

## South Adriatic phenomena observable through VOS XBT and other ADRICOSM data

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*The VOS2 XBT track was established through the cooperation of ENEA and IOF during the ADRICOSM<sup>1</sup> period on the Dubrovnik–Bari route, monthly in the cold season and biweekly in the warm season, and the acquired data were sent to the ENEA<sup>2</sup> database in near real time. The results presented in this work comprise a compilation of data collected from different sources in the framework of the ADRICOSM project in the South Adriatic region. XBT profiles were compared to oceanographic ship-based measurements from CTDs from the recent cruise. In addition, the recently observed phenomenon of increased productivity of South Adriatic open waters is described and related to deep convection in the region.*

**Key words:** VOS XBT, temperature, South Adriatic, AVHRR, pigments, SeaWiFS<sup>3</sup>, LIW<sup>4</sup>, NAdDW<sup>5</sup>, deep convection, upwelling

### INTRODUCTION

In the southern Adriatic Sea, temporal variability of the thermohaline structure in the intermediate and deeper layer is caused by interannual variability of the intensity of advection of LIW from the Mediterranean to the Adriatic. Surface layers are influenced by air-sea interactions, river discharge, mixing and seasonally dependent circulation (ZORE-ARMANDA, *et al.*, 1999). A buoyancy source is provided along the Italian side by the north Italian rivers, the influence of which is spread in

a narrow strip along the Italian coast, and on the southeast side from the Albanian River Bojana. Both influences may spread further offshore, mainly in the warm period of the year.

Investigations of the VOS2 area (Fig. 1) had already started 100 years ago. One of the first systematic measurements was during the Najade-Ciclope joint Italo-Austrian expedition. In the fifties, the IOF<sup>6</sup> initiated seasonal measurements at a couple of oceanographic stations. Therefore, basic processes that generate thermohaline conditions are well known in this area, but more profound understanding

<sup>1</sup> ADRICOSM – ADRIatic sea integrated COastal areaS and river basin Management system pilot project

<sup>2</sup> ENEA – Ente per le Nuove tecnologie, l' Energia e l' Ambiente

<sup>3</sup> SeaWiFS – Sea viewing Wide Field-of-view Sensor

<sup>4</sup> LIW – Levantine Intermediate Water

<sup>5</sup> NAdDW – North Adriatic Deep Water

<sup>6</sup> IOF – Institute of Oceanography and Fisheries

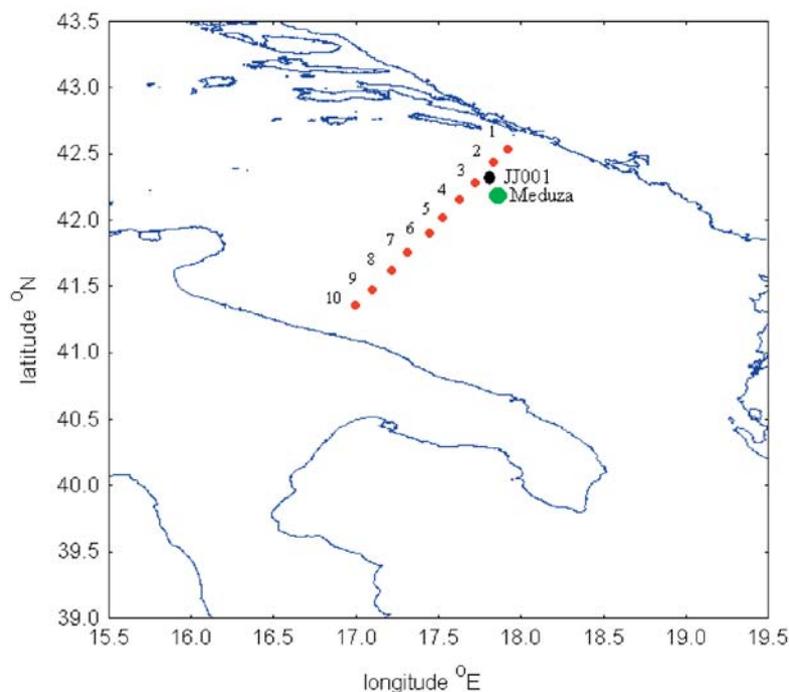


Fig. 1. Location of 10 XBT locations, the long term station JJ001 and area of Meduza survey in July 2003

was expected from better spatial and temporal resolutions of the measurements during the ADRICOSM campaigns.

Thermohaline conditions in the South Adriatic are under different influences from the east to the west coast. Intermediate layers of the South Adriatic are regulated by inflows of more saline ( $>38.7$  psu), warmer and nutrient richer LIW from the Mediterranean (MARASOVIĆ *et al.*, 1990; ZORE-ARMANDA 1969; 1971; 1972; BULJAN & ZORE-ARMANDA, 1976; ZORE-ARMANDA *et al.*, 1991). The continental slope of the west coast is under the influence of the cold and less saline flow of modified NAdDW. The LIW intrusions are stronger in the winter period, especially when influenced by the strong atmospheric pressure fluctuations over an area wider than the Mediterranean (ZORE-ARMANDA *et al.*, 1999). The conditions that generate NAdDW in the Northern Adriatic and the conditions that reinforce LIW intrusions, although independent, seem to coincide in time. Both occur during cold winters (GRBEC *et al.*, 2003).

Through long-term measurements and research, numerous phenomena were consecu-

tively observed. Only few decades ago, data collection by satellite became routine which enabled observation of increased productivity in the South Adriatic Pit.

All the measurements performed during the ADRICOSM VOS campaign enabled more profound studies of the processes in the South Adriatic Pit.

## MATERIAL AND METHODS

The profiles of 14 VOS2 XBT cruises at 10 stations across the Dubrovnik-Bari transect (Fig. 1) in the period from 1 October 2002 to 31 September 2003 comprise the basic data for this research. Satellite images used for comparison were AVHRR NOAA-16 images and color SeaWiFS images produced by GOS ISAC Rome, within the frame of the ADRICOSM project (<http://gos.ifa.rm.cnr.it/adricosm/>).

The data from the MEDUZA<sup>7</sup> project experiment in July 2003 were used for comparison to the VOS XBT profiles.

<sup>7</sup> MEDUZA is the "Collaborative international research on the gelatinous zooplankton in the Adriatic Sea". See [www.izor.hr/Meduza/index.htm](http://www.izor.hr/Meduza/index.htm)

## RESULTS

### Seasonal temperature changes

From the vertical distribution of temperature at a single station, development and breakdown of the thermocline was observed (Fig. 2). Deepening of the thermocline was visible

through the autumn and winter months. In February and March the water column became vertically homogenous. In April, it was observed that heating from the surface had begun. In May, heating continued and by the second cruise of May the surface had been heated to 19 °C and a very shallow thermocline was already

