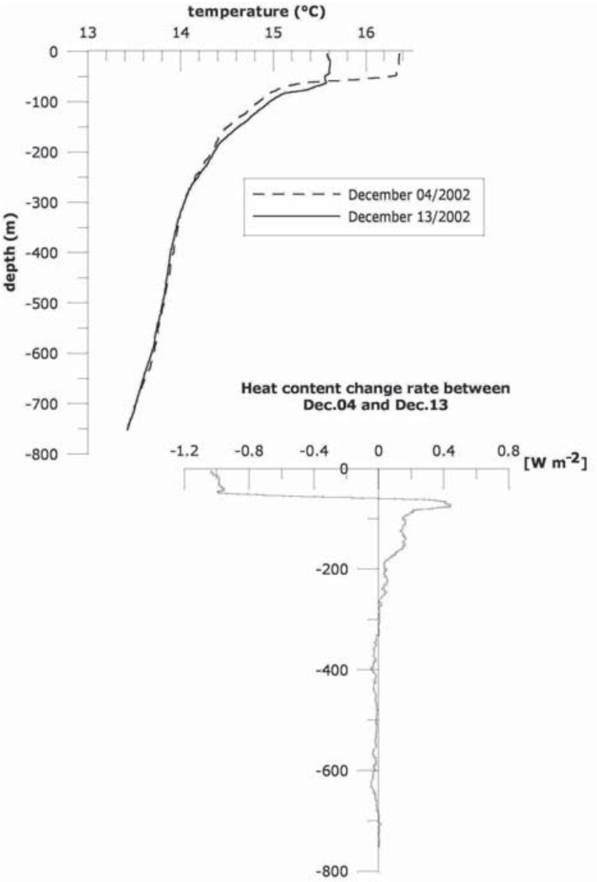

Fig. 4. *Vertical temperature profiles and heat content change in December*

high and the vertical temperature stratification appeared the strongest if compared with the other three January situations (2000, 2001, and 2002) (Fig. 5). In addition, comparison of the four winter seasons evidences that interannual variability in vertical convection does not manifest only in the vertical extent of mixing but also in the timing when the convection occurs. In winter 2003 only at the beginning of March did the water column became vertically mixed down to 600 m (Fig. 2b) while in 2002 mixing processes up to the same depth were already onset in the second half of January (Fig. 5). A strong year-to-year variability of mean monthly heat losses is evident during these four years (Fig. 6), confirming that interannual variability of climatic conditions represents one of the important controlling factors in determining the intensity and vertical extent of deep convection and mixing as well as its timing. In fact, strong heat loss during the pre-conditioning phase in 2001 followed by rather intense heat losses in January 2002 yielded the onset of vertical convection and mixing already in January. On the other hand, relatively weak December and January fluxes in winter 2002/

