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Is the southeastern Adriatic Sea coastal strip an eutrophic area?

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ABSTRACT

This study intends to understand and assess the effects of the discharge from the Buna/Bojana river delta watersheds on the eutrophic status of the southeastern Adriatic Sea, and contrast this area with the northwestern Adriatic region where the Po River dominates the freshwater discharge into the coastal ocean. We compare observations of inorganic nutrients, turbidity, and physical variables from the two regions and use numerical model results to characterize the physical circulation of the two areas.

The area affected by the Po River discharge extends at least one hundred kilometers southward from the delta and approximately 20 km offshore. Maximum chlorophyll concentrations typically occur within the river plume. Similarly, in the southeastern Adriatic Sea, the Buna/Bojana River discharge extends northward along the coasts for approximately one hundred kilometers and contains a large maxima in the regional chlorophyll distribution. The two coastal areas tend to have opposing physical forcing processes: the Po River tends to be affected area by northerly to northeasterly winds that cause downwelling, whereas the Buna/Bojana River on the opposite side of the basin is typically characterized by northerly, upwelling favorable winds. However, during the study period, upwelling is not a dominant feature of the circulation and both the shelf slope current (SouthEastern Adriatic – SEAd current) and the along shore currents in the southeastern Adriatic Sea are northward. The along shore current probably dominated by the river runoff is here described for the first time and called the southeastern Shelf Coastal (SESC) current.

Under these conditions, primary productivity is high in both regions leading us to conclude that river plume dynamics and the associated nutrient inputs determine the eutrophication status of the coastal strip, regardless of the circulation regime in the southeastern Adriatic Sea area. The Adriatic southeastern coastal area is an eutrophic area that is strongly affected by freshwater inputs particularly from the Buna/Bojana River system.

1. Introduction

Eutrophication of coastal waters has been considered one of the major threats to the health of marine ecosystems for more nearly 40 years (Ryther and Dunstan, 1971; Smith et al., 2006). Many of the effects of coastal eutrophication have been well documented (Cloern, 2001; Conley et al., 2002; Rönnberg and Bonsdorff, 2004) and eutrophication "represents one of the most severe and widespread environmental problems for coastal zone managers" (IOCCG, 2000).

Eutrophication is the process by which anthropogenically enhanced nutrients inputs including nitrogen, silicate and phosphorus, contribute to excessive accumulation of algal biomass and can modify the phytoplankton community composition. In the Adriatic Sea nutrient inputs come from the large surface runoff catchments, from underground water discharges, from direct urban discharges and from aeolian inputs.

Often the regions of the ocean are classified as oligotrophic (<0.1 μgChl L^{-1}), mesotrophic (0.1–1 μgChl L^{-1}), or euthropic (>1 μgCh L^{-1}) with satellite-based ocean color measurements of chlorophyll concentration (IOCCG, 2003). However under this

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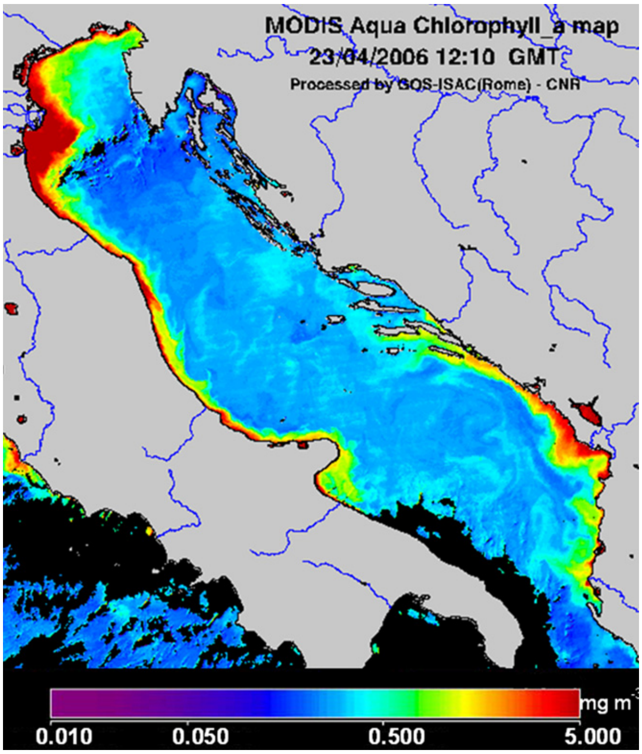

Fig. 1. MODIS image of chlorophyll *a* concentration on April 23, 2006 (provided by CNR-ISAC, Rome). The area ranges from bottom left 12°E and 39°N to the top right 20°E and 46°N.

classification the eutrophic condition can be caused by natural processes such as upwelling, or other processes that contribute natural nutrients to the upper ocean. Based on this classification approach the Adriatic Sea contains two euthropic regions: the coastal region off the Po River delta and extending southward along the western coastal region, and the second area in the southeastern Adriatic Sea, along the coasts of Montenegro and Albania (Fig. 1). In this paper we will contrast these two euthropic regions, evaluate their similarities and differences, and evaluate the extent to which eutrophication might be occurring.

The effects of the Po River discharge into the northwestern Adriatic and the effects of this discharge on the eutrophication of the region have been well documented (e.g., Vollenweider et al., 1992). The Po is the largest river discharging into the Adriatic Sea and its waters affect the overall coastal and sub-regional hydrodynamics (Kourafalou, 1999, 2001; Zavatarelli et al., 2002; Zavatarelli and Pinardi, 2003; Oddo et al., 2005). A good correlation exists between low salinity river plume and high chlorophyll concentrations along the western coastal strip (Zavatarelli et al., 2000; Polimene et al., 2006) clearly indicating the contribution of the buoyancy-driven flow to the trophic status of the Western Adriatic coastal zone (Campanelli et al., 2004; Marini et al., 2008).

The second high chlorophyll region occurs in the southeastern Adriatic Sea along the coasts of Montenegro and Albania (Fig. 1). The river called Buna in Albania and Bojana in Montenegro partially forms the border between the two countries and provides the primary freshwater inflow to the southeastern Adriatic region. The regionally high chlorophyll concentration is associated with the Buna/Bojana River plume and elevated chlorophyll concentrations can extend northward for more than 150 km along the eastern coastline. The eutrophication status of the southeastern Adriatic