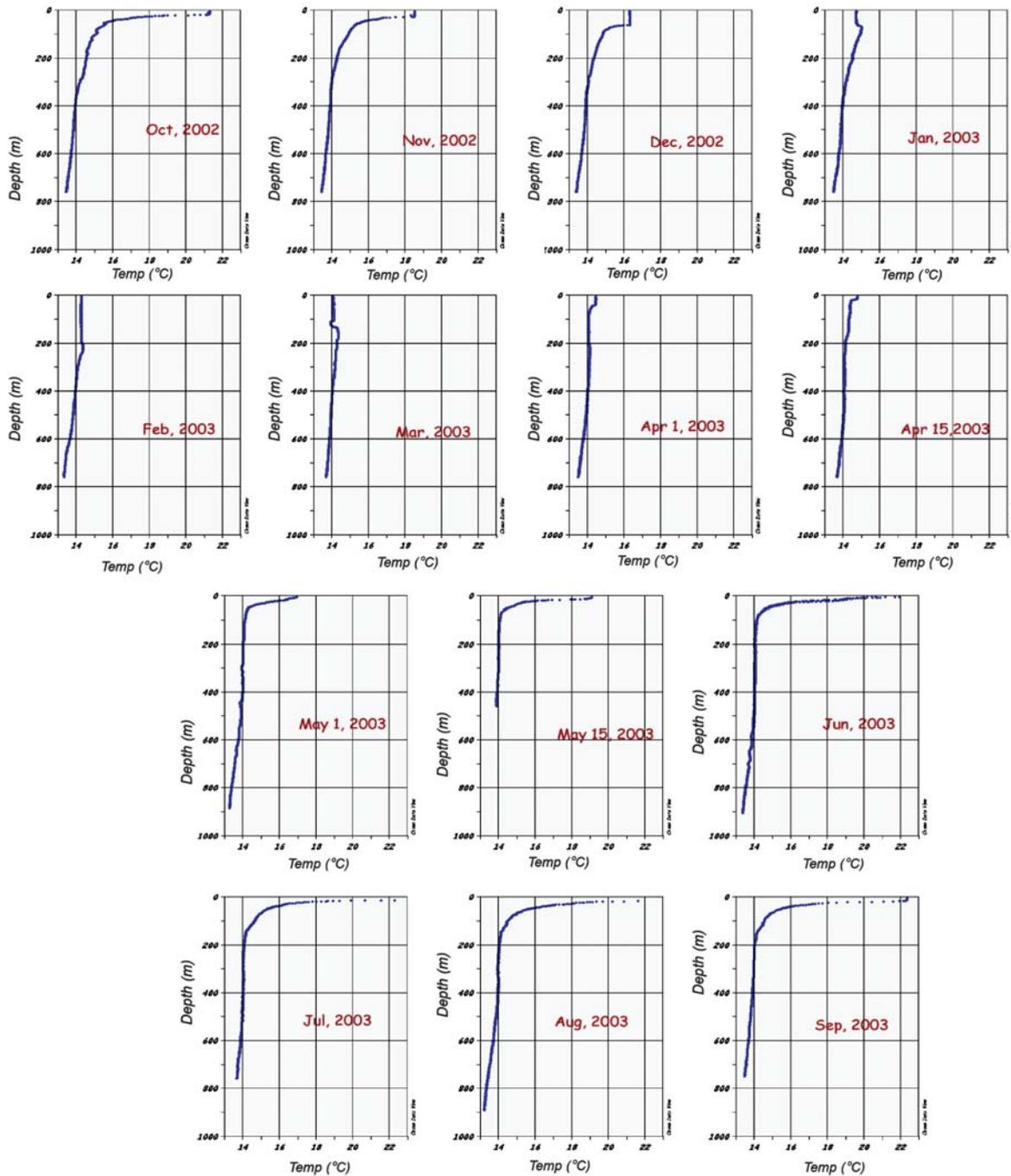


Fig. 2. Vertical temperature profile at the station P3 during VOS2 ADRICOSM campaigns during October 2002-September 2003 period

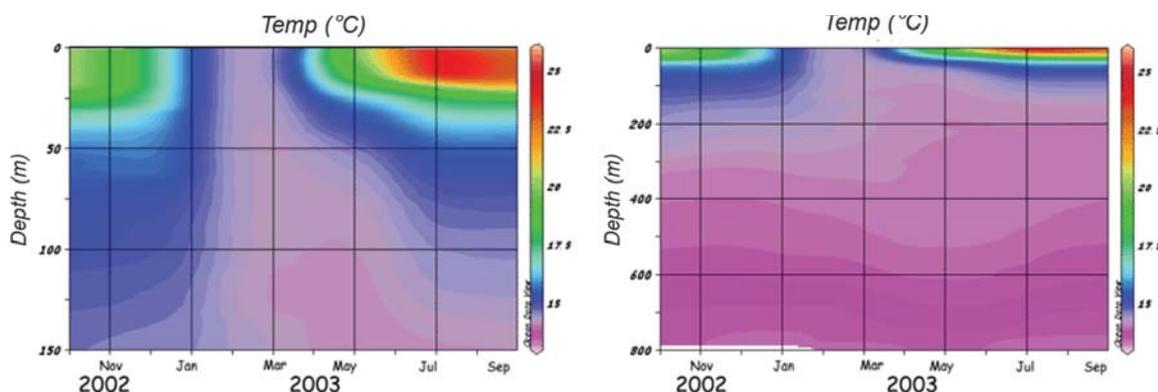


Fig. 3. The seasonal course of vertical temperature distribution at the station P4 during VOS2 ADRICOSM campaigns in the October 2002- September 2003 period

present. In June, the thermocline was developed only down to 10 m. The thermocline remained shallow during the first campaign in July. After a strong bora wind episode in the second July cruise ('August' is indicated in the image yet the dates were 30-31 July) deepening of the thermocline was observed.

At station P4 in the South Adriatic Pit, it was seen that below 400 m changes of temperature were practically insignificant (Fig. 3). Down to 150 m temperature changes were related to the seasonal heat and water fluxes. The range of temperature at particular depths decreased with depth; at a depth of 5 m the range was 12 °C; at 50 m it was 5 °C and at 150 m only 2 °C. In February and March the water column was well mixed, so that the first 150 m had practically the same temperature. The deepening of the thermocline advanced slowly with the season and in July it still remained relatively shallow. After the influence of an intense bora wind episode the thermocline had further progressed in depth, and to an even greater extent in September.

#### Temperature profiles and supporting satellite images

In addition to XBT measurements satellite AVHRR NOAA-16 images and color SeaWiFS images (produced by GOS ISAC, Rome) for the October 2002 to September 2003 period were also analyzed in order to better explain oceanographic conditions of measurements and

phenomena observed in the South Adriatic. Only images from dates closest to dates on which VOS2 XBT measurements were made are displayed. In October 2002, the surface layer was still warm compared to the deep layers (Fig. 4). However, isotherm slopes suggest that the warm layer is deeper at the Dubrovnik side of the transect than at the Bari side, caused by intrusions of warmer LIW into the eastern Adriatic. The influence of this intrusion continued in November, while the surface layers began to cool down due to the colder atmosphere.

In October and November, from the sea surface temperature there was evidence of warmer water entering from the Mediterranean along the southeast Adriatic coast. This is the usual advection phenomenon of LIW that enters through the Otranto Strait and continues, while being uplifted, towards the north and north-west. A coastal temperature front was absent. In the first October days, concentration of pigments seemed to be high in the entire basin. In October and November a moderately extended coastal color front was present.

Cooling at the surface continued in December, and was even stronger in January (Fig. 5) along the entire transect after strong bora episodes, whereas the presence of warmer water in deep layers persisted at the eastern side, as seen from XBT profiles. In December, cloud free satellite images were very rare. In January, very cold coastal water spreading along the Italian side was seen, induced by the river runoff, while warmer water continued intruding along the