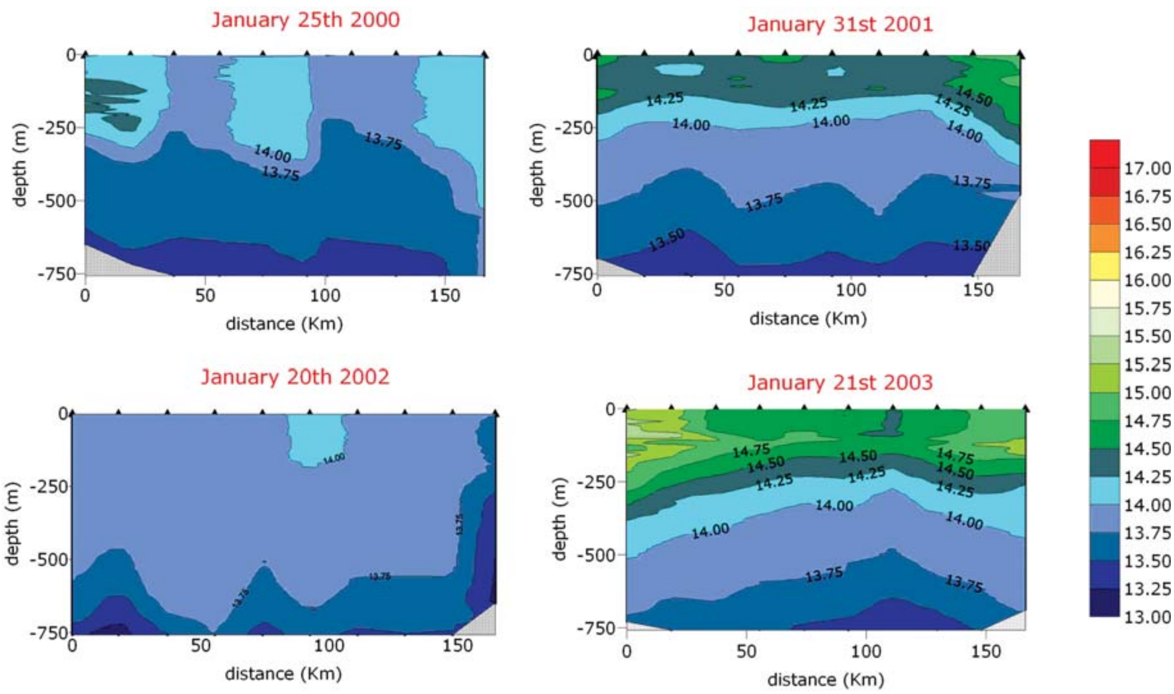

Fig. 5. *January temperature transects along the Sušac-Brindisi track for the years 2000, 2001, 2002, and 2003*

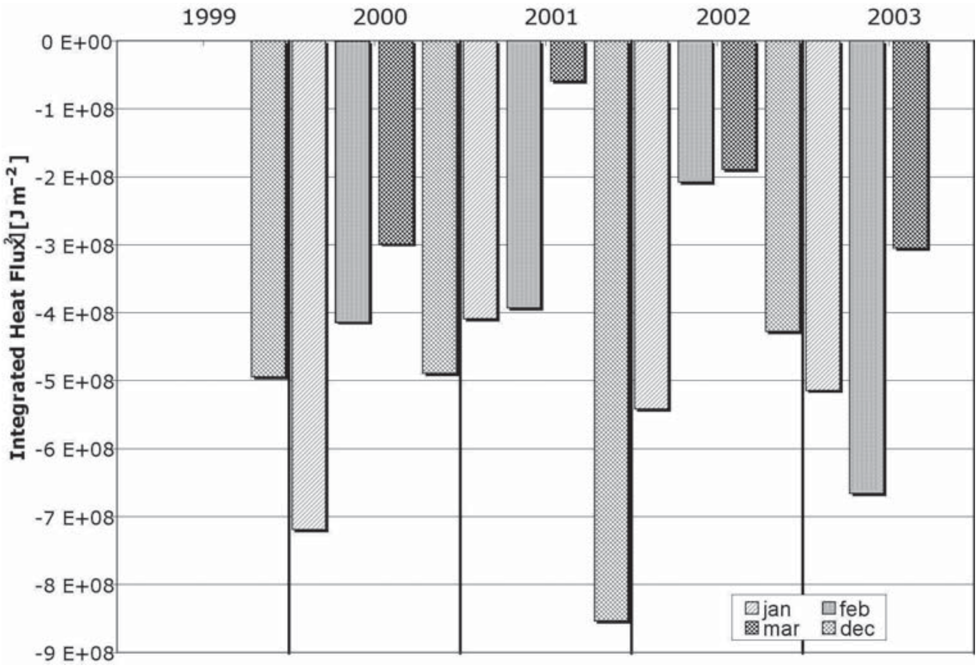

Fig. 6. Integrated monthly heat fluxes (Jm^{-2}) for four consecutive winters

03 followed by strong February heat losses resulted in a vertically mixed water column down to 700 m only in March, as evidenced in Fig. 2b. From the point of view of the year-to-year variability, it is interesting to look closer into the monthly mean heat losses of winter 2000/01 when relatively weak December heat flux was followed by the weakest January flux of all four years. Also, the March fluxes in that winter were the smallest of all four years. This had as a consequence an almost complete absence of the winter convection and persistence of the vertical stratification over all the winter period.