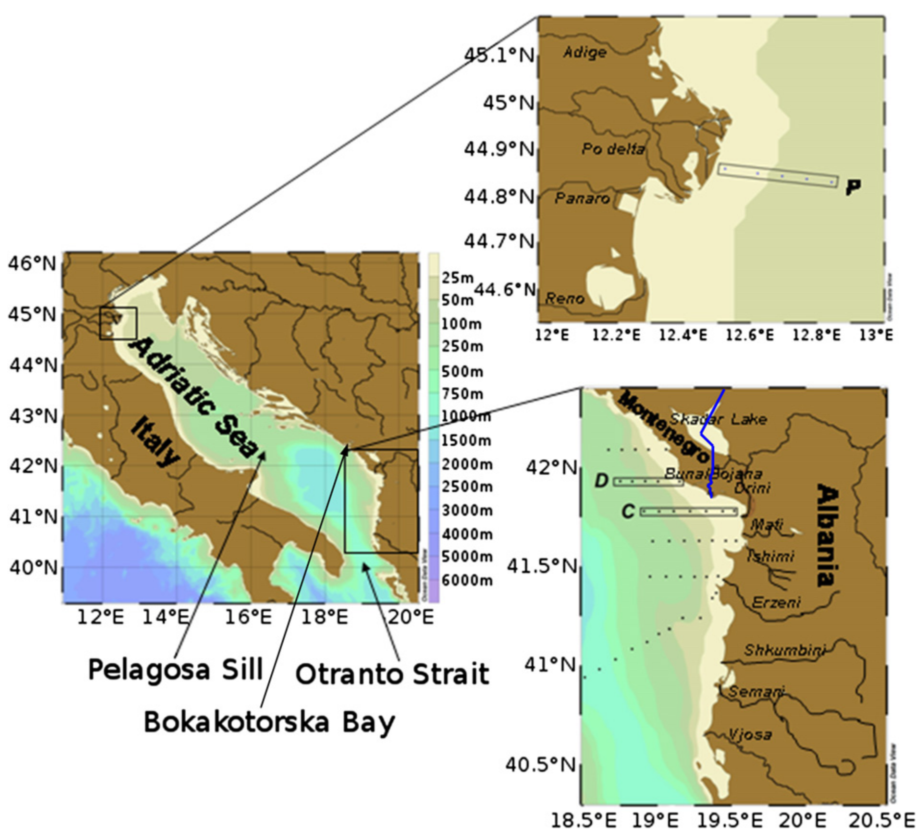

Fig. 2. Geography and sea bathymetry of the Adriatic basin with the two areas contrasted in this paper, the northern Adriatic coastal zone and the southeastern coastal areas of Montenegro and Albania. The dots represent the sampling points and the rectangles indicate the position of the transects.

Table 1
General characteristics of the Albanian rivers that flow into the southeastern Adriatic Sea. Source HMI-Tirana, 1995 (UNEP 1996).

River basin	Catchment area (km^2)	Station and period of measurements	Mean annual discharge rate ($m^3\ s^{-1}$)	Mean annual volume ($m^3\ 10^6$)
Buna/Bojana	19,582	Dajc (1958–1985)	675	21,263
Mati	2441	Fani Rubik (1951–1986)	87	2753
Ishimi	673	Sukth Vendas (1968–1992)	20	624
Erzeni	760	Sallmonaj (1949–1992)	17	532
Shkumbini	2440	Rroqzhine (1948–1991)	59	1849
Vjosa	6710	Mifol (1948–1987)	190	5954
Semani	5649	Mbrostar (1948–1987)	86	2709
Bistrica	447	Krane (1949–1987)	32	1011
Pavla	374	Bogaz (1951–1991)	7	210
Other river	4028		72	2271
Total	43,104		1244	39,186

has not been adequately characterized prior to now due to lack of observations. However, the similarity with the Po River plume's high chlorophyll suggests that the high chlorophyll feature extending northward along the coast from the Buna/Bojana River likely derives from the river-born input of nutrients into the coastal ocean. Our hypothesis is that the riverine flux of nutrients into these two regions causes the apparent eutrophication independent from the wind-driven circulation. It is well known that the eastern Adriatic Sea is characterized by upwelling favorable winds and that winds on the western side of the basin are typically downwelling favorable (Orlic et al., 1994).

The goal of this study is to understand the eutrophying processes that occur along the southeastern coastal region of Albania and Montenegro and contrast them with the northwestern Adriatic in order to understand the similarities and/or differences between the physical and bio-chemical regimes of the two areas. We present observations collected from two different years, 2003 (NW Adriatic) and 2006 (SE Adriatic) and use numerical model results to characterize the circulation dynamics of the region.

1.1. The contrasting coastal regions of the northwestern and southeastern Adriatic Sea

The geography and bathymetry of the study areas in the northwestern and southeastern regions of the Adriatic Sea areas are shown in Fig. 2. These two areas are both characterized as Regions Of Freshwater Influence (ROFI); the northwestern area is mainly affected by the Po River and the southeastern area by the Buna/Bojana River. Each of these rivers account for more than one third of the freshwater entering the coastal ocean in their respective areas. In the following two sections we will describe the characteristics of each region separately.

1.1.1. The northwestern coastal Adriatic Sea

Freshwater is discharged into the northern Adriatic from major rivers along the northern and northwestern coasts. The Po River provides the major buoyancy flux with an annual mean freshwater discharge rate of 1500 $m^3\ s^{-1}$ (Raicich, 1996). The riverine waters discharged into the northern Adriatic form a buoyant layer that typically flows southward along the Italian coasts and is constrained close to the coast over the continental shelf, above 50 m depth (Poulain and Cushman-Roisin, 2001).

In the Adriatic Sea atmospheric forcing, heat, water and momentum fluxes, and lateral river discharges contribute to a seasonally varying circulation with large amplitude eddy variability. The large freshwater flux makes the Adriatic Sea a dilution basin with an estuarine buoyancy budget (Pinardi et al., 2006) even if deep waters exit from the Otranto Strait. The southward coastal flow, the Western Adriatic Coastal Current (WACC, Artegiani et al., 1997a,b), is driven by the Po River buoyancy flux (low-salinity waters) and northeasterly Bora winds that characterize the region during the winter months. Bora winds cause elevated sea surface height along the western coasts, producing downwelling and transport of coastal dense waters toward the open sea (Boldrin et al., 2009).

The nutrients from the Po River plume influence the coastal area for about two-three hundred kilometers southward from the delta and approximately 20 km across the coast. Nutrient concentrations decrease from north to south, cross-shelf from the coast to the open sea, and from the surface to the bottom (Zavatarelli et al., 1998; Marini et al., 2008). The nutrient-rich waters from the northwestern Adriatic are flushed out of the basin by the WACC and the buoyancy-driven flow along the Italian coasts (Hopkins et al., 1999; Marini et al., 2002a; Campanelli et al., 2004). However, this nutrient transport varies significantly both seasonally and interannually. During spring and summer, some eastward transport of DIN (Dissolved Inorganic Nitrogen) and orthosilicate may result from the offshore extension of the Po River plume (Grilli et al., 2005).

1.1.2. Southeastern coastal Adriatic area

In the southeastern Adriatic, in addition to the flow from the Buna/Bojana River, several additional rivers contribute to the

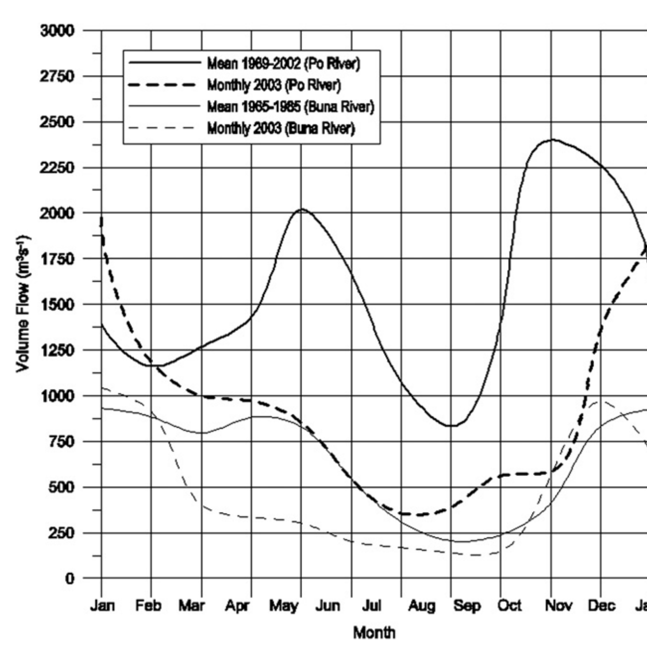

Fig. 3. Monthly averages of the Po (thick solid line) and Buna/Bojana River (thin solid line) flows for the period 1989–2002 and 1965–1985, respectively, and the month-by-month flow for the year 2003 (thick dashed line for Po River and thin dashed line for the Buna/Bojana River).