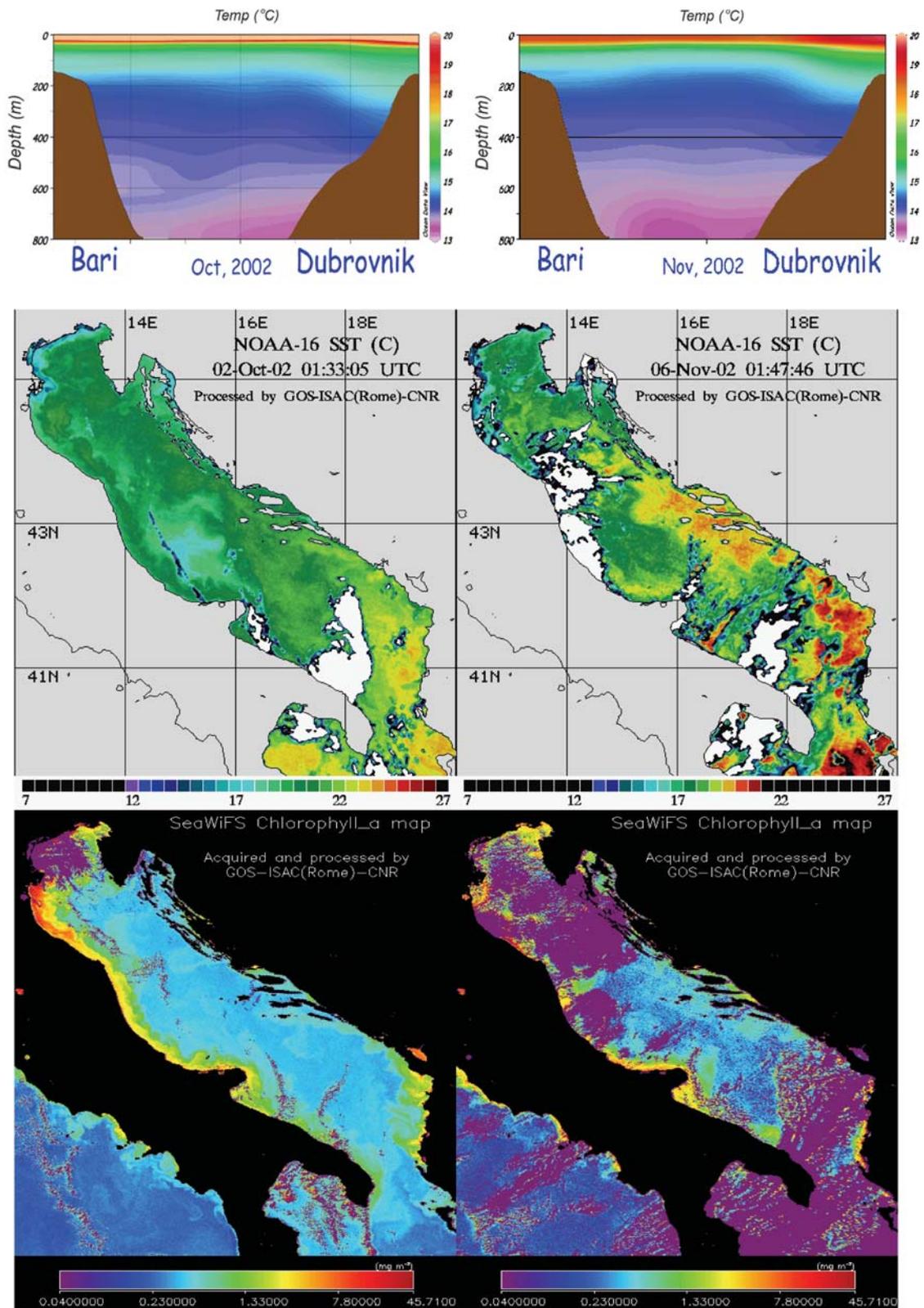


Fig. 4. XBT measurements at the Dubrovnik-Bari profile on 1-2 October (left) and 5-6 November 2002 (right), surface temperature (middle) and chlorophyll concentration (down) from the closest time to XBT measurements

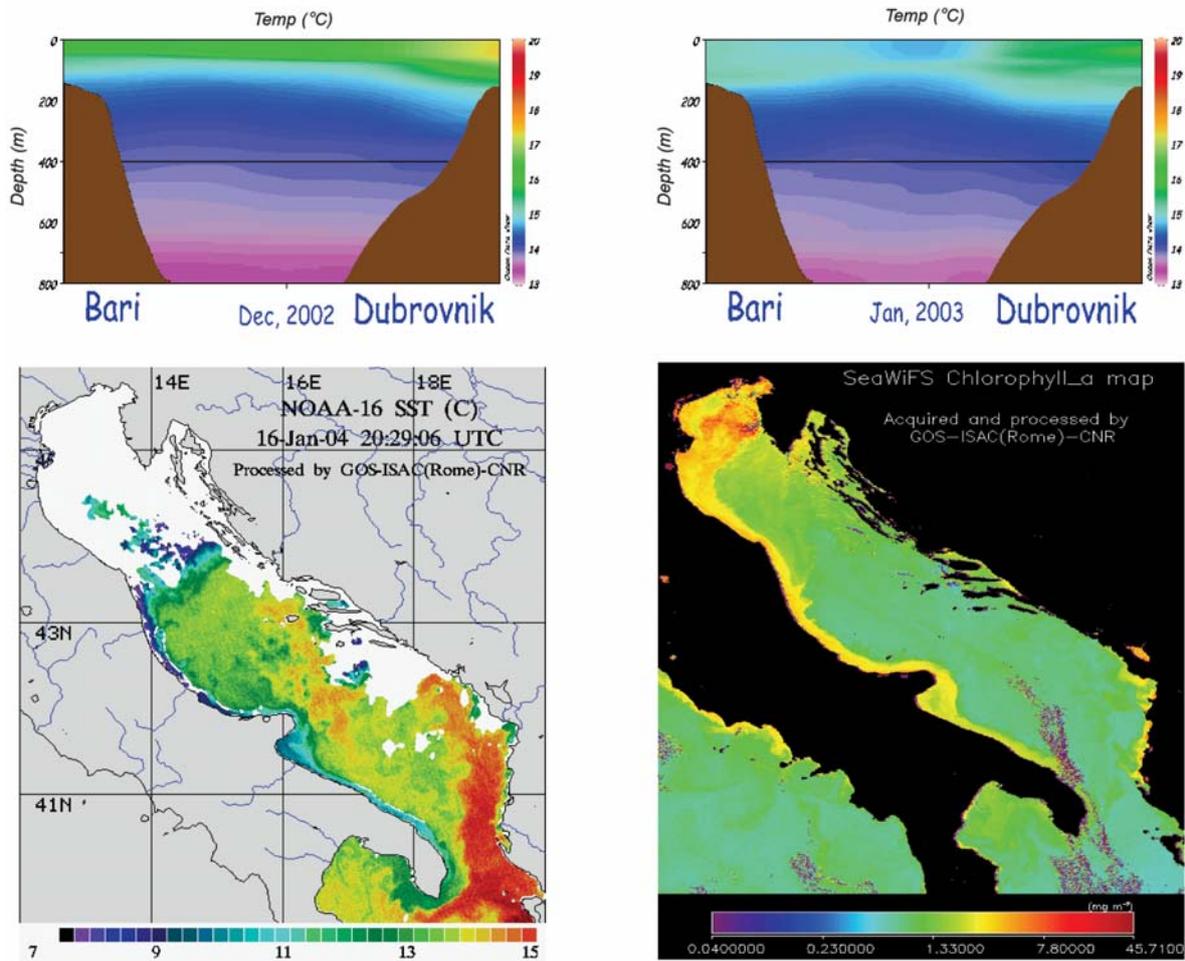


Fig. 5. XBT measurements at the Dubrovnik-Bari profile on 3-4 December and 14-15 January 2003 (up), surface temperature (middle) and chlorophyll concentration (down) from the closest time to XBT measurements (in December satellite images were not available)

southeast coast, contrasting with colder water in the middle of the southern basin. A strong thermal front was present in the Otranto Strait. In mid January pigment concentrations seemed to have relatively increased in the entire basin. This could partly be due to wind induced mixing (MOROVIĆ, 2002; MOROVIĆ & PRECALI, 2004). The extension of the coastal color front had increased in the Gulf of Manfredonia, although further south it followed the coast with a constant extension.

