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Surface fluxes and thermohaline variability over the ADRICOSM polygon Pelješac-Vis-Drvenik

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Thermohaline properties in the east Adriatic coastal area were measured bi-weekly during the cold season of 2002/2003 and weekly in the warm season of 2003 at 14 stations. The collected data set has space and time coverage suitable for comparison with general thermohaline climatology of the region. Temporal salinity changes registered during the experiment show strong departures from the typical annual cycle in which salinity follows average surface water flux variability. Throughout the experiment, high salinity values were measured as a consequence of prolonged bora events in the cold period, and unusual spring-summer atmospheric conditions. Due to the anomalously long and strong heating season, corresponding surface temperatures were also higher than the long-term averages. Surface heat and water fluxes were calculated for the research period, and were compared with climatological values originating from meteorological stations in the ADRICOSM polygon.

Key words: observing system, thermohaline climatology, air-sea interaction, eastern middle Adriatic

INTRODUCTION

The eastern middle Adriatic is a region of strong thermohaline dynamics, and consequently ecosystem variability, on time scales ranging from synoptic and seasonal to interannual, and attributed to the atmosphere through air-sea interactions, river discharges, mixing, and seasonally dependent circulation (ZORE-ARMANDA & BONE, 1987; ZORE-ARMANDA *et al.,* 1999).

The thermohaline complexity of the region was documented via intensive long-term measurements of hydrological parameters established in the early 1950 as a part of oceanographic investigations performed by the Institute of Oceanography and Fisheries (BULJAN & ZORE-ARMANDA, 1966; PUCHER-PETKOVIĆ, 1991). Investigations in the open sea and in small coastal basins along the eastern Adriatic allowed us to distinguish between estuaries of the main Dalmatian rivers and the wider shelf-sea. In the coastal subregion river discharges provide a strong buoyancy source causing complex vertical and horizontal hydrodynamic characteristics. Outside the coastal zone, the thermohaline structure is a result of seasonally dependent circulation and vertical processes in the upper layer on the water column. Systematically collected data in the Dalmatian coastal zone has shown an increase of almost 3 ^{0}C in the mean annual surface temperature, between the middle and the southern Adriatic. A temperature drop at

20 m depth in August indicates upwelling at the Palagruža Sill (BULJAN & ZORE-ARMANDA, 1969). In the upper layer, close to the coast, salinity has two minima: in the April-May and November-December periods depending on fresh water spreading and the water flux across the air-sea boundary. Away from the coast, surface salinity has a single minimum (ADRICOSM report, 2003). A secondary surface salinity minimum in open waters occasionally occurs due to the influence of the south Adriatic rivers (BULJAN & MARINKOVIĆ, 1952; BULJAN, 1953; BULJAN, 1965).

Taking into consideration the complexity of thermohaline variability in the Pelješac-Vis-Drvenik (PVD) (Fig. 1) area, 14 CTD stations were positioned along three transects, that are under different influences, during the ADRICOSM project. After a year of intensive measurements, space and time variability of temperature and salinity were analyzed and compared to the climatology of the area. Since historical data were spatially sparse, the climatology analysis was documented for three stations only where long-term data sets exist. However, the chosen climatological stations allowed detection of the different thermohaline structures in the region.

In order to document conditions in the atmosphere above the sea during the ADRICOSM project, e.g. heat and water budgets, meteorological measurements of relevant parameters were also made. For the Adriatic Sea area surface fluxes were provided, for particular locations in the northern and middle part, using climatological data from various meteorological stations (PICCO, 1991; GRBEC, 1997; SUPIĆ & ORLIĆ, 1999). Different parameterization schemes were used in analysis for various time scales and locations. The main inconsistency was found for evaporation, where this parameter strongly depends on the selected parameterization (GRBEC *et al.*, 1997). A major limitation of many bulk parameterizations is that they are not well defined for light wind conditions (BRADLEY *et al.*, 1991). As there is no ideal standard or generally accepted method for the heat and water flux estimation, surface fluxes can be calculated in many different ways which can produce different forcings

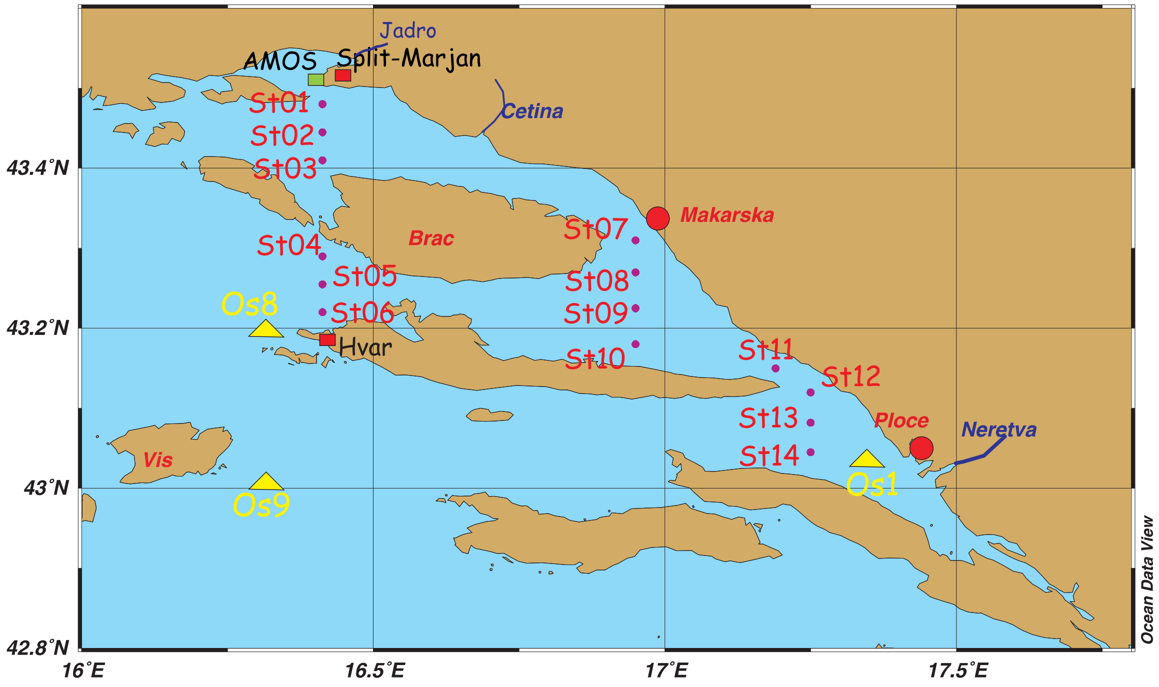

Fig. 1. Coastal scale observing system in the PVD area with positions of fourteen CTD stations (●) and three climatological stations (▲). The Split-Marjan and Hvar meteorological stations are denoted by 🟥 and the AMOS station by 🟩

for hydrodynamic models or inconsistencies in air-sea interaction studies.