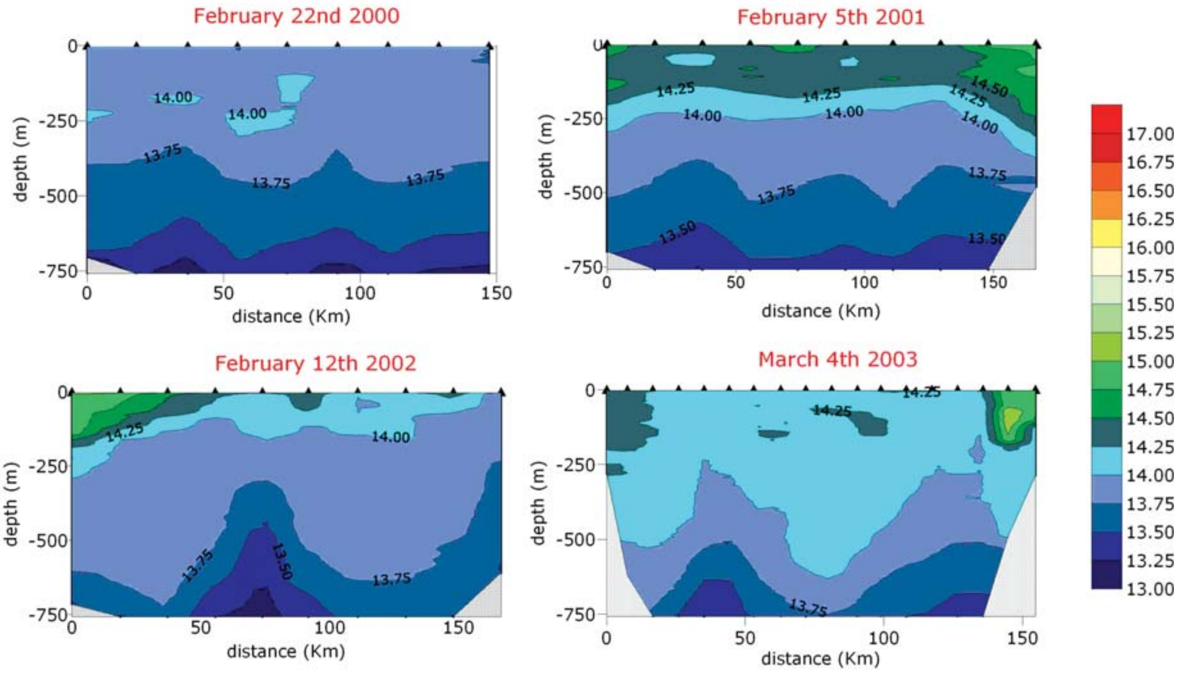

Fig. 7. February temperature transects along the Sušac-Brindisi track for the years 2000, 2001, 2002, and 2003

Comparison of thermal conditions corresponding to the spreading phase that often already starts around mid-February or the beginning of March for the four years, shows that in winter 2002/03 the vertical convection was as strong as in 2001/02, but the temperature of the vertically mixed part of the water column was slightly higher (Fig. 7).

Further development of the thermal structure in the convection season 2002/03 as evident from transects of April, May and June (Fig. 8) confirmed that the vertical convection was completed at the beginning of March, while April transects already showed the occurrence of the re-stratification due to solar heating. The second survey in April, however, again shows the vertically mixed surface layer but this was due to an intense atmospheric perturbation that passed over the area in the period before and during the cruise (see Fig. 3). In April the basin-wide cyclonic gyre transformed into several sub-basin scale doming structures. Also, an intensification of the inflow of Ionian/Eastern Mediterranean Waters, evident in May and June at the Dubrovnik-Bari transect, took place. This was followed by stronger re-circulation at the Palagruža Sill in June. Additionally, along the Italian shelf and continental slope at the Dubrovnik-Bari transect a rather clear signal of the cold bottom outflowing vein of water of northern Adriatic origin became evident in early March (Fig. 2b), and was then present through April and May. The vein intensified and deepened from March through May.