February and March (Fig. 6) were characterized by an almost vertically homogenous distribution, as observed from XBT profiles. In both months the warmer LIW was present at the eastern side of the South Adriatic Pit, whereas

along the west side the cold outflow was visible in the vertical profile. Both in February and March, warmer water was present along the southeast Adriatic coast, as seen from AVHRR images. Evidence of winter cooling were visible very close to the southeast coast by the presence of colder water. However, the closest XBT measurements were a little offshore and more to the north of the observation of this phenomenon. In March a narrow coastal front of colder water was driven southwards along the Italian coast. It coincided with a narrow color front of increased pigments; along the Albanian coast a very narrow color front was also present. In February the color front was more extended off the Albanian coast than off the south Italian Adriatic coast.

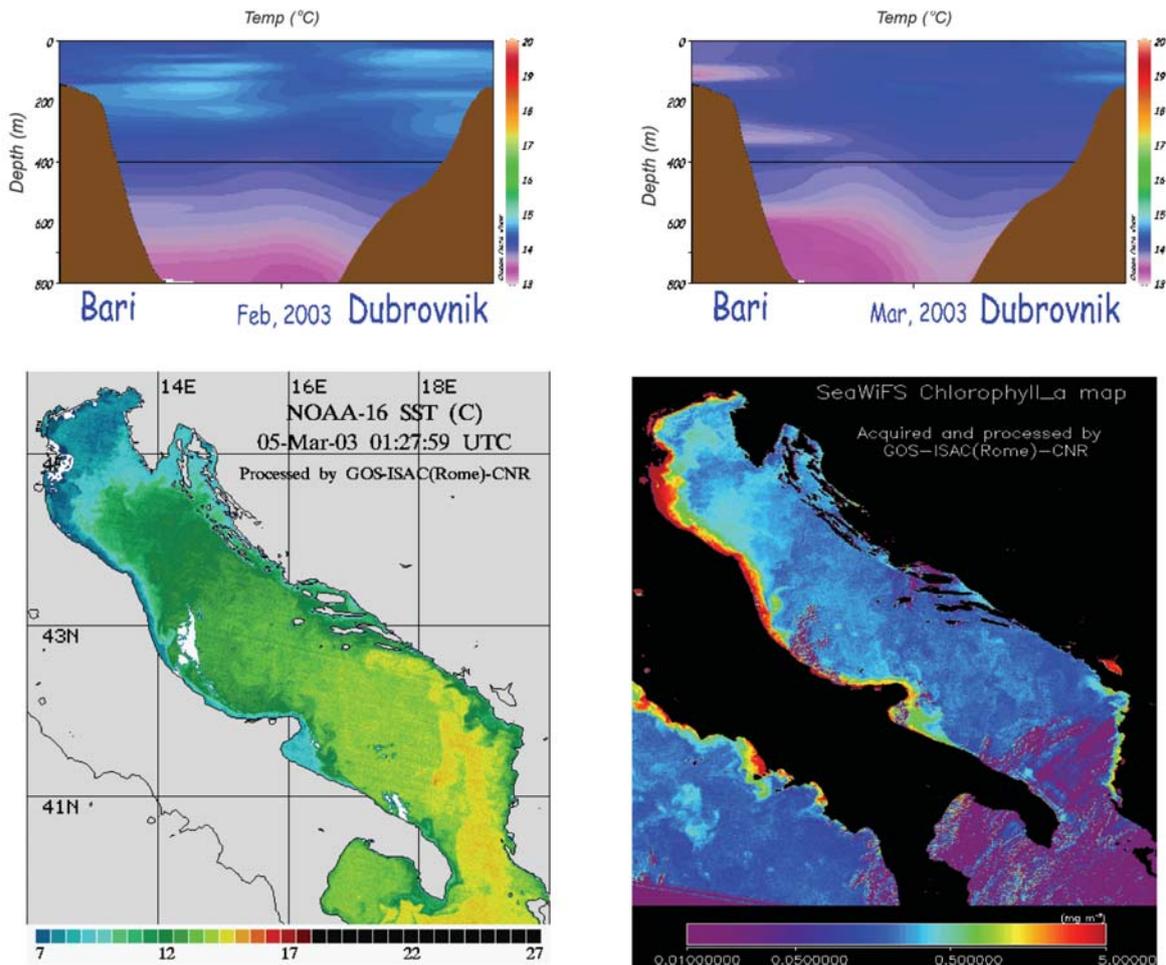


Fig. 6. XBT measurements at the Dubrovnik-Bari profile on 11-12 February and 4-5 March 2003 (up), surface temperature (middle) and chlorophyll concentration (down) from the closest time to XBT measurements (in February satellite images were not available)

The first measurements in April (Fig. 7) showed that heating of the surface began especially at the eastern side. In the deeper layers, outflow of the colder water is present near the Italian side, and remains there in the following months. Bora wind, blowing between the two cruises in April, reduced heating at the surface due to turbulent convection in the surface layers.

In April, the surface temperatures were still low in the northern part, contrasting with the warmer south Adriatic Sea. This was caused by meteorological conditions of strong bora wind episodes which caused deep sea mixing in the South Adriatic Pit, enabling vertical injections of nutrients in the euphotic zone (GAČIĆ *et al.*, 2002).

The consequences were observed in increased concentration of pigments, especially later in April. However, the same feature was not visible in the surface temperature field. Several days earlier, OGS performed a cruise along the VOS1 XBT profile in the Southern Adriatic (Fig. 8). The area with increased pigment concentration corresponded to the center of a cyclonic mesoscale eddy, and the vertical temperature profile indicated that this was not just a surface phenomenon but extended to deeper layers.

The influence of LIW was observed in the very deep layers at the beginning of May (Fig. 9). The two May measurements made in succession showed continuous heating at the