The outline of the paper is as follows. After the introduction, an overview of the historical meteorological and hydrological datasets, and a description of the ADRICOSM coastal scale observing system and sampling procedure is given. The methodology used for the thermohaline and budget studies is presented in the next section. In Results and Discussion, surface fluxes and thermohaline climatology for the PVD area, categorization of thermohaline properties based on intensive CTD measurements during the ADRICOSM period and surface fluxes for the ADRICOSM period are presented.

DATA SETS AND SAMPLING PROCEDURES

Historical data

Meteorological and hydrological data sets were used to document general surface flux and thermohaline climatology (Table 1). All the parameters were obtained from meteorological and oceanographic stations located in the ADRICOSM coastal PVD area. The meteorological data set includes mean monthly values of the parameters required for heat and water flux calculations: air temperature, air pressure, wind speed, precipitation, cloud fraction and relative humidity from the Split-Marjan and Hvar meteorological stations. Sea surface temperature was measured at the same stations with classical bulk thermometers at 0.5 m below the sea surface. The meteorological and sea surface temperature data from the Split station were from the 1961-1990 period whereas those for the Hvar station were from the shorter period of 1961-1980. Temperature and salinity were collected on regular monthly cruises from January 1961 to December 2000 at permanent oceanographic stations OS8 (station Pelegrin near Hvar island) and OS9 (station Stončica near Vis island) of the Institute of Oceanography and Fisheries, Split. At these stations, measurements were made monthly, although on exception several times per month. Temperature and salinity data from the time interval 1976-2000 from station OS1 (station Ploče), in the vicinity of the Ner-

Table 1. Meteorological and oceanographic data set included in analysis

	Meteorological station Split-Marjan	Meteorological station Hvar	Automatic station AMOS
Meteorological data set	Available time scale / Period		
Air temperature	Mean monthly 1961-1990	Mean monthly 1961-1980	Mean hourly Oct 2002-Sep 2003
Air pressure			
Cloudiness*			
Wind speed			
Precipitation*			
Relative humidity			
SST			

* available for stations Split-Marjan and Hvar

	Ocean station OS1	Ocean station OS8	Ocean station OS9
Hydrographic data set	Available time scale / Period		
Temperature	Monthly values 1979-2000	Monthly values 1961-2000	Monthly values 1961-2000
Salinity			

etva estuary, were also included in the analysis. All the data were quality controlled, using the procedure developed for the MEDAS database according to DADIĆ & IVANKOVIĆ (2005). Until 1998 samplings were made with NANSEN bottles with reversing thermometers at standard oceanographic depths: 0, 10, 20, 30, 50, 75 and 100 m, whereas from May 1998, measurements were made with CTD probe. Earlier measurements at station OS1 were available at depths of 0, 10 and 18 m, and at standard oceanographic depths for stations OS8 and OS9. CTD measurements were made with fine vertical resolution (10 cm) and were averaged for every 1 m. Because of the various vertical resolutions, mean monthly temperature and salinity for stations OS8 and OS9 were not calculated for standard oceanographic depths but rather for layers.

The coastal scale observing system in the ADRICOSM polygon

As a part of the ADRICOSM project intensive biweekly and weekly CTD profiling was performed in the period between October 2002 and September 2003 at 14 stations. Stations were organized in three transects, with a total length of 125 Nm, in the channel area of the eastern middle Adriatic region (Fig. 1). Measurements were carried out with the speed craft "Navicula" with a CTD probe of Seabird-25 type. The probe was lowered with a constant speed of about 0.5 ms^{-1}, which was recommended as an optimal speed after the joint CTD validation experiment among the ADRICOSM partners (ADRICOSM report, 2003).

In the PVD polygon, data for one cruise was collected within one day, under various weather conditions with the sea state, according to the Beaufort scale, less than or equal to 3. The well-known problem of "salinity spikes" which results from the mismatch in the time response between the temperature and conductivity sensors occurred frequently. To remedy this problem we have carefully applied SBE software (http://www.seabird.com), according to the sea state conditions and measured vertical temperature gradients in the water column. The collected raw CTD data were quality controlled onboard using SBE software and visually checked. After the last lowering procedure was completed, data were prepared for Internet transmission in reduced MedAtlas format to ENEA and IOF centers. For the purpose of the ADRICOSM project, the web page (http://www.izor.hr/adricosm/) was developed where, besides the raw CTD data one can find vertical temperature and salinity presentations using the Ocean Data View (SCHLITZER, 2004) graphical software for each cruise. At the end of the observing period, animations of thermohaline evolution during a year of measurements were organized separately for each profile. Surface heat and water fluxes were calculated using hourly averaged 10 minute interval values of air and sea temperature, relative humidity, incoming solar radiation, and air pressure from the automatic met-ocean station AMOS from 1 January 2000 to 31 December 2003. Cloud cover and daily precipitation data were obtained from the Split-Marjan meteorological station located 124 m above sea level, just 2 km northeast of the AMOS met-ocean station. Since the AMOS station is located in an area protected from the two most frequent winds, i.e. bora and sirocco (GRBEC *et al*., 2001), wind data from the Split-Marjan station were used for the surface flux calculations.

METHODS

Surface fluxes and thermohaline climatology

Surface flux climatology has been documented using mean monthly values from the Split and Hvar stations following the methodology described in GRBEC (1997).

The thermohaline climatology of the investigated area was obtained using data from stations OS1, OS8 and OS9. In order to define seasonal variability represented by data from different years, a function of the form:

$$X_z(t) = A_0 + A_1\sin\left(\frac{2\pi}{T}t + \varphi_1\right) + A_2\sin\left(\frac{4\pi}{T}t + \varphi_2\right) \quad (1)$$

was least-squares fitted to the mean monthly temperature data for each vertical layer for stations OS8 and OS9. For station OS1 there were only three sampling depths at 0, 10 and 18 m and therefore mean seasonal temperature cycles were obtained for these depths. The mean seasonal salinity cycles were determined by averaging available monthly data for all climatological stations. The procedure used here to obtain seasonal cycles is documented in the paper by GRBEC & MOROVIĆ (1997).

Air-sea flux calculations

Heat exchange across the sea surface was computed as the difference between downward solar radiation (Q_S) and upward flux (Q_{UP}). Only the solar radiation flux (Q_S) was directly measured at the automatic station AMOS with an AANDERAA sensor 2770. Components of the upward flux were determined through parameterization schemes of sensible, latent and long-wave heat fluxes (MATIĆ, 2005).