In order to study in more detail the intra-seasonal evolution of the thermal conditions in the southern Adriatic we averaged temperature in the area between 41.5°N-42.0°N latitude and 16.8°E-17.6°E longitude for each cruise and presented it in the form of time-depth diagram (Fig. 9). Stratified conditions continued well after the summer season reaching almost to the end of the autumn period. The seasonal thermocline was located at about 40 m depth. The effects of the erosion of the seasonal thermocline and vertical mixing/convection processes became evident by the end of January 2003. These processes yielded an almost homogenous layer down to about 600 m by mid-March 2003 with temperatures between 14°C and 14.25°C. Solar

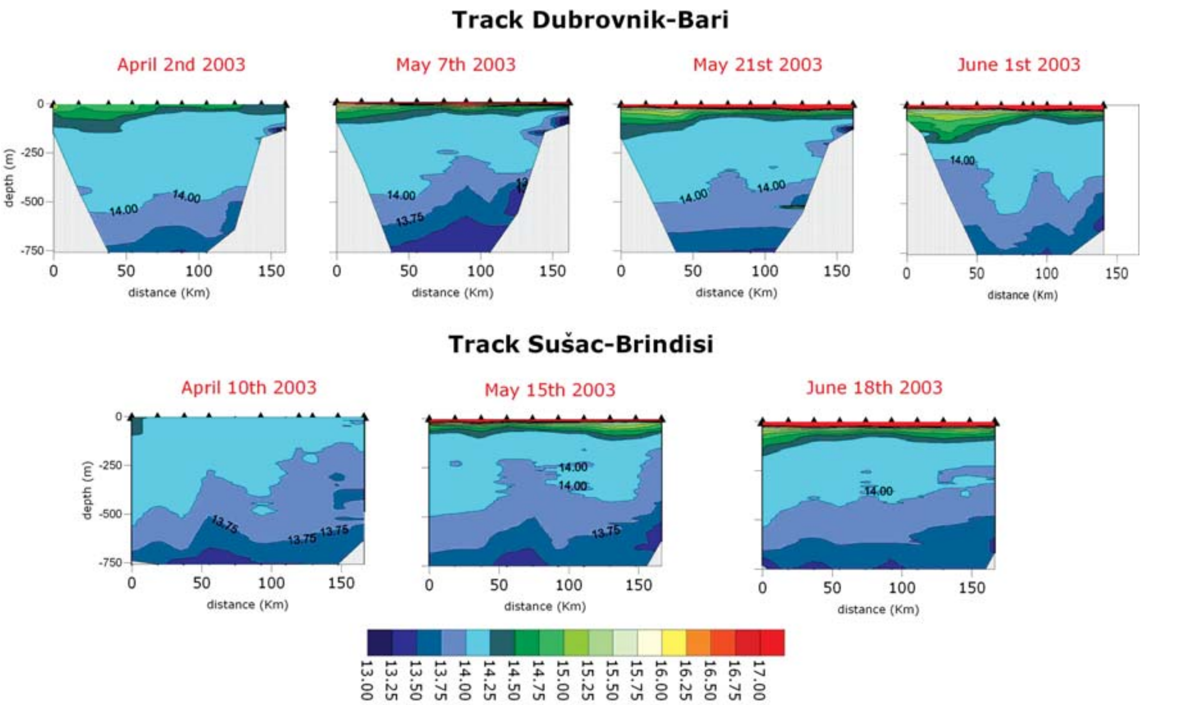

Fig. 8. Sequence of temperature transects from April through June 2003 along Dubrovnik-Bari and Sušac-Brindisi sections. Eastern coast (Dubrovnik) and the northern part of the Sušac-Brindisi transect are on the left-hand side of the respective graphs

heating of the surface layer already caused a regeneration of the seasonal thermocline in April 2003. The temperature of the mixed patch appeared rather high, both with respect to the early 1990's (13.2 °C in 1992) and to the period immediately preceding the 2002/03 winter. This temperature increase of the vertically mixed patch was explained in terms of changes in the water mass inflowing to the Adriatic (KLEIN *et al*., 2004; MANCA *et al*., 2004). This change in the thermohaline characteristics of the southern Adriatic was attributed to the inflow of the highly saline and warmer Cretan Intermediate Water (CIW) that replaced the Levantine Intermediate Water (LIW) in the upper part of the water column. The increase in the heat content and temperature of the vertically mixed patch in the intermediate layer in the southern