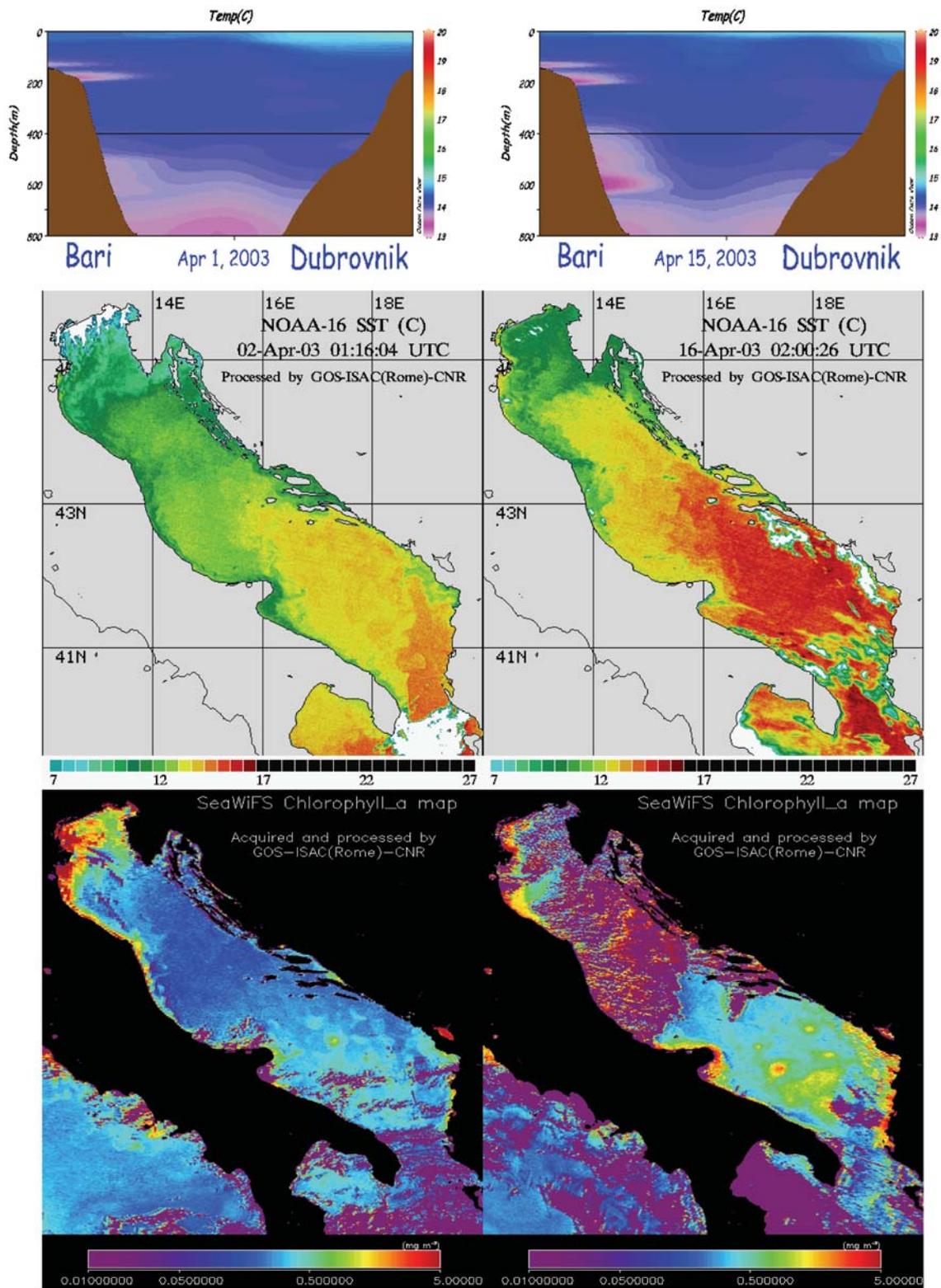


Fig. 7. XBT measurements at the Dubrovnik-Bari profile on 2-3 April 2003 and 15-16 April 2003 (up), surface temperature (middle) and chlorophyll concentration (down) from the closest time to XBT measurements

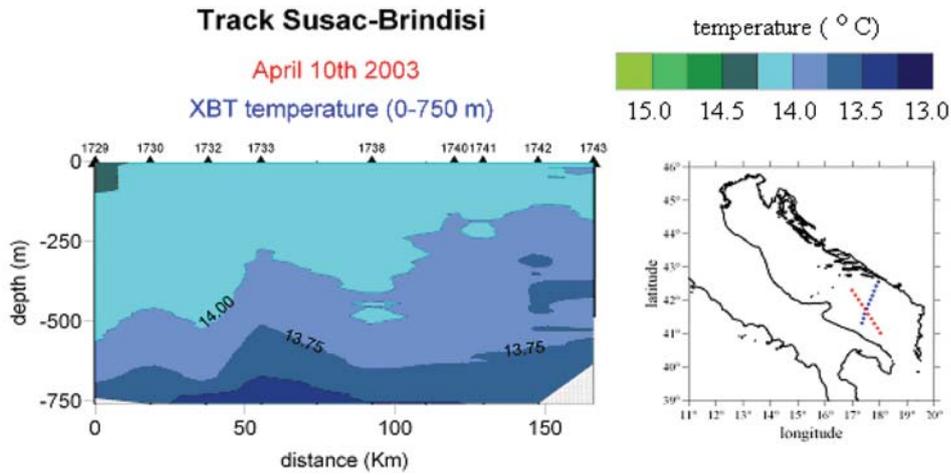


Fig. 8. VOS1 XBT profile along the southern Adriatic pit (according to GAČIĆ, personal comm.)

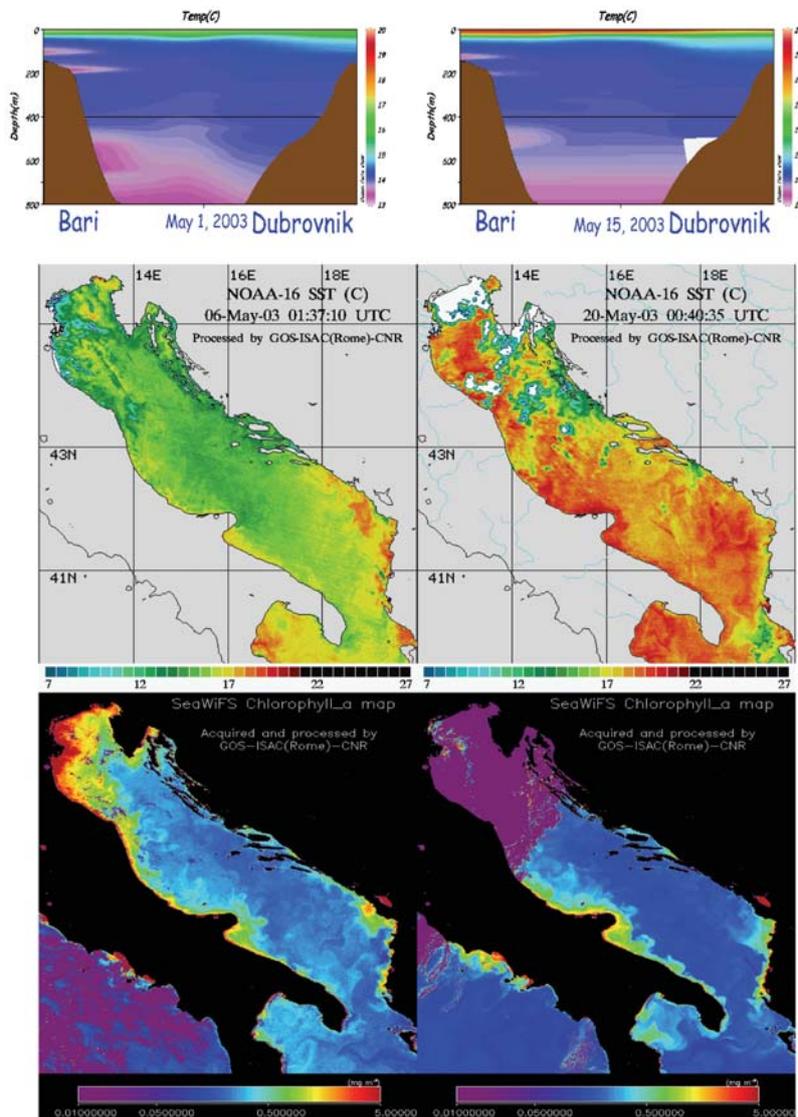


Fig. 9. XBT measurements at the Dubrovnik-Bari profile on 6-7 May 2003 and 20-21 May 2003 (up), surface temperature (middle) and chlorophyll concentration (down) from the closest time to XBT measurements

surface, and development of the thermocline. The surface temperature had increased over the Adriatic, but the coastal temperature front had disappeared except near the Albanian coast. The color front was reinforced near Albania, while off the Gargano peninsula and in the Gulf of Manfredonia cyclonic mesoscale eddies were observed. The second part of May was characterized with increased temperatures near the coast of Italy, while very near to the eastern coast there was evidence of colder water. In the second part of May the color field was dominated by very low pigment concentrations in the southern pit, while the coastal color front showed mesoscale features at the Italian side, some of which may have been anti-cyclonic.

The influence of reinforced river runoff was observed near both coasts.