The sensible and latent heat fluxes (Q_H and Q_E) have been calculated using classical bulk formulae (GILL, 1982):

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

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

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

Longwave radiation (Q_L) for PVD area is calculated using the formula by MAY (1986):

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

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

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

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

RESULTS AND DISCUSSION

Surface fluxes and thermohaline climatology

Surface flux climatology determined using monthly mean values from the Hvar and Split meteorological stations (Fig. 2) shows that from April to September the sea is receiving heat from the atmosphere, reaching maximum in July. Maximal heat loss occurs in December. On an annual scale the heat loss is caused by long-wave radiation (60%), evaporation (33%) and by conduction (7%). Unlike the heat flux, which shows no significant difference between the Hvar and Split areas, the seasonal course of water flux for the coastal and open sea stations shows strong differences. The seasonal evaporation cycle over the coastal area of the PVD polygon has a maximum in the heating season, whereas away from the coast (Hvar station) this maximum disappears. The difference in evaporation between Split and Hvar can be attributed to the more maritime exposure of the Hvar station (Fig. 3).

The mean annual temperature and salinity cycles for station OS8 were determined for 6 layers from the surface to the bottom. The function (1) shows the well-developed seasonal temperature cycle at all depths, with isothermal conditions in autumn and winter (Fig. 4). The seasonal salinity cycle shows a strong May minimum in the upper layer, which coincides with surface water flux variation and the Neretva River discharge maximum. Seasonal variations decrease with depth, for both temperature and salinity.

Salinity in the open water around the island of Vis has a different annual cycles due to different advection contributions both in the surface and bottom layer (Fig. 5). Upper layer

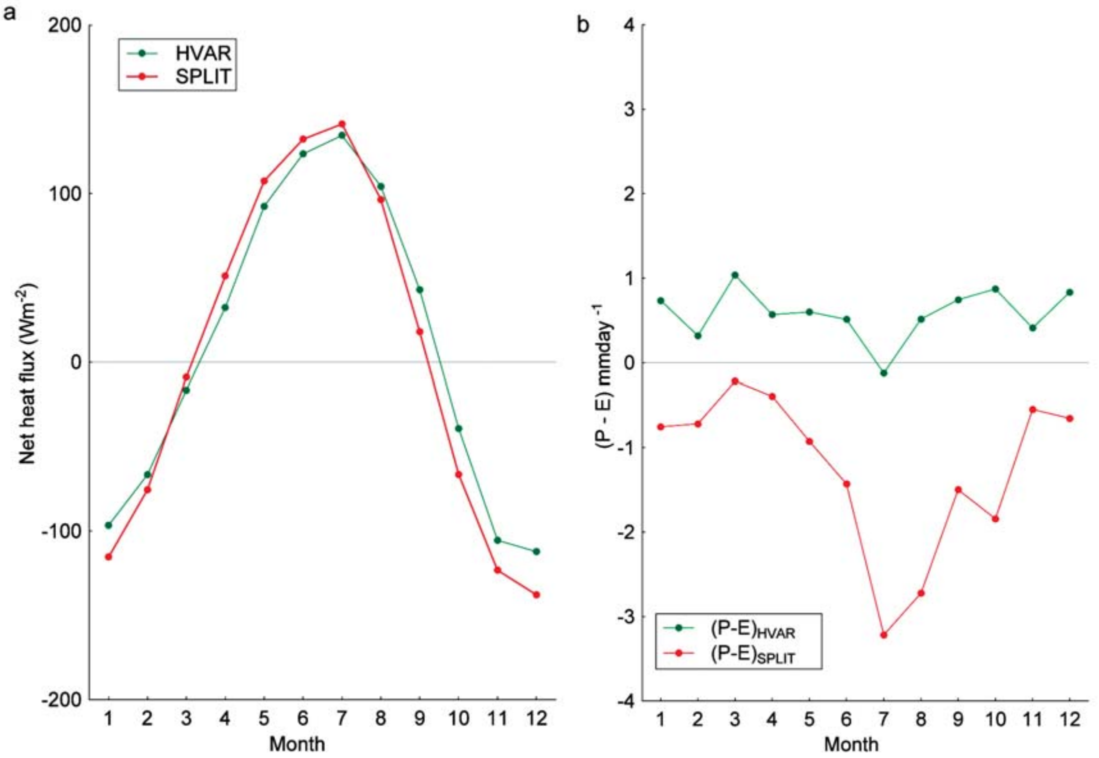

Fig. 2. Mean seasonal cycles of surface heat (a) and water (b) fluxes at Hvar and Split

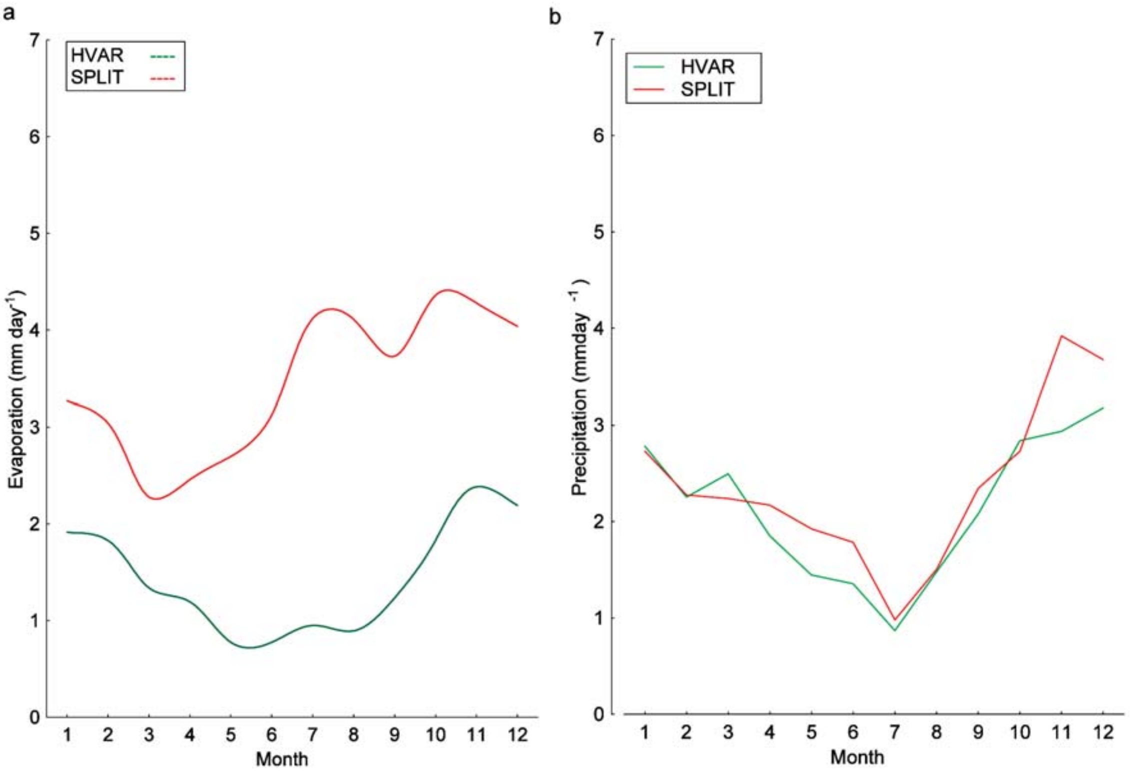

Fig. 3. Mean seasonal cycles of evaporation (a) and precipitation (b) at Hvar and Split stations