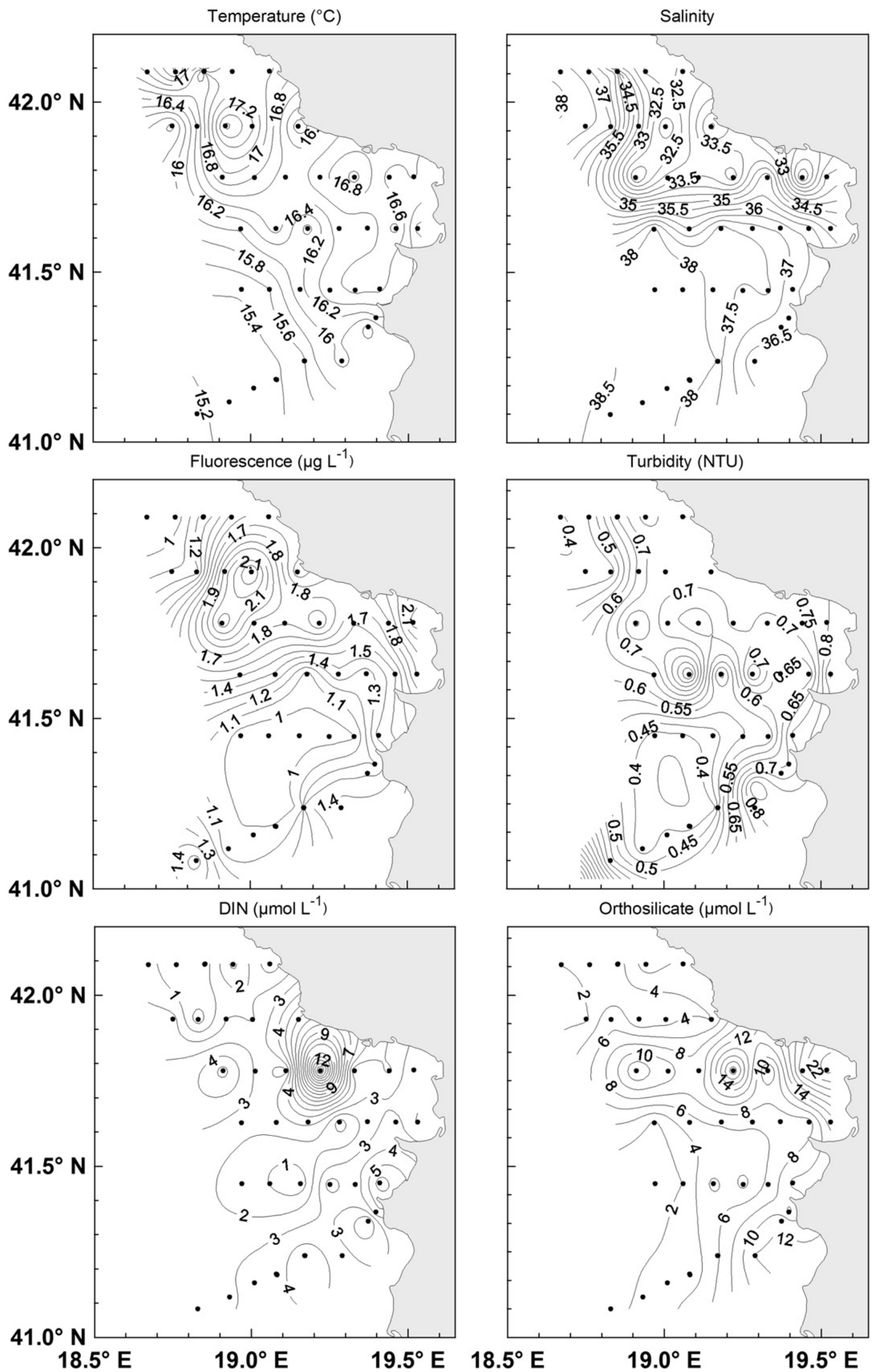

Fig. 4. Horizontal distribution at 1 m depth of temperature, salinity, fluorescence, turbidity, DIN and orthosilicate in the southeastern coastal areas of Albania and Montenegro in April 2006. The dots represent the sampling points.