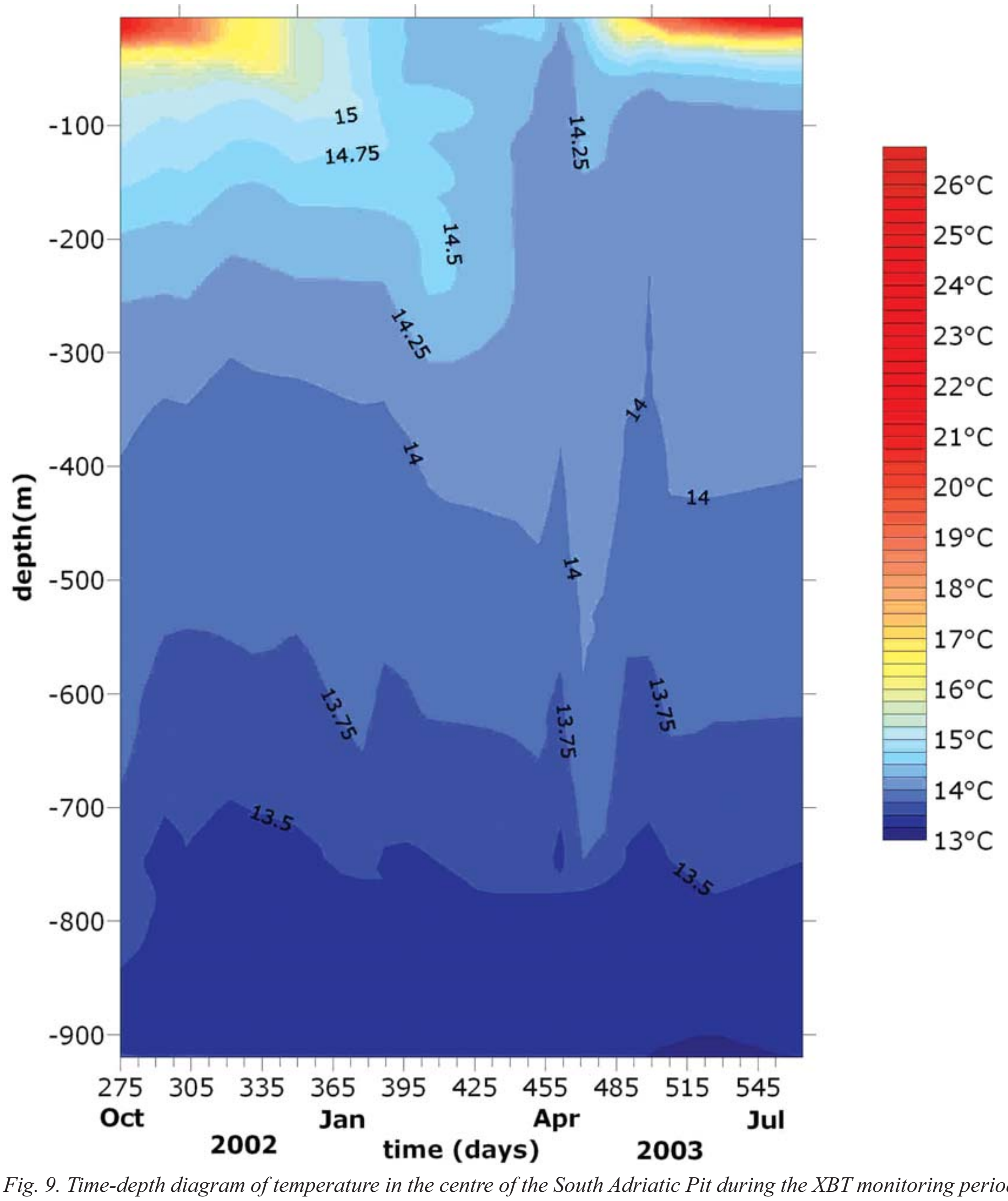

Fig. 9. Time-depth diagram of temperature in the centre of the South Adriatic Pit during the XBT monitoring period (October 2002-June 2003)