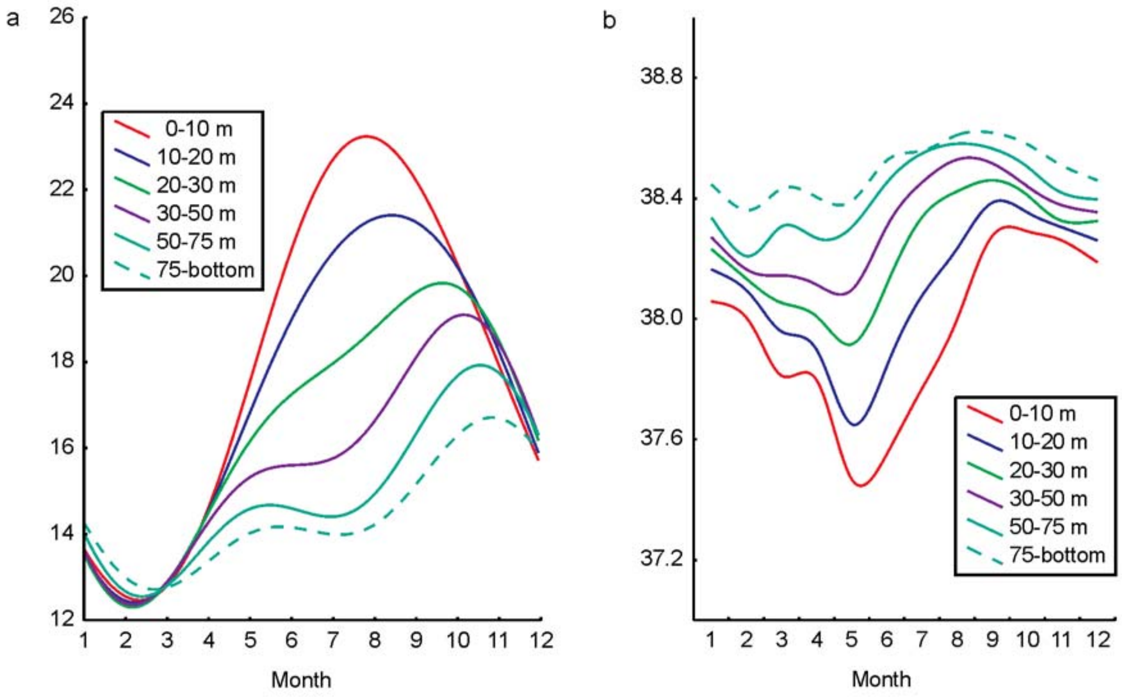

Fig. 4. Mean seasonal temperature (a) and salinity (b) cycles for station OS8 based on mean monthly values from the 1961-2000 period

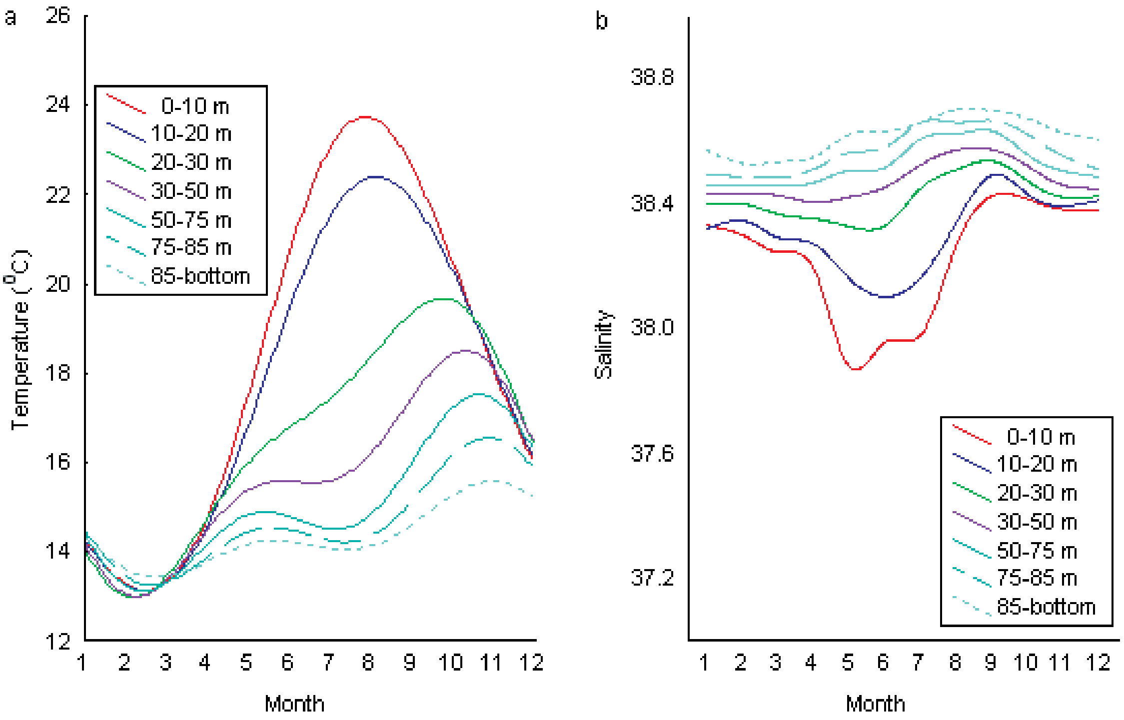

Fig. 5. Mean seasonal temperature (a) and salinity (b) cycles for station OS9 based on mean monthly values from the 1961-2000 period