In June, warming from the surface continued and the thermocline was fully developed (Fig. 10). At the east side it was warmer at depths below 70 m, but the surface became warmer at the west side in June and later in summer when the thermocline was deeper at the west side. In June, surface temperatures had further increased, while the color front extended less from the coast than in May. In July, there was evidence of warmer surface waters closer to the Italian side and colder water along the eastern side. This may be due to the action of wind. The same situation was also observed at the end of July (Fig. 11). The coastal color front was very

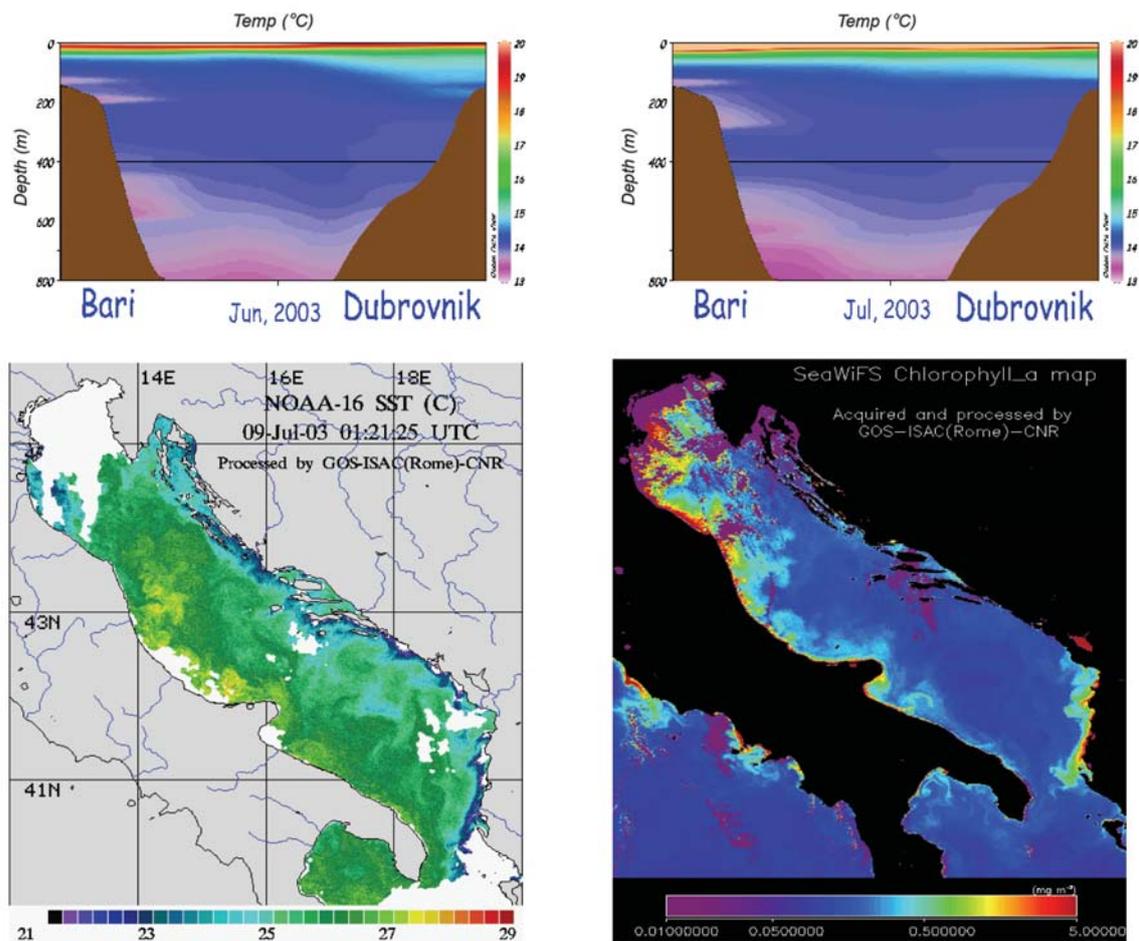


Fig. 10. XBT measurements at the Dubrovnik-Bari profile on 1-2 June 2003 and 9-10 July 2003 (up), surface temperature (middle) and chlorophyll concentration (down) from the closest time to XBT measurements (in June satellite images were not available)

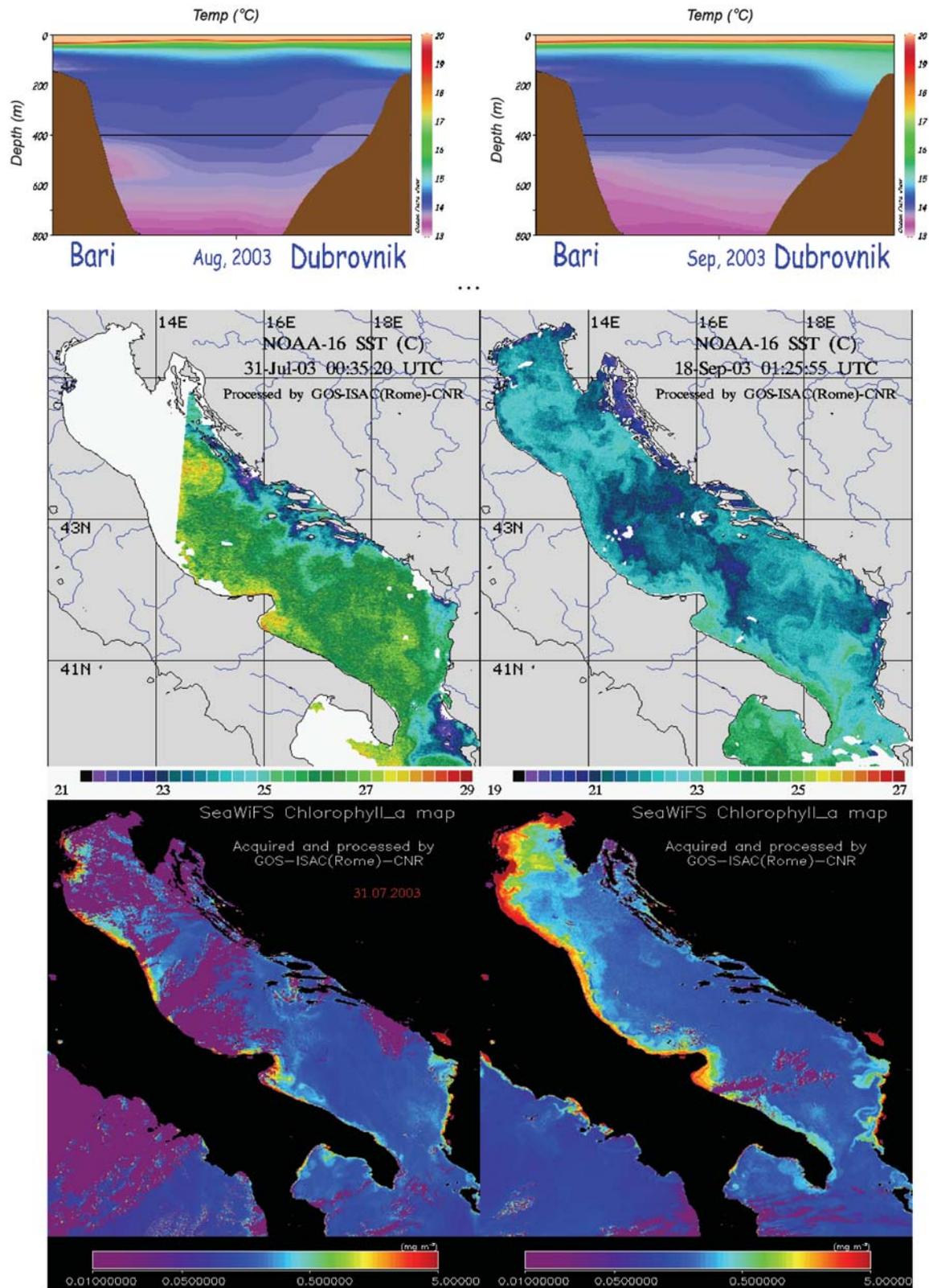


Fig. 11. XBT measurements at the Dubrovnik-Bari profile on 30-31 July 2003 and 17-18 September 2003 (up), surface temperature (middle) and chlorophyll concentration (down) from the closest time to XBT measurements

narrow at the Italian side, which is its usual summer characteristic, while off the Albanian coast under the Bojana River influence, it was somewhat more extended at the beginning of July, although had disappeared by the end of the month.

In September, warmer water resided at the surface at the Italian side and was colder along the east side. The color front was present in a very narrow alongshore strip except in the Gulf of Manfredonia where it was more intense.