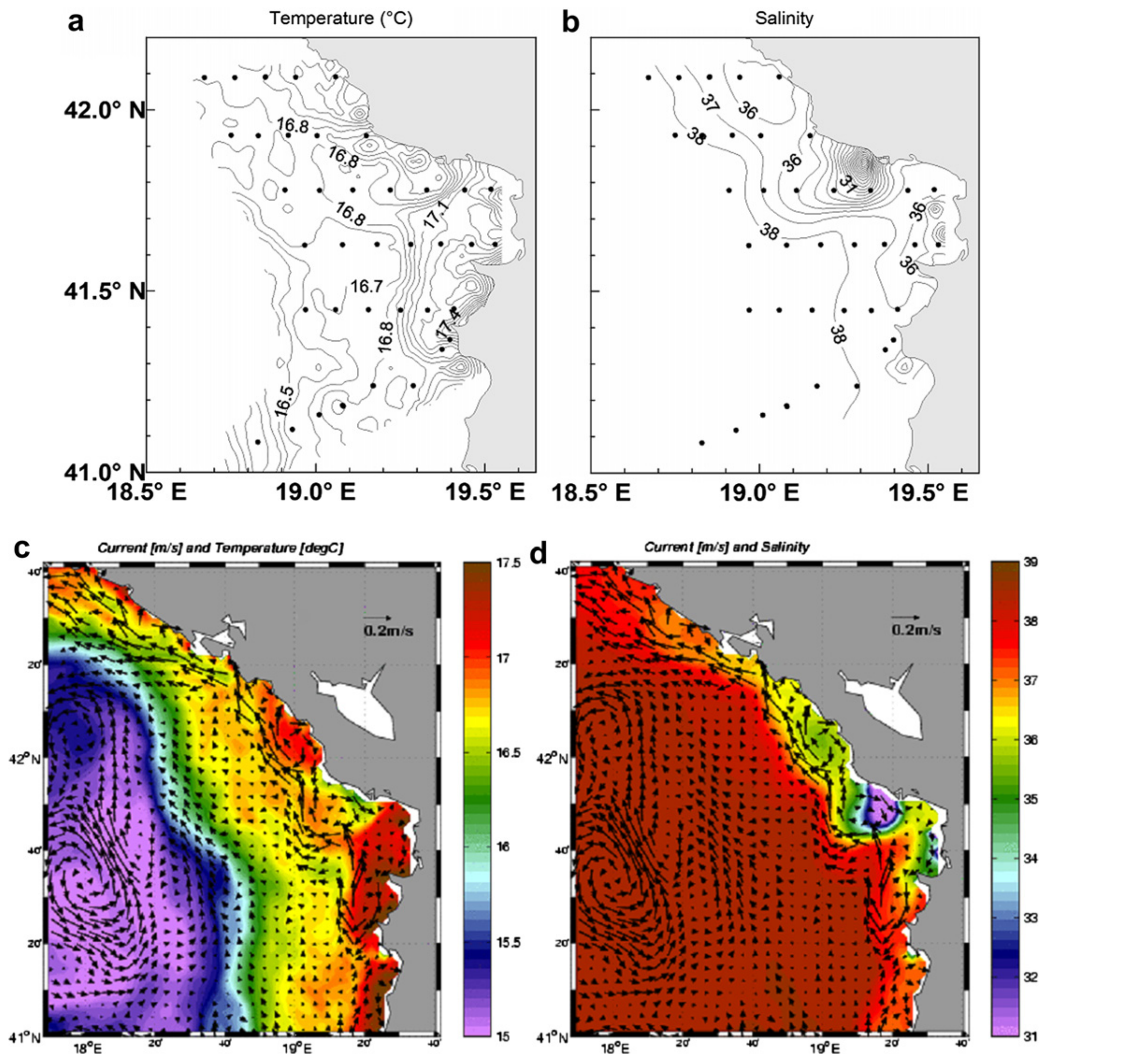

Fig. 5. Mean horizontal surface distributions of modeled nearsurface temperature (°C) and salinity in the southeastern coastal areas of Montenegro and Albania. The model data are averaged on April 22-23, 2006 when the samples were collected at sea. Starting from top: modeled temperature (a; contour interval 0.1) and salinity (b; contour interval 1); modeled temperature (c) and salinity (d) overlaid with currents at 2 m.

freshwater flux including the Drini, Mati, Ishimi, Erzeni, Shkumbini, Semani and Vjosa Rivers (Fig. 2; Table 1). The Buna/Bojana River has the largest single discharge (about 700 $m^3\ s^{-1}$) and the combined discharge of all of the Albanian rivers is about 1250 $m^3\ s^{-1}$ (UNEP 1996; Table 1).

The Buna/Bojana River is the southeastern Adriatic counterpart to the Po River in the northwestern Adriatic. Several of the coastal plumes from the Albanian and Montenegrin rivers are readily distinguished in the chlorophyll image (Fig. 1) but the largest chlorophyll feature is off the Buna/Bojana delta. The northward turning of the river plume is consistent with the Coriolis effect (Kourafalou, 1999) and it is also in the direction of the prevailing currents in the southeastern Adriatic (Artegiani et al., 1997a). The buoyancy induced northward flow is however contrary in direction to what is expected for a region where the winds are typically upwelling favorable.

Based on climatology, the southern Adriatic Sea extends approximately from the Pelagosa Sill to the Otranto Strait (Artegiani et al., 1997a). It is characterized by a wide depression more than 1200 m deep and exchanges water with the Mediterranean Sea through the Otranto Strait where the sill depth is about 800 m. According to Manca et al. (2002) the surface cyclonic circulation transports relatively freshwater along the western boundary via the southward density-driven WACC. The SouthEastern Adriatic current (SEAd) transports Ionian Surface Water (ISW) along the eastern boundary northward into the Adriatic Sea. Deeper water, Modified Levantine Intermediate Water (MLIW), contains high levels of nitrate, but is deficient in phosphorus (Marini et al., 2002b). The circulation on the southeastern shelf of the Adriatic basin had not been mapped prior to this investigation and no information exists in the literature regarding nutrient and biogeochemical characteristics for the region.

2. Materials and methods

2.1. In situ observations

The *in situ* data used for this study were obtained from a cruise in front of the Po River mouth in June 2003 and from one in April 2006 on the Montenegro-Albanian shelf. The hydrographic data set from the Po River mouth was obtained on June 8, 2003 during a cruise aboard the *R/V Knorr* (Lee et al., 2005). The southeastern

Adriatic region off Albania and Montenegro was sampled by the *R/V G. Dallaporta* during April 21–23, 2006. The hydrographic station locations for the two cruises are shown in Fig. 2. The two regions were sampled in different years and are slightly offset seasonally, but simultaneous observations for the two regions do not yet exist. However both sets of observations were taken with similar procedures and similar stages of river discharge, as shown in Fig. 3. During the year 2003 Po River discharge rates in early June were less than half the average for the 14 preceding years. In particular, during spring 2003 the Po runoff approximated the climatological discharge rate for the Buna/Bojana River, likely to be similar to the Buna/Bojana discharge rate in 2006. Therefore, this comparison of the Po and Buna/Bojana dissolved nutrient fluxes provides situations where the discharge rates are similar for the two systems.

The CTD data were collected with a SeaBird Electronics SBE 911-plus CTD equipped with a SeaBird SBE43 oxygen sensor, SeaPoint turbidity sensor, Wetlabs ECO-AFL fluorometer (*R/V Knorr*) and an SCUFA fluorometer on the *R/V G. Dallaporta*. The 24 Hz CTD data were processed according to UNESCO (1988) standards, and pressure-averaged to 0.5 db intervals. Water samples were obtained on the upcasts with a SeaBird Carousel rosette water sampler equipped with 5-L Niskin bottles. Nutrient water samples were filtered (GF/F Whatman®, 25 mm, nominal pore size 0.7 μm) and stored at −22 °C in polyethylene vials. Nutrients (ammonium—NH_4, nitrite—NO_2, nitrate—NO_3, orthophosphate—PO_4 and orthosilicate—SiO_4,) were analyzed colorimetrically (Ivančić and Degobbis, 1984; Parsons et al., 1985). Absorbances were measured with a Technicon TrAAcs 800 AutoAnalyzer. Dissolved inorganic nitrogen (DIN) was calculated as the sum of NH_4, NO_2 and NO_3 concentrations.

2.2. Model data

The model results are from simulations of an operational model of the Adriatic Sea, based on the Princeton Ocean Model, that produces daily three dimensional fields of sea level, currents, temperature and salinity (Oddo et al., 2005; Guarnieri et al., in press). The model domain includes the entire Adriatic Sea and is horizontally resolved at approximately $1/45° \times 1/45°$ of latitude and longitude and vertically by 31 unevenly spaced sigma levels. The model is forced by atmospheric surface fields coming from the analyses of the European Centre of Medium Range Weather Forecast (ECMWF) which are available every 6 h and with a resolution of half a degree. Furthermore the model considers 30 climatological river runoff estimates from Raicich (1996) in addition to daily mean values of the Po runoff. The Buna/Bojana runoff is set equal to the climatological daily values presented in Fig. 3. At the southern lateral open boundary in the northern Ionian Sea the model is forced by analyses from the Mediterranean Sea operational model (Tonani et al., 2008) which allows for MLIW and SIW to enter the domain. The model is integrated from year 2000 up to present and in this paper we will use daily mean values of the relevant fields for the year 2006.

3. Results

3.1. Spatial distributions and circulation in the southeastern Adriatic Sea

The *in situ* data set described above was collected on transects shown in Fig. 2. The station data were spatially gridded either into horizontal maps or vertical sections using the Kriging tool of Surfer® software. In Fig. 4 we show the measured variables as horizontal distributions based on measurements from 1 m depth beneath the surface.

