Is the southeastern Adriatic Sea coastal strip an eutrophic area?

Mauro Marini[1], Federica Grilli[1], Antonio Guarnieri[2], Burton Jones[3], Zoran Klajic[4], Nadia Pinardi[5], Mitat Sanxhaku[6]

[1]Institute of Marine Science, National Research Council, Ancona, Italy

[2]Istituto Nazionale di Geofisica e Vulcanologia, Bologna, Italy

[3]University of Southern California, Los Angeles, USA

[4]Institute of Marine Biology Kotor, Montenegro

[5]*CIRSA*, University of Bologna, Ravenna, Italy

[6]Institute of Hydrometeorology, Tirana, Albania

Acknowledgements.

Special thanks are also given to the captain and crew of the R/V "G. Dallaporta" for their help during cruises, and to Pierluigi Penna, Giuseppe Caccamo, Vesna Macic, Emirjeta Adhami and Aleksandar Jovicic, for their helpful assistance in field activity, Alessandra Campanelli for her helpful in laboratory analyses and Emanuele Böhm for the MODIS image of chlorophyll *a* concentration. The research was supported by the ADRICOSM-EXT program funded by the UNESCO-IOC, under the financing of the Italian Ministry of Foreign Affairs and the ADRICOSM-STAR project funded by the Italian Ministry of Environment, Land and Sea, Department of Research and development.Data from the Po Delta region was obtained with the support of the captain and crew of the R/V Knorr. B. Jones was supported by the U.S. Office of Naval Research (Award number N000140210854).

Abstract

The aim of the present study is to understand and assess the eutrophic state of the Buna-Bojana river delta coastal strip, in the southeastern Adriatic Sea, and contrast it with the northern Po river dominated shelf area. We present and compare observations of chemical and physical state variables from the two areas of the Adriatic Sea and we also use a numerical model output to depict the circulation structures of the two areas.

The area affected by the Po River discharge extends at least one hundred kilometres southward of the delta and approximately twenty kilometres offshore. Maximum chlorophyll concentrations follow closely the river waters. Similarly to the northern Adriatic Sea, the Buna/Bojana river discharge extends northward along the coasts for one hundred kilometres and shows large maxima in chlorophyll. The two coastal areas have opposite dominant dynamical processes: while the Po river affected area is a downwelling region, the Buna/Bojana is characterized by upwelling favourable winds. However, during the period of study, upwelling is not a dominant feature of the circulation and both the shelf slope current and the along shore currents in the southeastern Adriatic Sea are northward, the along shore current probably dominated by the river runoff. Under these conditions, primary productivity is high in both areas which allows us to conclude that river plume dynamics with the associated nutrient inputs control the eutrophication state of the coastal strip, regardless of the general hydrodynamics regime of the southeastern Adriatic Sea area.

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 Report Number 3 2000).

Eutrophication is the process by which nutrients inputs, primarily nitrogen, silicate and phosphorus, contribute to the 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 (e.g. Shaw et al. 2006).

Nowadays it is becoming customary to classify eutrophication on the basis of the maximum of chlorophyll-a evaluated from satellite images and in this paper we will start with this approach. In Fig.1 we show an image of the chlorophyll distribution from satellite ocean color. The maximum of chlorophyll concentration is found in two different locations: the first, offshore the Po river delta area and in the western Adriatic coastal strip while the second is in the southeastern Adriatic Sea, along the coasts of Montenegro and Albania. In this paper we will contrast these two chlorophyll maxima areas and try to find analogies and differences.

In the past years eutrophication events and regimes have been thoroughly discussed for the northern Adriatic Sea related with the Po River runoff (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 the low salinity river plume and waters extension and the high chlorophyll concentration coastal strip (Zavatarelli et al. 2000; Polimene et al. 2006) which underlines the importance of the buoyancy-driven flow in the definition of the coastal zone trophic state (Marini et al. 2008; Campanelli et al. 2004).

The second largest chlorophyll-a concentration maximum in Fig.1 appears in the southeastern Adriatic Sea, in the coastal strip off Montenegro and Albania. The local maximum is associated with the Buna-Bojana river delta and the area of influence of these waters is seen to extend northward, for few hundred kilometers along the coastline. The eutrophication state of this coastal area has not been fully documented in the literature but the similarity with the Po delta high chlorophyll area lead us to hypothesize that the two areas might be dominated by the same basic biogeochemical processes. Our hypothesis is that eutrophication dominates these two areas even if the wind-driven hydrodynamics regimes are opposite. It is in fact well known that the eastern Adriatic Sea is dominated by upwelling favourable winds at the contrary of the western side of the basin which is a downwelling region.