#### Earlier evidence of increased offshore pigments in the Southern Adriatic

The general pattern of pigment concentration from satellite data highly corresponds to the historical productivity distribution (Fig. 12, left). This is characterized by increased productivity in the northern Adriatic and a narrow strip of increased pigment concentration along the coasts, with variable extension offshore. The eastern side is generally less productive and open south and middle Adriatic waters are mainly considered oligotrophic.

The highest pigment concentrations result from the influence of large northern rivers, especially the Po River, that brings sediments and dissolved colored substances. The waters near Albania are under the influence of the Bojana River. The two rivers have different temporal dynamics (BARALE *et al.*, 1984; BARALE *et al.*, 1986). Most satellite color images display features that correspond to the spatial distribution of euphotic zone depth (Fig. 12, right), within the oligotrophic southern pit. However, in some periods, south Adriatic waters have higher temperature and salinity in the intermediate layer from LIW and may also be enriched with nutrients by it. Fluctuations of LIW advection in the Adriatic also influence productivity (ZORE-ARMANDA, 1971; 1972; GRBEC & MOROVIĆ, 1997; GRBEC *et al.*, 1998; GRBEC, *et al.*, 2003; ZORE-ARMANDA *et al.*, 1999; MARASOVIĆ *et al.*, 1995) affecting the entire south and middle Adriatic ecosystems. Comparison of the two periods in Fig. 12b indicated a considerable reduction of euphotic zone depth after more than a decade, which is attributed mainly to anthropogenic influences from the coasts and partly to other changes in the environment.

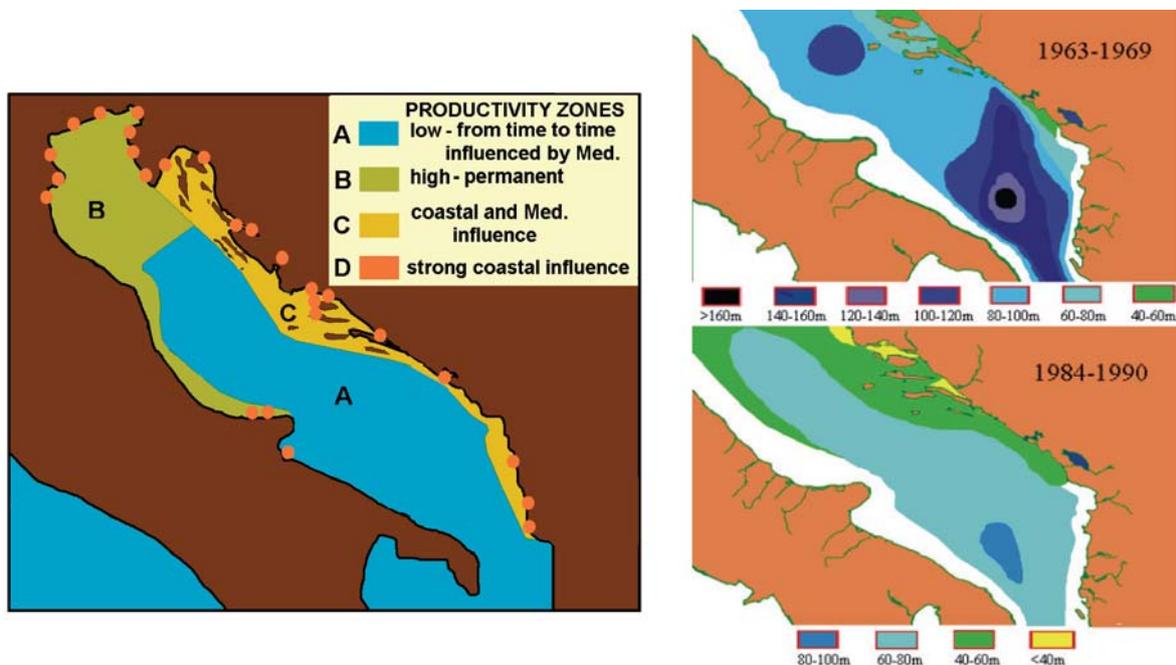


Fig 12. Division of the Adriatic to productivity zones (BULJAN, 1964) (left) and euphotic zone depths (right) from light attenuation data for summer period (MOROVIĆ & DOMIJAN, 1990)

Recently, the unusual phenomenon of increased offshore pigment concentrations was observed in the southern Adriatic. The phenomenon is found in some years but only between March and the end of April. Chlorophyll-like pigment concentrations higher than  $0.25 \text{ mg m}^{-3}$  are relatively high for the open Southern Adriatic, and some concentrations (Fig. 13) in April 1998 and 1999 exceeded even  $1 \text{ mg m}^{-3}$ . This phenomenon is also characterized by decreased concentrations near both coasts. This can be explained by the spreading of surface waters from the center of the cyclonic gyre towards the edges of the basin (VILIBIĆ & ORLIĆ, 2002) and uplifting of nutrient richer waters from the deeper layers in the centre of the gyre, which

has led to the increase of pigment concentrations. Weather conditions accompanying this phenomenon (MOROVIĆ *et al.*, 2004) are characterized by a cyclone passage, which ends with a strong bora wind episode. However, it seems that maximum pigments occur after a few calm days (GAČIĆ *et al.*, 2002).

The waters in the South Adriatic Pit circulate within the topographic constraints (GAČIĆ *et al.*, 1999) and cyclonic circulation may uplift nutrients from the deeper layers (ARTEGIANI *et al.*, 1997) towards the surface. Productivity may be reinforced due to dynamical and biological reasons, when enriched waters rise to the euphotic zone. Mixing agitation while deep waters rise may introduce more nutrients which,