The salinity map shows that the Buna/Bojana River area of influence extends 30 km offshore as well as northward and southward from the Buna/Bojana delta where the 35.5 isohaline is used to delineate between the offshore ambient water and the core of the river plume. Within the plume turbidity is high (more than 0.7 NTU), as well as chlorophyll fluorescence, 1.5–2.2 (μg L^{-1}), DIN and orthosilicates, approximately more than 4 (μmol L^{-1}) and 10 (μmol L^{-1}) respectively. The distribution of the dissolved nutrients is patchy and shows a local maximum of DIN and orthosilicates northward the Buna/Bojana River mouth, as expected if river-born nutrients were injected in the coastal area and not used by the primary producers. Patterns of chlorophyll fluorescence and salinity are well correlated while turbidity, DIN and orthosilicates show uncorrelated patchy structures inside the Buna/Bojana freshwater influence area. The turbidity field is at least correlated with salinity, perhaps because sinking of particles and flocculants from the river plume rapidly decouple nonalgal particles from the dissolved constituents of the river plume.

Fig. 5 shows the modeled temperature, salinity and currents, averaged for April 22 and 23, 2006. The modeled temperature and salinity fields are similar to the observed spatial patterns of T and S shown in Fig. 4. Comparing the simulated temperature map (Fig. 5) with the observed values (Fig. 4) there is a general consistence, in particular in the areas close to the coastlines and North of the Drini (see Fig. 2), while in open sea and South of the Drini, the model appears to overestimate temperature. In general, the modeled salinity approximates the observed salinity gradients close to the Buna/Bojana River mouth and northward extension of the freshwater plume toward Bokakotorska Bay.

Because the modeled fields of temperature and salinity are similar to the observed ones, we will use the modeled currents in a slightly expanded domain to describe the circulation patterns for this area (Fig. 5c and d). Fig. 5 shows two northward velocity features, one along the shelf slope along the temperature front and the other near the coast along the salinity front that bounds the river plume. The slope and coastal currents merge northward of 42° 30′ N. We believe the SEAd current described in Artegiani et al.

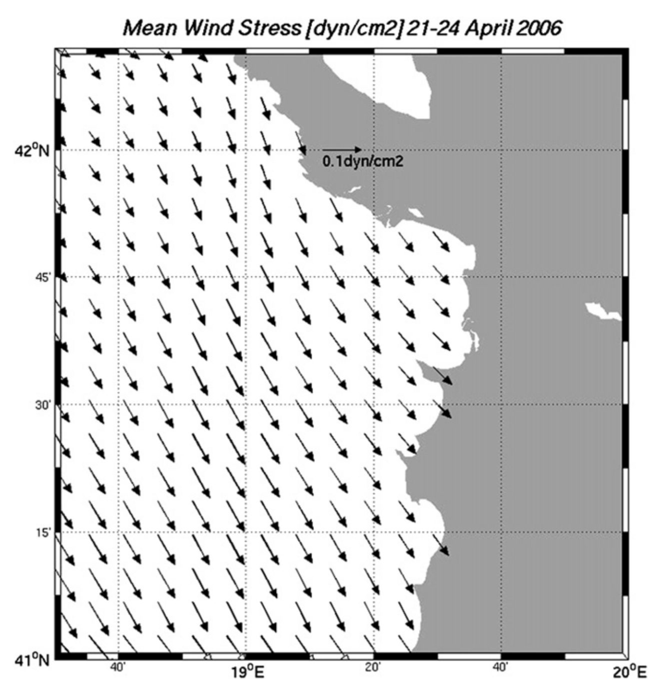

Fig. 6. Wind stress averaged on the days April 21–24, 2006 calculated from ECMWF atmospheric forcings.

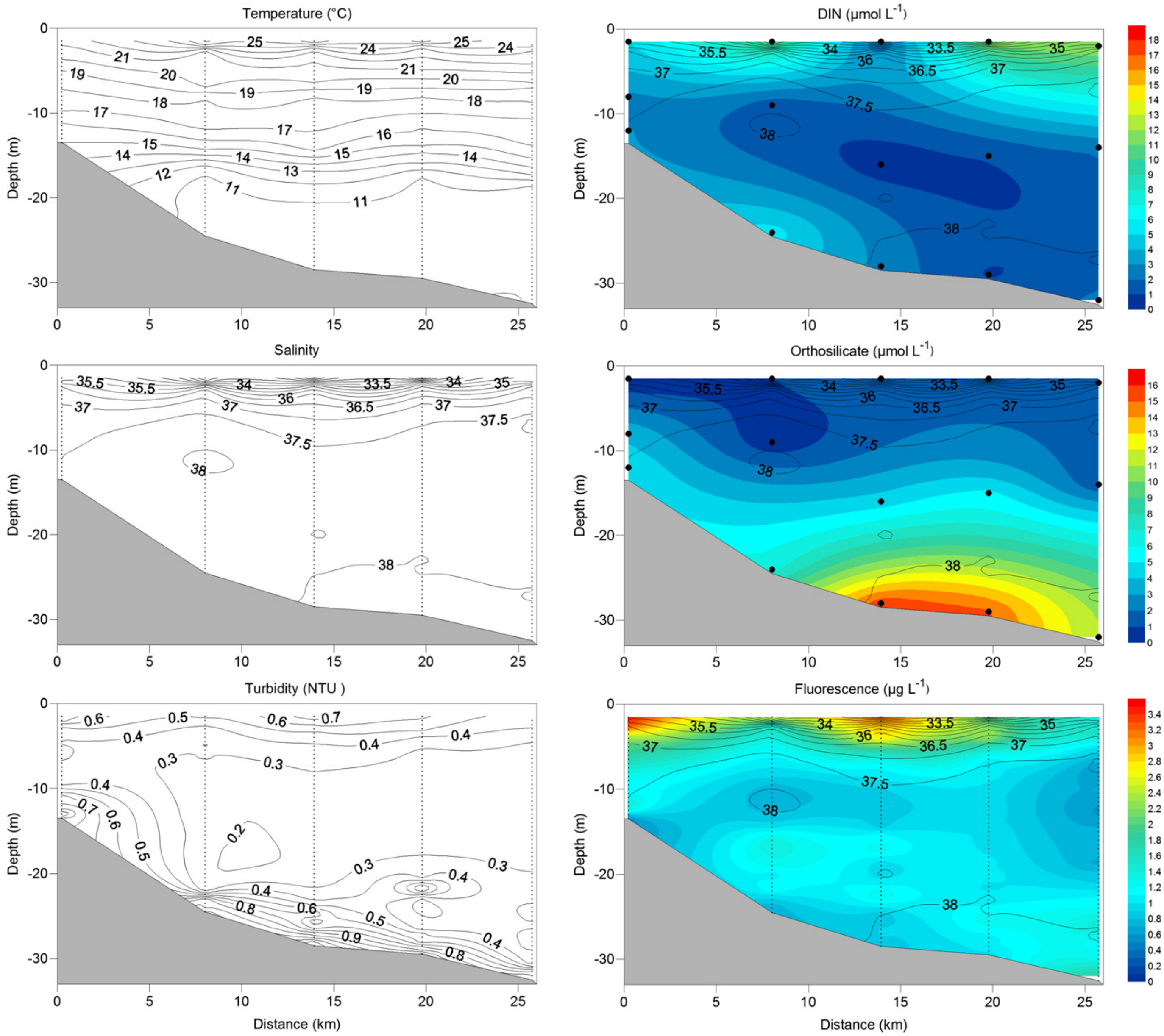

Fig. 7. Vertical sections along the Po transect for June 5, 2003 (the position of the transect is plotted in Fig. 2). The left panels represent the vertical distribution of temperature, salinity and turbidity. The right panels represent the vertical distribution of DIN, orthosilicate and fluorescence concentration (colored shading) overlaid with salinity contours (black contours; contour interval 0.5). The dots represent the sampling points.