The aim of the present study is to understand the eutrophic processes occurring in the southeastern coastal areas of Albania and Montenegro and contrast them with the Northern Adriatic coastal zone trying to understand the differences between the physical and bio-chemical regimes. We will do so by using observations collected from two different years, 2003 and 2006 and using numerical model outputs to describe in a more complete way the dynamics of the region.

The contrasting coastal regions of the northwestern and southeastern Adriatic Sea

Fig. 2 shows the geography and bathymetry of the northwestern and southeastern coastal Adriatic Sea areas where the study concentrates. These two areas can be both characterised as Regions Of Freshwater Influence (ROFI), the northern mainly affected by the Po and the southern by the Buna-Bojana runoff since each of these two rivers account for more than one third of the freshwater entering the two coastal areas. In the following two sections we will describe the characteristics of each of the regions separately.

Northwestern coastal Adriatic area

Freshwater is discharged into the northern Adriatic from major rivers along the north 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 flows southward along the Italian coasts. The buoyant layer is directed predominantly southward from the Po River delta and it is confined in the coastal part of the continental shelf, above 50 meters depth (Poulain et al. 2001). In the Adriatic Sea, all the atmospheric forcings, heat, water and momentum fluxes, and lateral river discharges contribute to produce 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. 2005) even if deep waters exit from the Otranto Strait. The southward coastal flow, so-called Western Adriatic Coastal Current (WACC, Artegiani et al. 1997a and b), is driven by the Po river buoyancy flux (low-salinity waters) and the Bora winds that characterize this region during the winter months. Bora winds cause elevated sea surface height along the western coasts, producing downwelling and transport of coastal dense waters towards the open sea (Boldrin et al. 2009). The Po river born dissolved nutrients influence the coastal area about two-three hundred kilometres southward of the delta and approximately twenty kilometres across the coast: the nutrient distribution follows a diminishing trend from north to south, 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 out of the northern 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. 2002; Campanelli et al. 2004). This nutrient transport is however very variable seasonally and interannually. In particular the transport of DIN (Dissolved Inorganic Nitrogen) and $Si(OH)_4$ (orthosilicate) could also be eastward especially in spring and summer (Grilli et al. 2005) due to the offshore extension of the Po river plume.

Southeastern coastal Adriatic area

A large number of rivers such as the Buna/Bojana, Drini, Vjosa, Semani, Shkumbini, Erzen, Ishimi and Mati discharge into the southern part of the Adriatic Sea (Fig. 2). The Buna/Bojana river has the largest single discharge (about 700 $m^3 s^{-1}$) while the combined discharge of the Albanian rivers is about 1250 $m^3 s^{-1}$ (UNEP 1996). In Table 1 the general characteristics of the main rivers in this area are described.

The Buna/Bojana river in the southeastern Adriatic sea is the counterpart of the Po river in the northwestern Adriatic Sea. Several of the river plumes from the Albanina and Montenegrin rivers are readily distinguished in the chlorophyll image (Fig. 1) but the largest chlorophyll feature is from 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 of what it should be expected for an upwelling favourable wind area such as this one, as we will show later.

The southern Adriatic Sea, according to climatological investigations, extends approximately from the Pelagosa Sill to the Otranto Channel. It is characterized by a wide depression more than 1200m deep and the water exchanges with the Mediterranean Sea take place through the Otranto Channel, having a sill of 800 m. According to Manca et al. (2002) the surface cyclonic circulation is characterized, along the western coasts, by a relatively fresh water stream concentrated along the western coasts which marks the southward density-driven WACC. Along the eastern boundary the northward South Eastern Adriatic current (SEAd) transports Ionian Surface Water (ISW) into the Adriatic Sea. At depth, the water masses are characterised by Modified Levantine Intermediate Water (MLIW) which contains high levels of nitrate but is phosphorus deficient (Rixen et al. 2005). The circulation on the southeastern shelf of the Adriatic basin has never been mapped from data prior to this investigation and nothing is known in the literature about the nutrient and biogeochemical characteristics of the investigated area.