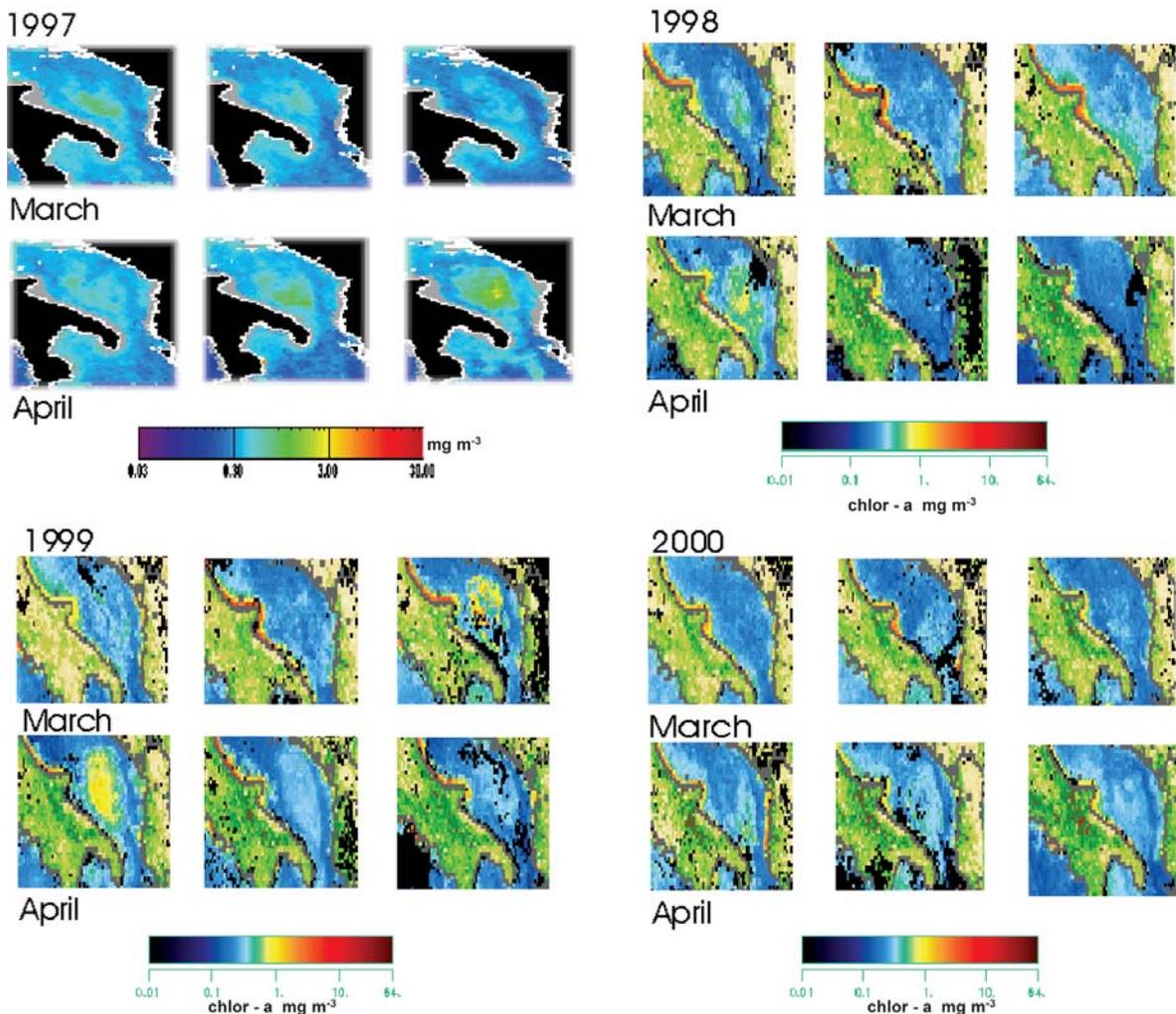


Fig. 13. Color satellite images from decades in March and April months from Polder CNES for 1997 and SeaWiF's NASA for 1998-2000

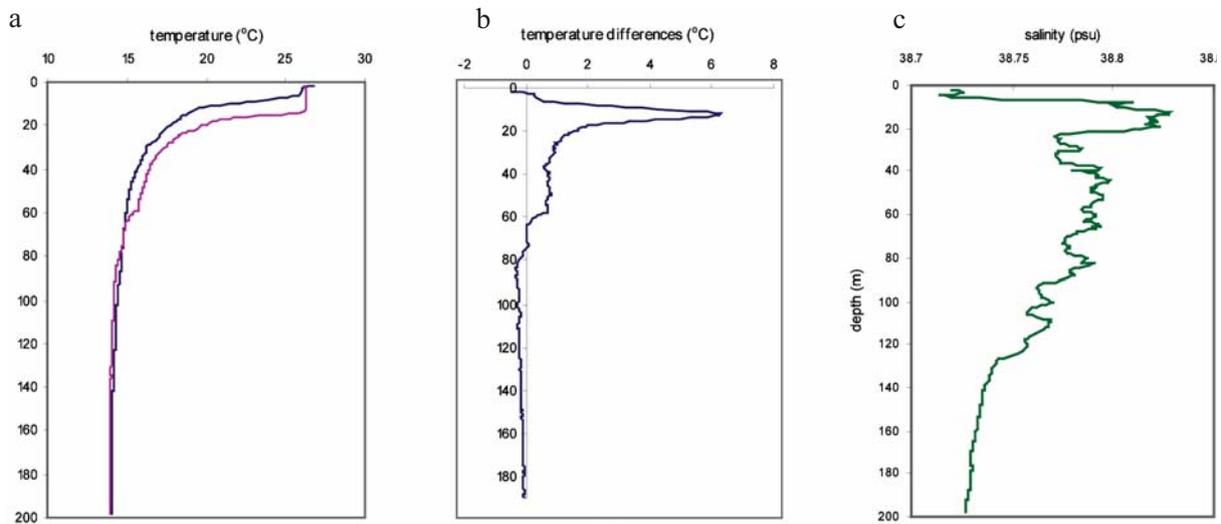


Fig. 14. Comparison of a) measured temperature with XBT (pink line) and with the Seabird CTD probe (blue line) b) temperature difference between the two measurements and c) salinity profile from the Seabird CTD probe

in the presence of increased light intensity, can allow a spring bloom in the offshore cyclonic gyre. Evidence of the phenomenon was found from *in-situ* measurements for the first time in spring 1986 and 1987 (VILIČIĆ *et al.*, 1989; MARASOVIĆ *et al.*, 1999).

The process of LIW intrusion (observed through salinity increases) is, however, well correlated to the large scale SLP (sea level pressure) distribution (from the Atlantic to the southeast Mediterranean; GRBEC *et al.*, 2003), while the SLP distribution also corresponds to a certain wind distribution.

#### Comparisons to CTD measurements

The comparison was made between XTB and CTD temperature measurements acquired during the summer cruise of the international project MEDUZA at locations (see Fig. 1) and times close to those of the XBT stations. The vertical temperature profiles (Fig. 14) showed a similar shape in both curves. It was found that both measured temperatures in the deep layers corresponded very well. However, above the thermocline layer, the temperature from XBT was higher, while at the very surface the CTD temperature was higher. The differences may be partly because of spatial scale variability at small

distances of a few miles. It may be also due to the internal waves that occur in the summer period. There could have been variability in time due to currents as well. The differences between the two temperatures are highest in the thermocline layer, which corresponded to the layer of high vertical salinity gradient (see Fig. 14) that can also be observed from the MEDUZA project data.

## CONCLUSIONS

The VOS2 campaigns in the southern Adriatic Sea enabled the studying of temporal and spatial variability of the thermohaline structure, especially the formation and breakdown of the thermocline. The thermocline was formed in June, and remained very shallow until August when, after some strong bora episodes, it became deeper.

Together with satellite data, it was possible to distinguish seasonal changes in temperature structure over the Southern Adriatic, and formation and spreading of the coastal temperature front. The change of concentration of pigments and the development of a coastal color front under the influence of rivers was also detected.

The VOS2 experiment enabled observing longer periods of intrusions and upwelling of warmer LIW towards the eastern coast and the presence of the cold vein of NAdDW outflow along the west coast.

Combining XBT profiles with color satellite data, it was possible to detect a mesoscale eddy in late April 2003, a relatively rare spring phenomenon associated with deep sea mixing in the southern pit, which occurs after particular weather conditions.

The comparison of XBT with CTD data has shown good correspondence in deep layers and a lower correspondence between the temperature data above the thermocline layer.

## ACKNOWLEDGEMENTS

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## Pojave uočene na južnom Jadranu, prema VOS XBT profilima i drugim podacima iz projekta ADRICOSM

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### SAŽETAK

U suradnji s ENEA-om, Institut za oceanografiju i ribarstvo je uspostavio mjerenja na transektu u južnom Jadranu koristeći prugu između Dubrovnika i Barija (tzv. VOS2 XBT profil) za vrijeme projekta ADRICOSM, i to mjesečno u hladnom periodu godine a dvomjesečno u toplom razdoblju. Prikupljeni podaci vertikalnih profila temperature mora su u realnom vremenu slani u bazu podataka u ENEA-i.

U ovom radu se opisuju rezultati XBT mjerenja s mjerenjima iz ostalih izvora u okviru projekta ADRICOSM za područje južnog Jadrana. Nadalje, vertikalni XBT profili temperature su uspoređeni s nekim ranijim i recentnim podacima mjerenim CTD sondama ili prekretnim termometrima. Opisan je i fenomen povećane produktivnosti otvorenog južnog Jadrana, koji je primijećen u novije vrijeme, a povezan je s podizanjem južno-jadranske vode.

**Ključne riječi:** VOS XBT, temperatura, južni Jadran, AVHRR, pigmenti, SeaWiFS, LIW, NAdDW, dubinska konvencija