(1997b) corresponds to the shelf slope current, while the shelf/coastal current has to our knowledge not been described before. We will hereafter refer to the shelf/coastal current as the SouthEastern Shelf Coastal (SESC) current.

The SESC current detaches from the coast especially between the Ishimi and the Buna/Bojana River outflows (Fig. 2) and recirculating coastal eddies help to expand the offshore extension of the river plumes. The eddy circulation on the South side of the Buna/Bojana discharge appears to contribute to the freshening of the area South of the Buna/Bojana delta. Additional eddy-like features are expected to form along the boundaries of the cyclonic circulation around the basin because the coasts are sources of anticyclonic vorticity and thus anticyclonic features can form when conditions are favorable. Similar eddy generation happens along the western side of the Adriatic Sea landward from the WACC (Zavatarelli and Pinardi, 2003).

The average wind stress for the region during the period April 21–24, 2006, was toward the SSE with an average stress of about 0.1 dyn/cm^2 (Fig. 6). Such winds are upwelling favorable, indicating the physical conditions that may contribute to the vertical upward movement of the water along the water column. Generally, in the northern hemisphere, in presence of a wind parallel to the coast, the induced stress on the water surface is favorable for upwelling if the coastline is located to the left of the direction of the wind, since the Ekman pumping mechanism induces offshore currents perpendicular to the coastline, creating a region of depression close to coast where cooler waters are sucked upwards toward the surface. Vice-versa downwelling will be favored if the wind has an opposite direction or the coasts is on the right of the wind direction. In our case, in spite of upwelling favorable wind, the flow field is northward and shows no indication of reversal in response to the wind stress, so we contend that the controlling mechanism for the

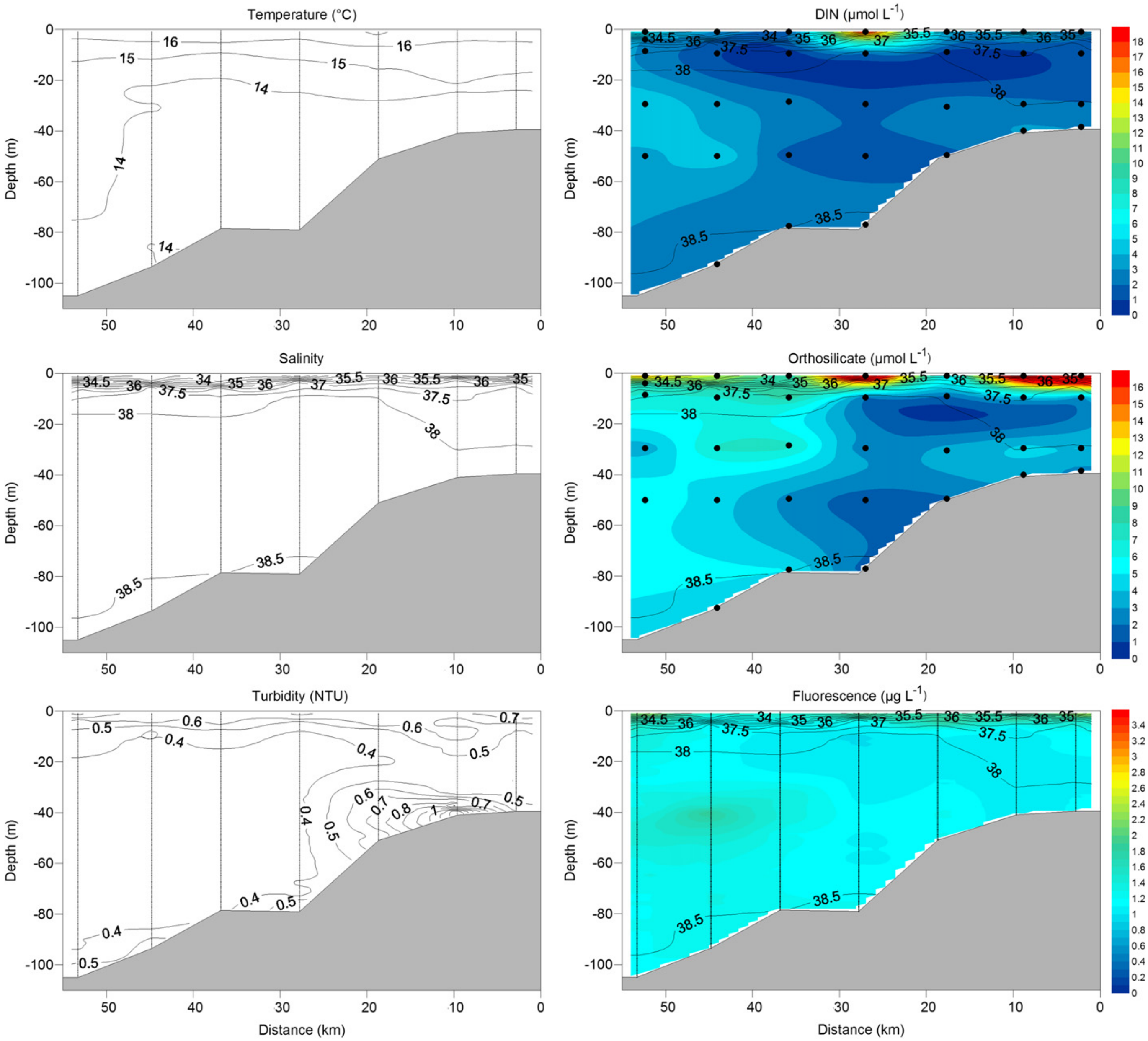

Fig. 8. Vertical sections along the transect C, shown in Fig. 2 on April 23, 2006. The left panels represent the vertical distribution of temperature, salinity and turbidity. The right panels represent the vertical distribution of DIN, orthosilicate and fluorescence concentration (colored shading) overlaid with salinity contours (black contours; contour interval 0.5). The dots represent the sampling points.

SESC is not local wind stress, but the buoyancy flux from the river waters and its effects on the circulation of the nearshore area. There may be other periods of the year when the local current dynamics are more responsive to the wind stress, but during this particular period the wind stress was insufficient to overcome the coastal buoyancy flux and its forcing of the coastal currents.

We conclude then that during spring the southeastern Adriatic Sea coastal circulation is characterized by a northward current, now called SESC, which becomes more clearly defined northward of the Shkumbini River. The width of the current is approximately 10 km, it has an average speed of about 15 cm s^{-1} and extends about 30 km offshore between the 40 m and 100 m isobaths. This current is the seaward edge of the Buna/Bojana ROFI area and it is parallel but distinct from the SEAd current which hugs the shelf slope and to which it reconnects after the Bokakotorska Bay, when the extended shelf of the southeastern Adriatic ends.