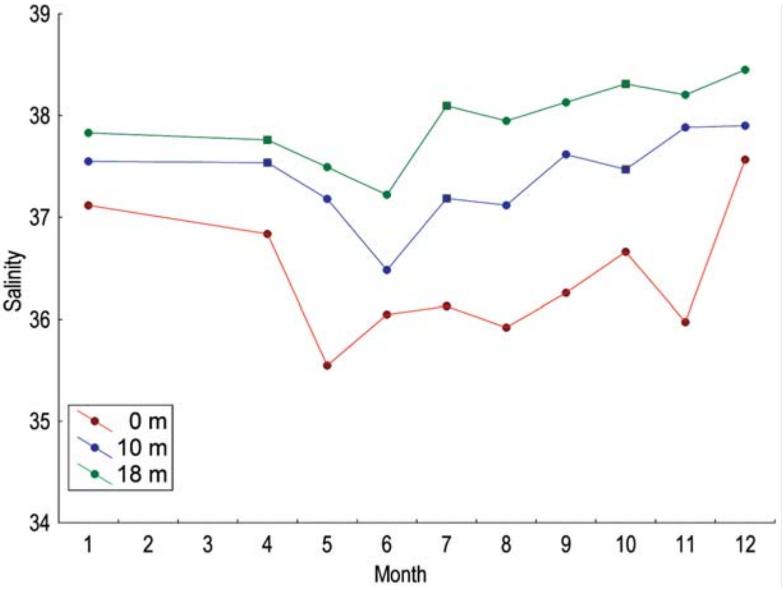

Fig. 6. Mean seasonal salinity cycles for station OS1 based on mean monthly values from the 1979-2000 period

salinity shows two minima in May and July. The first minimum in May could be related to the Neretva River discharge, whereas the spreading of water influenced by Albanian rivers is probably responsible for the second one. In the layer below the thermocline, due to the inflow of warmer and saltier Levantine Intermediate Water, the deviations of salinity from the mean are larger than those occurring in the vicinity of station OS8. In the area exposed to the Neretva River influence, represented here by OS1 station, annual salinity cycles are shown for depths of 0, 10, and 18 m (Fig. 6). An annual salinity minimum is observed in spring and coincides with the Neretva discharge maximum. The second minimum in November is caused by a precipitation maximum occurring over the area (ADRICOSM report, 2002).

Surface fluxes and thermohaline variability in the ADRICOSM period

The weather during 2003 started with normal air temperatures in January. However, February was characterized by strong, dry and cold bora wind that occurred rather frequently, decreasing temperature and humidity in the area as low as 1.5 standard deviations below the average. Very low air temperatures were recorded in February over the entire Croatia and much lower than the 1961-1990 average. On the other hand, temperatures considerably above the normal were recorded in the whole period between May and August. The summer of 2003 had been even more extreme, undoubtedly being the warmest summer ever recorded in the region (BAJIĆ, personal comunication). The warmest month was June with a mean monthly temperature 3-6 ºC higher than the 30-year mean, thus exceeding average values in June by more than 5 standard deviations. The major precipitation anomaly occurred between February and August, when almost no precipitation was recorded in the area, with exception of July when the average had been reached through mesoscale systems and storms over a very limited area. Almost all of Croatia was extremely dry in spring and dry to extremely dry in summer due to the dominant and lasting influence of a high atmospheric pressure field. The driest month was March (ADRICOSM report, 2003) with monthly precipitation amounts less than 15% of the average monthly value.

Air-sea fluxes followed weather conditions over the area (Fig. 7). Large heat losses occurred in the winter period, with extreme values in February (-210 Wm^{-2}). The departure from the mean in February was about -100 Wm^{-2}. The opposite situation occurred in the summer of 2003 when heat gain was significantly higher than average, exceeding by one standard deviation the means in May and June. Water flux was even more anomalous, especially between February and June. The strong winds enhanced water losses from the sea during February, whereas in the heating season evaporation increased due to high temperatures. Since precipitation was below the averages values, water flux was about 4 times higher than the average, exceeding it by one standard deviation between February and April 2003. It should be added that, due to the low precipitation over the Adriatic, river runoffs were extremely low and the coastal sea water intruded into the river deltas. 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. These atmospheric conditions prevailed over the entire middle Adriatic, inducing extremely high salinity values at almost all CTD stations in the PVD polygon. Throughout the entire experiment a strong positive trend in salinity was observed (Fig. 8).

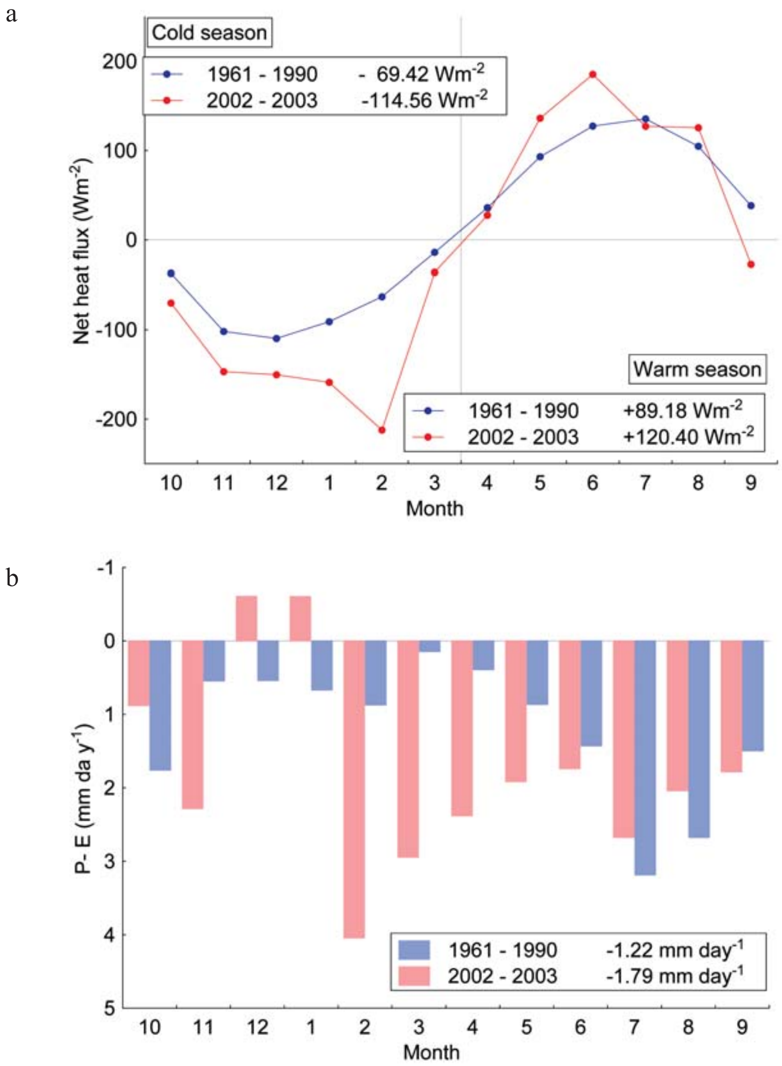

Fig. 7. Mean monthly net heat (a) and water flux (b) for the 1961-1990 period and for the 2002-2003 ADRICOSM period for the Split station