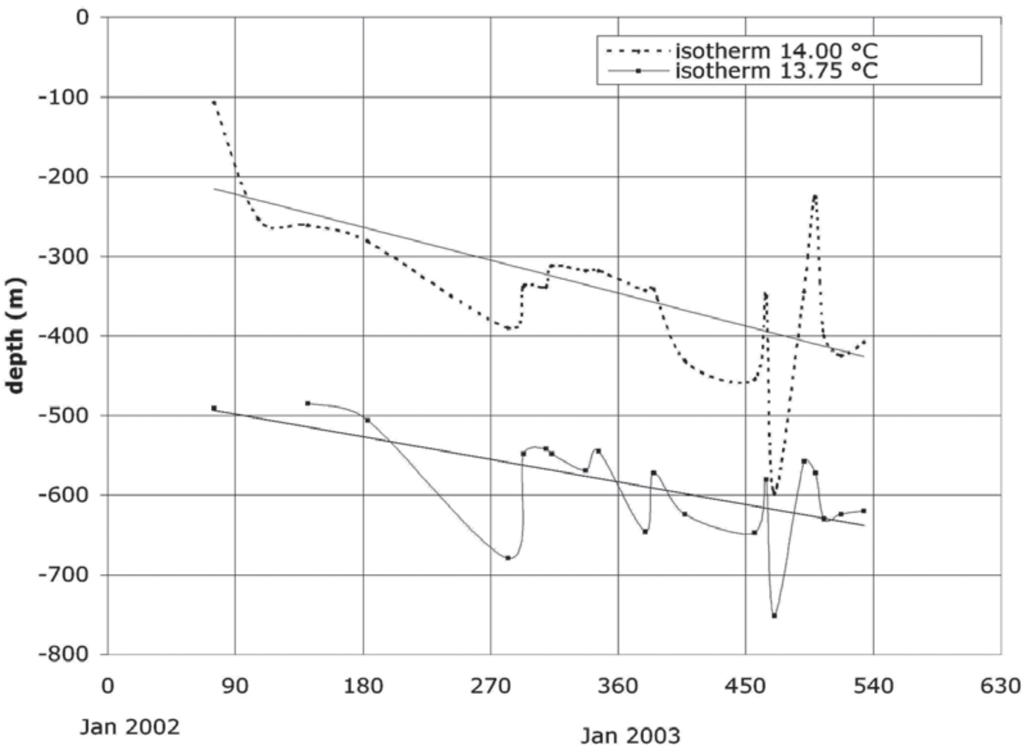

Fig. 10. Vertical displacement of the 13.75 °C and 14 °C isotherm between October 2002 and November 2003

Adriatic within the last two years is evident from the temporal variations of the 13.75 °C and 14 °C isotherm depths as presented in Fig. 10. During the studied period the two isotherms have deepened by about 200 m in average.

CONCLUSIONS

Based on XBT data collected along two transects in the southern Adriatic in the period October 2002 – June 2003, the time evolution of the thermal conditions over a period, from the pre-conditioning, through winter convection and then spreading phase was discussed. The pre-conditioning phase was characterized by intense Ionian/Eastern Mediterranean Water inflow and the strengthening of the south Adriatic cyclonic circulation. The vertical convection started in late January and by early March reached 600 m depth. The impact of air-sea heat fluxes on the vertical convection was to a large extent mitigated by the buoyancy advection into the vertically mixed patch. In the spreading phase, starting from early March, the signal of the cold water vein flowing along the Italian shelf break was clearly evident at the Dubrovnik-Bari transect. Although the vertical convection reached rather deep layers, the average temperature of the water column was higher than in previous years and showed the continuation of the increasing trend documented earlier.

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Varijacije termičkih uvjeta u južnom Jadranu prema batitermografskim mjerenjima u periodu od listopada 2002. do lipnja 2003. godine

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SAŽETAK

Redovna batitermografska mjerenja obavljana su dva puta mjesečno u južnom Jadranu u periodu od listopada 2002. do lipnja 2003., kako bi se analizirale vremenske promjene termičkih svojstava vezanih za formiranje pridnene vode. U jesenjem razdoblju prostorna raspodjela temperature ukazuje na pojačanu ciklonalnu cirkulaciju i intenziviranje utjecaja vode iz Jonskog mora. U ožujku vertikalno miješanje dosiže do 600 m dubine, ali je utjecaj gubitka topline na površini mora ublažen dotokom toplije vode s juga. Usporedba termičkih prilika u vertikalno izmiješanom stupcu vode ukazuje na nastavak višegodišnjeg porasta temperature mora uočenog u posljednjem desetljeću.

Ključne riječi : batitermografska mjerenja, oceanska konvekcija, interakcije more-zrak, Jadransko more