The SESC current is clearly related to the inertia of the buoyant flow from the Buna/Bojana and the adjustment of the velocity field to the density gradient due to Coriolis effect. This balance, on the eastern sides of basins, deflects river plumes to the North, producing a northward geostrophic currents. This area is often characterized by upwelling favorable winds, such as prevailed for the period April 21–24, 2006 (Fig. 6). If wind forcing dominated the local circulation, the SESC would be southward but our data and model results indicate that buoyancy driven plume dynamics dominate over the wind forcing to produce the northward surface flow. While the downwelling favorable winds in the northwestern Adriatic reinforce the plume dynamics (the Po River plume advects southward in the same direction as the typical wind forcing), in the southeaster Adriatic wind and river plume forcing oppose each other. During the period of observation in spring 2006, the buoyancy forcing exceeds the effects of the local wind stress. Other ROFI areas in upwelling

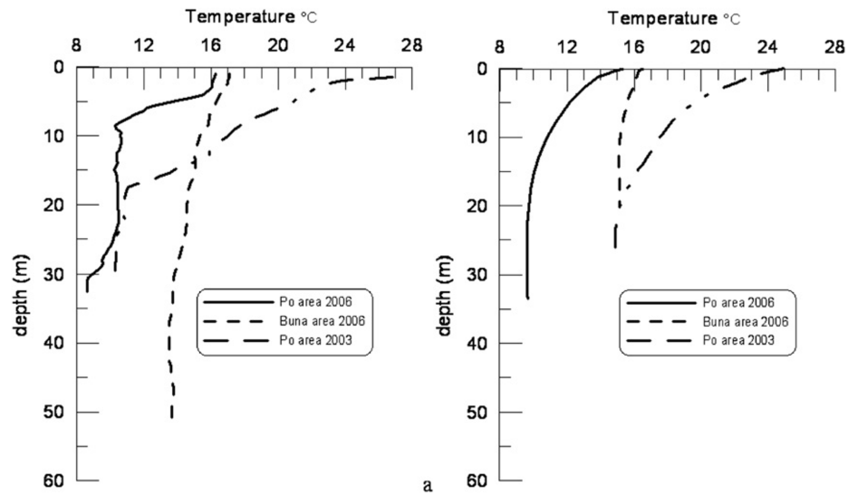

Fig. 9. *In situ* (a) and simulated (b) temperature profiles of the station in the Po area (April 25, 2006 and June 5, 2003) and in the Buna/Bojana area (April 23, 2006).

favorable wind regimes behave differently, as it is the case for the southern California Bight where river plumes dynamics are dominated by the large scale coastal currents that are influenced by the along shore pressure gradient (Warrick et al., 2007).

3.2. *Vertical cross-shelf structure in the southeastern and northwestern Adriatic Sea*

In this section we examine the observed physical and chemical distributions along the sections of Fig. 2, comparing the area North and South of the Buna/Bojana in the southeastern Adriatic Sea with the section in the northwestern Adriatic offshore from the Po River delta. The northwestern Adriatic transect in June 2003 is strongly stratified in temperature and salinity, especially within the upper 10 m (Fig. 7). In contrast, the vertical temperature gradient is much less for transect C upstream of the Buna/Bojana River in April 2006 (Fig. 8). A comparison of temperature profiles from the Buna/Bojana for 2006 and the Po River plume for 2003 from *in situ* and model data clearly shows the difference in stratification between the Po and the Buna/Bojana areas (Fig. 9).

The observed vertical salinity distributions, for both the Buna/Bojana and Po ROFI areas, reveal a shallow plume with steep gradients in the upper 5–10 m of the water column. The surface salinity minimum is present not only near the coasts but offshore in the middle of the transects, suggesting some horizontal complexity in the plumes. In the turbidity field for both areas (Figs. 7 and 8), maximum turbidities occur in the near-bottom nepheloid layer that can be up to 10 m thick. In the surface layer the maximum turbidity values coincide with the surface salinity minima of both regions. The nutrient distributions in the Po plume show that in stratified conditions the highest DIN concentrations (10 μmol L^{-1}) occur in the surface layer with a secondary maximum (5 μmol L^{-1}) near the bottom where the water depth is about 25 m (Fig. 7). The highest DIN concentrations in the Buna/Bojana plume, ~12 μmol L^{-1}, are also in the surface layer (Fig. 8). Secondary maxima of ~2.5 μmol L^{-1} are observed subsurface at intermediate depths of about 20–50 m offshore and near-bottom closer to the coast where the water depth is about 45 m.

The orthosilicate values in the Po transect are low (1–2 μmol L^{-1}) in the surface layer, while higher values are observed above the bottom (5 μmol L^{-1}; Fig. 7). In this area the concentration of orthosilicate does not appear to be controlled by river inputs, but by the active consumption by phytoplankton as reported by Cozzi et al. (2002). In Fig. 7 it is evident that the nearsurface high chlorophyll fluorescence and low salinity coincide with the area of low orthosilicate concentration. It is well known that the bottom layer orthosilicate maximum under the Po Plume results from the remineralization of the produced organic matter from the upper water column (Graf and Rosenberg, 1997; Tengberg et al., 2003). In contrast, for the Buna/Bojana River plume the highest orthosilicate concentrations coincide with the nearsurface low salinity layer (Fig. 8). The highest chlorophyll fluorescence in the Buna/Bojana plume is also found in the nearsurface low salinity layer.

The distributions of nutrients and chlorophyll for the two regions are similar, with high concentrations of both associated with the nearsurface low salinity layer. The regions differ in that nearsurface orthosilicate concentrations which were low in the Po plume, but relatively high in the Buna/Bojana plume. However, upcoast, and hence downstream, from the Buna/Bojana discharge, the surface orthosilicate concentrations were greatly reduced, and near-bottom concentrations were intensified (Fig. 10), more like the observed Po plume distributions. During early June 2003, there was very little surface forcing apart from the Po River discharge in the northern Adriatic, and thus there was little advection of the discharged river plume. But in the Buna/Bojana plume the model and the property distributions indicate significant northward advection of the plume. Thus for the Po plume the uptake, deposition, and remineralization of the nutrients were occurring locally, while for the Buna/Bojana plume, coastal advection displaced these processes from the region directly in front of the mouth of the discharge upcoast (downstream) from the source.

4. Discussion

Both of these river plume regions show similarities with each other. Both river systems provide significant inflows into the coastal region. However, on average, the volume flux from the Po River system is of the order of twice the volume flux from the Buna/Bojana River system. Both systems also show a distinct region of enhanced phytoplankton biomass along the coast as indicated by the chlorophyll concentrations observed in both satellite imagery (Fig. 1) and *in situ* observations (Figs. 4, 7 and 8).

A comparison of nutrient concentration ranges and Si/DIN ratios indicate that important differences exist between the nutrient loadings for the two inflows. The maximum concentrations of DIN and $Si(OH)_4$ in the coastal plume of the Buna/Bojana were both higher than for the Po plume (Table 2). Maximum DIN in the Buna/Bojana plume was 50% higher than for the Po plume and $Si(OH)_4$