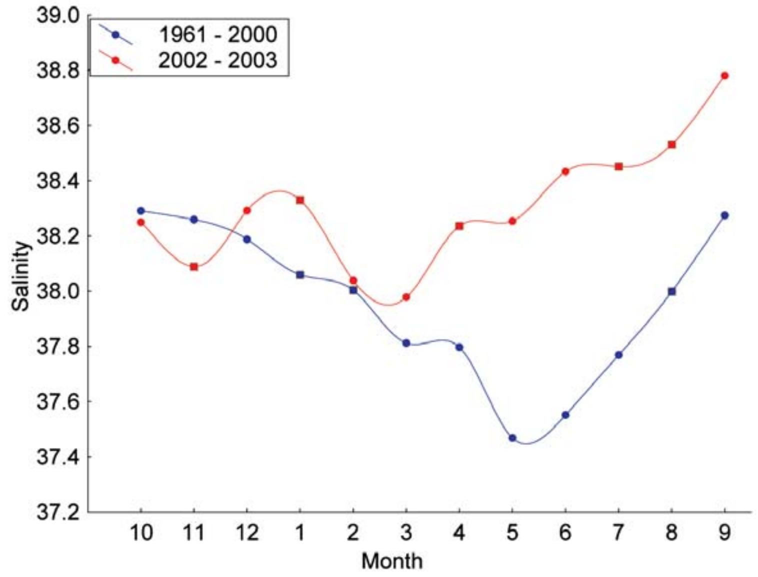

Fig. 8. Mean monthly surface salinity at station OS8 for 1961-2000 period (blue) and for the 2002-2003 ADRICOSM period (red)

By downscaling to daily values, higher heat losses during the episodes of strong wind could be observed. A sirocco episode in November 2002, and prolonged episodes of bora in the period from January-March induced large heat losses over the PVD area, with values below the average (Fig. 9).

Vertical thermohaline structures along CTD sections, as those given in Fig. 10, can be found at the ADRICOSM web site (www.izor.hr/adricosm). Temporal thermohaline variation (Fig. 11) from October 2002 to September 2003 shows high temperature and salinity in the surface layer. As a consequence of intensive heating, sea surface temperature became higher than the long-term mean. A strong temperature gradient was observed between the shallow surface layer and the layer below. The thermocline had disappeared after an episode of bora wind at the beginning of September. An unusual distribution

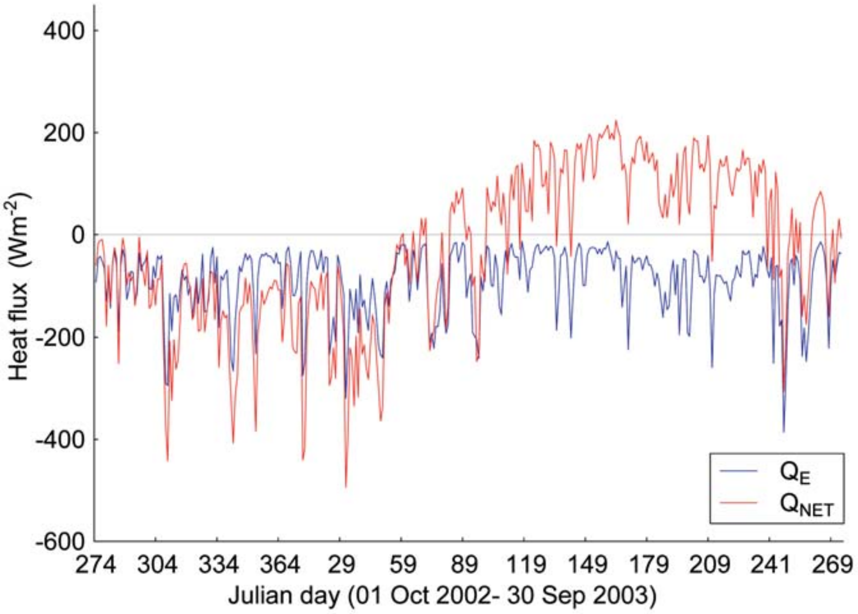

Fig. 9a. Mean daily latent and net heat fluxes for the 2002-2003 ADRICOSM period

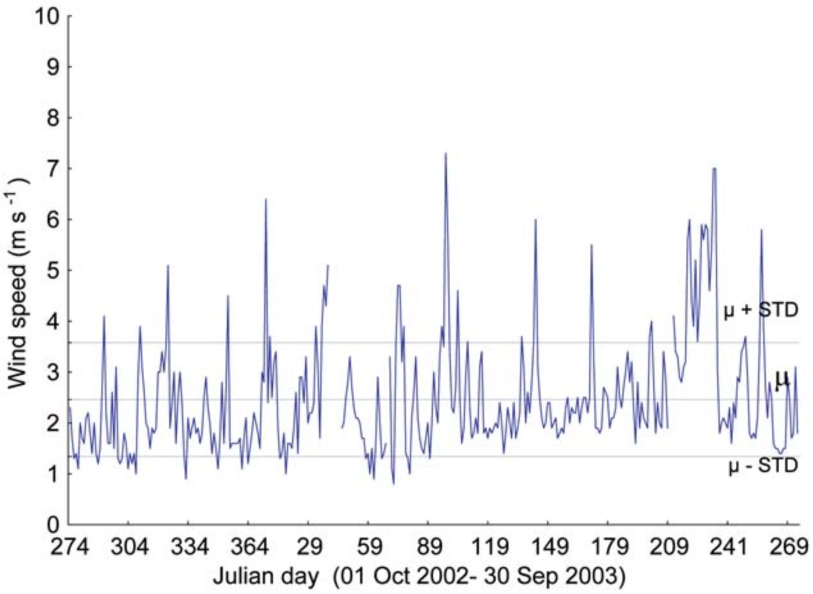

Fig. 9b. Mean daily wind speed for the 2002-2003 ADRICOSM period

of thermohaline properties also occurred at stations influenced by the Neretva River (Fig. 11b). Through most of the season lower salinity values were observed at the surface, although these low values were higher than climatological ones. Surface layers in the region near the Neretva estuary were sensitive to the instantaneous local wind conditions depending on the time of measurements through the day, since the local sea-land breezes have a 24-hour course. This points to the importance of the local wind for spreading the surface river-influenced waters.