Data sets

In situ observations

The in situ data used for this study were obtained from one cruise in front of the Po river mouth in 2003 and from one in 2006 on the Montenegro-Albanian shelf. The hydrographic data set from the Po River mouth was obtained on June 8, 2003 during a cruise on board 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 the period of April 21-23, 2006. The CTD station distributions are shown in Fig. 2 for the two cruises. The transects in the two locations are not at the same time but synchronous data in the two regions do not exist. However both sets of observations were taken with the same experimental procedures and under similar conditions of flow, as shown in Fig. 3. The year 2003 is in fact an anomalous year for the runoff, registering very low values in the Po delta region. In particular, during spring 2003 the Po runoff comes close to the average of the climatological runoff from the Buna-Bojana, likely to be similar to the one occurring in 2006. Thus we will compare the Po and Buna-Bojana river born dissolved nutrients in the two coastal strips in two years with similar runoff.

The CTD (Conductivity-Temperature-Depth) data were collected with a SeaBird Electronics SBE 911-plus CTD equipped with a oxygen sensor SBE43, SeaPoint turbidity, Wetlabs ECO-AFL fluorometer (R/V Knorr) and SCUFA fluorometer (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 by the upcasts with a SeaBird Carousel rosette water sampler equipped with 5-liter 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 analysed by spectrophotometric methods widely used in oceanography (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 the NH_4, NO_2 and NO_3 concentrations.

Model data

The model results are from simulations of an operational model of the Adriatic Sea 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 $1/45^0$ x $1/45^0$ 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 six hours 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 today and in this paper we will use daily mean values of the relevant fields for the year 2006.

Results

Horizontal distributions and circulation in the southeastern Adriatic Sea

The in situ data, comprehensive of temperature, salinity, fluorescence, turbidity, DIN and Orthosilicates, collected on the transects of Fig.2, were spatially gridded by the Surfer software both horizontally and vertically. In Fig. 4 we show the horizontal distributions at 1 metres depth of all the measured state variables.

The salinity map shows that the Buna-Bojana river area of influence extends 30 km offshore and both northward and southward of the Buna-Bojana delta, choosing the 35.5 isohaline to mark the boundary between the offshore and the river-borne waters. Within the plume area the turbidity is high (more than 0.7 μg/L), as well as florescence, 1.5 – 2.2 (μg/L), DIN and $Si(OH)_4$, approximately more than 4 ($\mu mol\ L^{-1}$) and 10 ($\mu mol\ L^{-1}$) respectively. The distribution of the dissolved nutrients is patchy and shows a local maximum of DIN and $Si(OH)_4$ north of the Buna-Bojana river mouth, as expected if river-borne nutrients were injected in the coastal area and not used by the primary producers. Patterns of 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 the most uncorrelated with salinity, implying perhaps that turbidity is dominated by inorganic sediments instead of organic material.

Fig. 5 shows the model temperature, salinity and currents, averaged between the 22 and 23 of April 2006. The temperature and salinity fields show similar patterns to the observations, with the area of the Buna-Bojana river outflow well marked and approximately of the same shape of 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 tends to underestimate/overestimate the temperature. For what concerns salinity we see that the salinity gradient is well represented close to the Buna-Bojana river mouth and that the area of freshwater influence extends northward up to the Bokakotorska Bay.

Being the temperature and salinity fields similar between model and data we will now consider the model circulation structure. Fig. 5 shows two northward currents, one along the shelf slope and the other near the coasts, along the salinity gradients that marks the area of freshwater influence. The slope and coastal currents merge north of 42^{o} 30' N. We believe the SEAd current described in Artegiani et al. (1997b) is here described by the shelf slope current while the shelf/coastal current is here described for the first time and we will call it the southeastern Shelf Coastal (SESC) current.

The SESC current is detached from the coasts, especially between the Ishimi (see Fig.2) and the Buna-Bojana river outflows, so that recirculations develop which help to enlarge the offshore extension of the area of freshwater influence from all these rivers. On the other hand, the southward reversed near-coast currents, part of the different anticyclonic recirculation gyres, contribute to the freshening of the area south of the Buna-Bojana delta. The recirculation areas are expected to form since at the borders of the general cyclonic circulation encircling the basin, the coasts are sources of anticyclonic vorticity and thus anticyclones can form when conditions are favourable. This happens also on the other side of the Adriatic Sea all along the WACC landward side (Zavatarelli and Pinardi 2003).

In Fig. 6 we show the dominant winds in the period of 21-24 of April 2006. They are southward winds, upwelling favourable but the flow field is northward: we argue then that the controlling mechanism for the SESC is not the wind but the river waters and their dynamics in the near shore area. We cannot exclude that in other seasons or months the flow could be southward but in this particular month the currents are all northward in general.