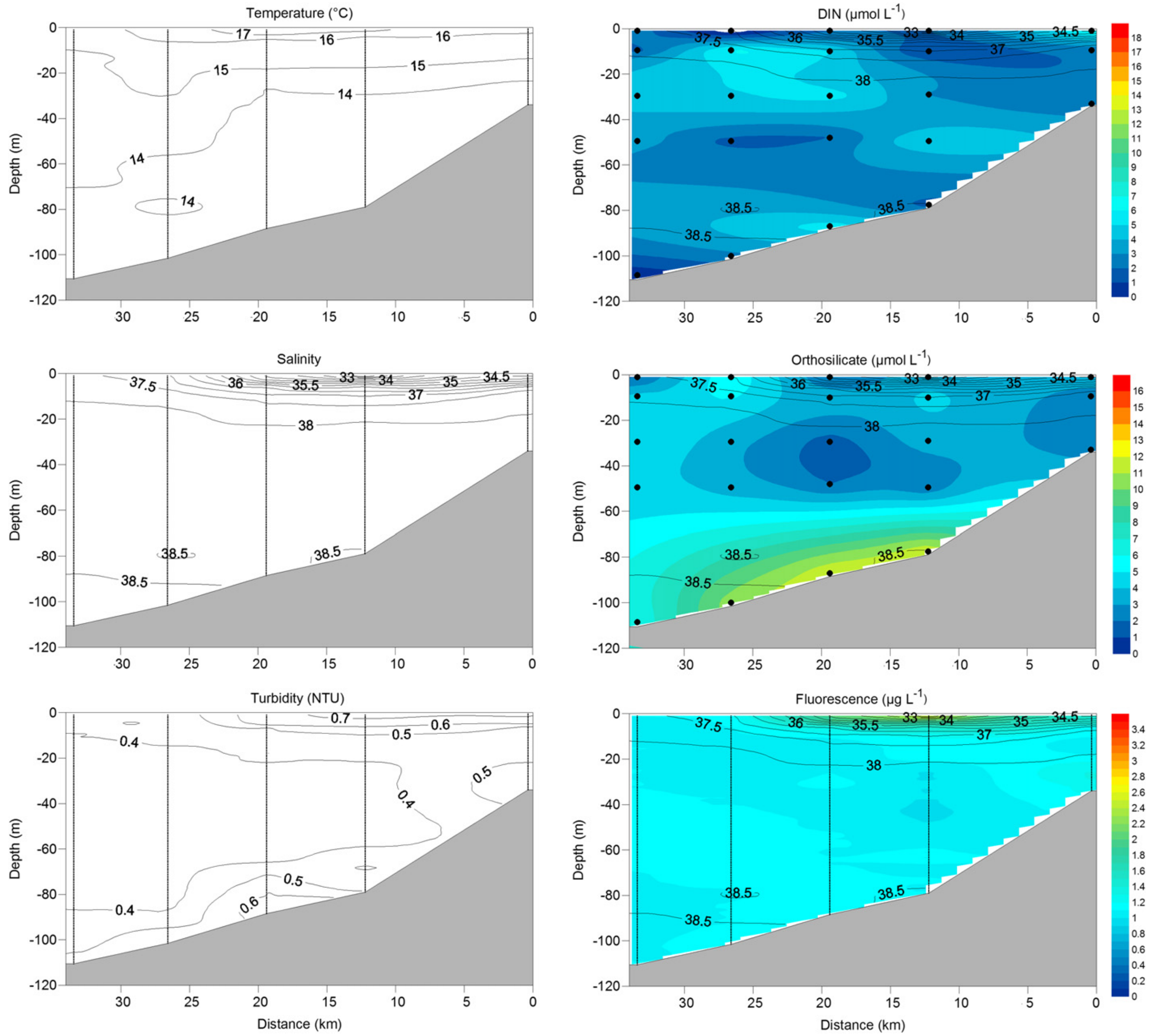

Fig. 10. Vertical sections along the transect D, shown in Fig. 2, on April 23, 2006. The left panels represent the vertical distribution of temperature, salinity and turbidity. The right panels represent the vertical distribution of DIN, orthosilicate and fluorescence concentration (colored shading) overlaid with salinity contours (black contours; contour interval 0.5). The dots represent the sampling points.

was an order of magnitude higher than observed in the Po plume where the nearsurface salinity was <37. As a result the Si/DIN was also significantly higher with maximum ratios up to 11, compared with a maximum ratio of 3 in the Po plume. Because the Po concentrations and ratios are similar to the results reported by Degobbis et al. (2005), we conclude that these are typical ratios for the Po River plume region. Lacking additional measurements for the southeastern region, we cannot make any inferences regarding how representative these measurements are.

Diatoms uptake of orthosilicate and their consequent sinking lead to accumulation of organic matter on the bottom (Mann, 1985; Brzezinski and Nelson, 1995; Pugnetti et al., 2004). Remineralization of this accumulated diatom biomass contributes to high concentrations of orthosilicate in the near-bottom water column. This is particularly important during summer when the combination of a significant buoyancy flux and weak wind forcing create a strongly stratified upper layer and the vertical mixing flux between the surface and near-bottom layers is minimal (Artegiani et al., 1993; Zavatarelli et al., 1998). Orthosilicate resuspension

Table 2
Nutrient concentrations near the mouths of the Po and Buna/Bojana. Values of orthosilicate ($Si(OH)_4$) and DIN are express as interval of concentration min-max in relation with different salinity areas.

	Salinity	Si/DIN	$Si(OH)_4$ ($\mu mol\ L^{-1}$)	DIN ($\mu mol\ L^{-1}$)
Northern Adriatic	<37	1–2	–	1–15
(Degobbis et al., 2005)	>37	3–10	–	1–2
Po Delta	<37	1–3	1–2	7–12
	>37	5–13	3–12	2–5
Buna/Bojana	<37	5–11	2–21	2–18
	>37	1–3	2–4	1–5

can be caused by natural events such as strong winds, tidal currents, large surface or internal waves, biological activities, and by human activities such as trawl fishing and dredging (Tengberg et al., 2003; Boldrin et al., 2009).

The area upstream (South) of the Buna/Bojana River plume (transect C, Fig. 8) shows surface concentrations of orthosilicates of more than 15 μmol L^{-1} and corresponding Si/DIN values of 5–11 (Table 2). This sharply contrasts with the Po plume where surface concentrations were only 1–2 μmol L^{-1}, and the Si/DIN ratio was 1–3. There are several possible explanations for these differences. One explanation is that both concentrations and the Si/DIN ratio in the source waters are quite different between the two river systems. Unfortunately, river concentrations are not available for the Buna/Bojana River and, hence, that possibility cannot be explored here. A second explanation is that the phytoplankton community responding to the local nutrient inputs and stratification is low in diatoms and silicoflagellates, perhaps dominated by dinoflagellates or other non-diatom species (Falkowski et al., 2004). Another possibility is that this particular transect may represent a transitional region from inputs down the coast to the input from the Bona/Bojana River and there are phytoplankton succession issues related to the spatial positioning of this transect. The presence of the bottom intensified maxima in orthosilicates in transect D North of the Buna/Bojana River mouth shows that diatoms may be a significant component of the phytoplankton community and what was seen in transect C may be due to a spatial/temporal positioning of the plume and the phytoplankton response to the input.

5. Conclusions

In conclusion, the Adriatic southeastern coastal area is characterized by significant eutrophic freshwater inputs particularly from the Buna/Bojana River. The Buna/Bojana plume dynamics are consistent with the Coriolis dynamical constraint resulting in a northward transport of the plume, independent from the dominant local southward wind forcing that should result in southward currents and localized upwelling.

The Buna/Bojana ROFI area contains higher nutrient concentrations and higher Si/DIN ratios compared with the Po River plume, yet nearsurface chlorophyll concentrations appear to be similar. These differences should contribute to differences in the phytoplankton community structure and to the nutrient recycling pathways in the system. The observations that have been presented indicate that for the Buna/Bojana coastal strip, organic matter is settling far from the primary production area, in the offshore extension of the shelf. Remineralization of the organic matter leads to the formation of the secondary, bottom intensified maximum of dissolved orthosilicate that is similar to the eutrophic coastal region at the northwestern Adriatic Sea influenced by the Po River plume.

We conclude that the combination of natural and anthropogenic nutrients in the river discharges from the southeastern Adriatic, although different in magnitude of flow and concentration of inorganic nutrients from the northwestern Adriatic, have similar effects on the coastal phytoplankton communities and the ensuing nutrient recycling that occurs along the coast.

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