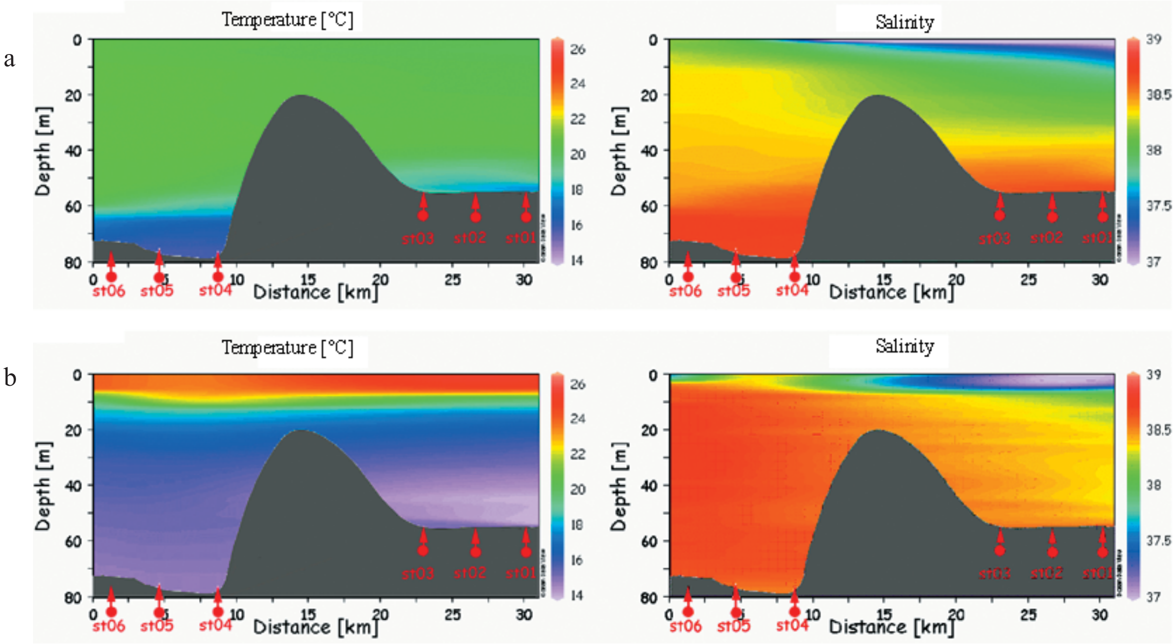

Fig. 10. Web presentation of the thermohaline structure across Profile 1 measured during the cruises of 15 October 2002 (a) and 19 June 2003 (b)

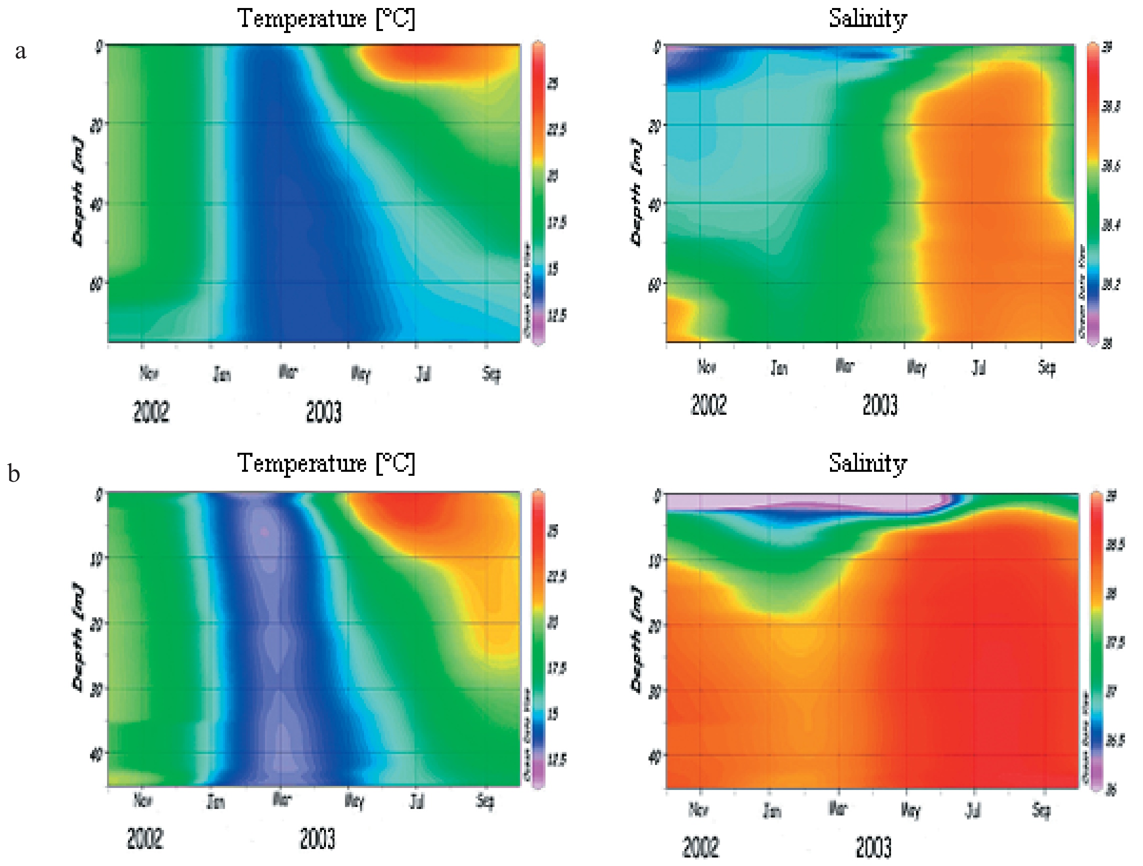

Fig. 11. Temporal thermohaline variations at station ST05 near the island of Hvar (a) and station ST13 near the Neretva River (b) from October 2002 to September 2003

Analysis of spatial and temporal temperature and salinity changes showed that three characteristic subregions can be distinguished (Fig.12):

- Neretva River estuary (ST11-ST14) characterized by a surface layer of permanently low salinity but spatially and temporally changeable under dynamics influenced by local meteorological conditions;
- Channel waters (ST01-ST03, ST07 and ST08) characterized by a low salinity surface layer and influenced by three main rivers: Neretva, Cetina and Jadro;
- Waters similar to the open sea (ST04-ST06) without considerable influence from river runoff and vertically well mixed in the cold period of year.

Since the observing period was quite anomalous, causing strong salinity departures from the climatological annual cycle, it was not possible to obtain the typical salinity structure for the region and to documented horizontal and vertical freshwater contributions in the surface water.

CONCLUSIONS

The climate anomaly from October 2002 to September 2003, which occurred over most of Europe, strongly influenced Adriatic air and sea properties, both in coastal and open sea regions. Confirmation of that is given through an analysis based on long-term meteorological and oceanographic data series from eastern areas of the middle Adriatic (Table 2). 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

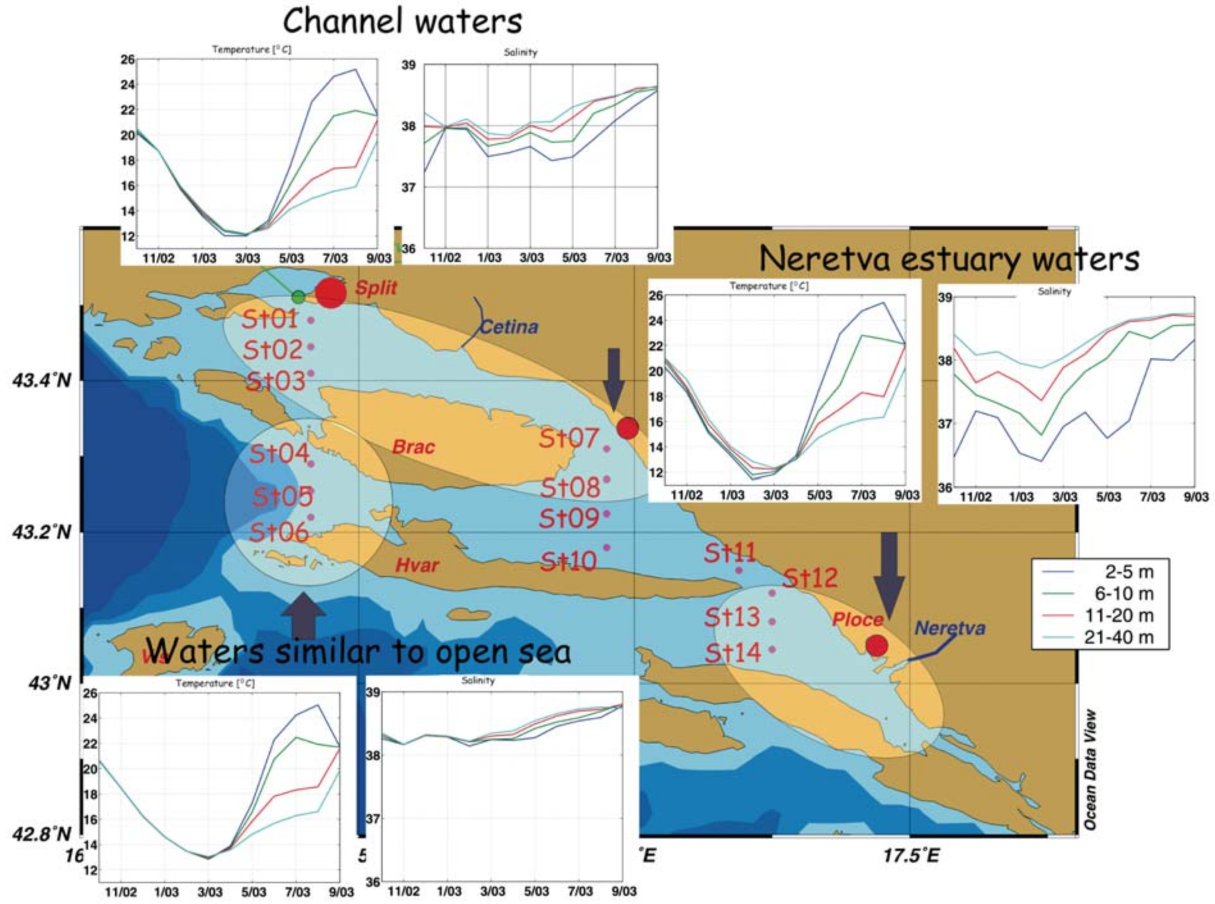

Fig. 12. Categorization of the PVD area based on experimental data according to thermohaline properties: channel waters, waters similar to the open sea and Neretva estuary waters

Table 2. Monthly averages of incoming solar radiation (Q_S), net (Q_{NET}) heat flux, precipitation (P), evaporation (E) and water flux (W) for the October 2002 – September 2003 period

Month	Q_S (W m $^{-2}$)	Q_{NET} (W m $^{-2}$)	P (mm day $^{-1}$)	E (mm day $^{-1}$)	W (mm day $^{-1}$)
Oct	113.17	-70.08	1.94	2.82	-0.88
Nov	62.75	-146.90	1.67	4.50	-2.83
Dec	33.08	-150.36	3.55	2.94	0.61
Jan	61.96	-158.86	3.81	3.21	0.60
Feb	106.47	-212.33	0.71	4.75	-4.04
Mar	159.81	-35.98	0.06	3.00	-2.94
Apr	192.20	27.49	0.60	2.98	-2.38
May	252.34	136.26	0.13	2.05	-1.92
Jun	298.55	185.34	0.20	1.94	-1.74
Jul	296.47	126.92	0.81	3.49	-2.68
Aug	250.52	126.03	0.58	2.62	-2.04
Sep	181.54	-27.42	2.17	3.94	-1.78

precipitation. Strong cooling in the winter season and heating afterwards resulted in high baroclinicity, concentrating the heat in the upper 10 m of the sea, that was transferred to deeper layers in late summer/autumn through vertical mixing and turbulence. Strong bora in February and low precipitation and high temperatures during spring and summer resulted in high evaporation, which increased surface salinity. Bottom salinity was also found to have been above average due to the inflow of saltier-than-average water into the Adriatic from the south and/or Mediterranean. The salinity increase was particularly anomalous in coastal waters due to the lack of freshwater inputs.

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Protoci na granici atmosfera-more i termohalina promjenjivost ADRICOSM poligona Pelješac-Vis-Drvenik

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SAŽETAK

Tijekom razdoblja listopad 2002. – rujan 2003. u području istočne obale Jadranskog mora, unutar poligona Pelješac-Vis-Drvenik, kao dio projekta ADRICOSM (Integrirano upravljajnje obalnom zonom Jadranskoga mora), obavljena su vrlo intenzivna mjerenja termohalinih osobina vodenog stupca na 14 postaja. Tijekom zimskog razdoblja mjerilo se jednom u dva tjedna, a kasnije jednom tjedno. Dobra prostorno-vremenska pokrivenost podacima omogućila je usporedbu s klimatološkim vrijednostima. Pokazano je kako su promjene saliniteta u ovom razdoblju znatno odstupale od prosjeka. Tijekom istraživanja uočen je iznadprosječno visoki salinitet koji je bio posljedica jakih i dugotrajnih epizoda bure u hladnom dijelu godine te neuobičajenih atmosferskih uvjeta tijekom razdoblja proljeće-ljeto 2003. Kao posljedica neuobičajeno duge i intenzivne sezone grijanja temperatura mora također je bila iznadprosječna. Procesi na granici atmosfera-more također su pokazali znatna odstupanja od klimatoloških vrijednosti.

Ključne riječi: sustav mjerenja, thermohalina klimatologija, međudjelovanje atmosfere i mora, istočna obala srednjeg Jadrana