We conclude then that the coastal southeastern Adriatic Sea circulation during spring is characterised by a northward current, now called SESC, which starts to be well defined north of the Shkumbini river. The current has a width of approximately 10 km, an average speed of about 15 cm/s and occupies the shelf in front of the Buna-Bojana extending about 30 km offshore along the between isobaths 40 m and 100 m. This current is the seaward side 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 force. This balance, on the eastern sides of the basins, would deflect the river plumes to the north, producing in fact northward geostrophic currents. This area is often characterised by upwelling favourable winds, as shown in Fig. 6 for the period between 21 and 24 of April 2006. If the wind driven circulation would prevail here, the SESC would be southward but our data and model results show that the buoyancy driven plume dynamics prevail over the wind forcing and produces the northward surface flow. While the downwelling favourable winds in the northwestern Adriatic reinforce the plume dynamics (Po river plume goes southward as well as the wind induced currents), in this area wind and river plume dynamics generate opposite direction currents. We are able here to show that in the spring of 2006, the river plume dynamics prevail over the local wind stress forcing. It is to be mentioned that other ROFI areas in upwelling favourable wind regimes behave different, as it is the case for the southern California bight rivers influenced areas (Warrick et al. 2007)

Vertical cross-shelf distributions in the southeastern and northwestern Adriatic Sea

In this section we compare the observed physical and chemical distributions along the sections of Fig. 2, marking the area north and south of the Buna-Bojana in the southeastern Adriatic Sea with the section in the northwestern Po river area. The northwestern Adriatic transect, shown in Fig. 7 is strongly stratified in temperature and salinity, especially within the upper 10 meters. 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 (Fig. 9) from in situ and model data shows very clearly the difference in stratification between the Po and the Buna-Bojana areas.

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 meters of the water column. The surface salinity minimum is both near the coasts and in the middle of the transect, suggesting some horizontal complexity in the plumes. In the turbidity field for both areas (Fig.7 and 8), the maximum values occur near the bottom in what appears to be up to a 10 meter thick nepheloid layer. In the surface layer the maximum turbidity values coincide in both areas with the surface salinity minima. The nutrient distributions in the Po area (Fig. 7) show that in stratified conditions the DIN values are highest (10 μmol L^{-1}) in the surface layer with a secondary maxima near the bottom of the shallow part of the transect (5 μmol L^{-1}). This is true also for the Buna-Bojana DIN distribution (Fig. 8) even of the subsurface DIN values are more homogenous (around 2.5 μmol L^{-1}) and the surface maxima is higher than in the Po area, about 12 μmol L^{-1}.

The orthosilicate values in the Po transect are low (1-2 μmol L^{-1}) in the surface layer while higher values are reached at the bottom (5 μmol L^{-1}). 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 area with high fluorescence and low salinity is approximately coincident with the area of low orthosilicate concentrations. It is well known that the bottom layer orthosilicates maxima is associated with the remineralization of the produced organic matter in the upper water column (Tengberg et al. 2003; Graf and Rosenberg 1997). For the Buna-Bojana river waters at the contrary, Fig. 8

shows orthosilicate concentrations that are high at the surface up to 10 meters depths, from the coasts to offshore. High nutrient concentrations are in correspondence of high surface fluorescence values and low salinities.

This first analysis shows that the high fluorescence area in the northwestern and southeastern coastal strips of the Adriatic Sea is characterized by similar dissolved nutrient concentration distributions, except for the orthosilicates which do not seem to be as strongly controlled by phytoplankton uptake in the upstream part of the Buna-Bojana part ROFI area with respect to the Po. However, in Fig. 10, we show the transect D that is downstream of the Buna-Bojana river plume and there the orthosilicate distribution is bottom intensified, reproducing partially the conditions of the Po ROFI area.

Discussion and conclusions

In Table 2 the nutrient concentration ratios near the Po and Buna-Bojana river mouths are shown. In the southeastern Adriatic the nutrient ratios are different compared to the northwestern Po river area, especially in the surface layer (indicated in Table 2 with salinity values less than 37) because higher concentrations of orthosilicate and Si/DIN are recorded. The values showed in Table 2 agree with those of Degobbis et al. 2005 regarding the data collected from the northern Adriatic Sea in 1999-2002 (Si/DIN ratio, 1-2 for water salinity <37 and 3-10 for water salinity> 37). It can therefore be inferred that concentrations reported in Figure 6 for the Po river are typical for the northern Adriatic coastal area.

The uptake of orthosilicate by diatoms (Mann 1985; Brzezinski and Nelson 1995; Pugnetti et al. 2004) leads to the formation of organic matter on the bottom which, due to remineralization, forms high concentration of orthosilicate at the bottom. This phenomenon is principally emphasized during the summer season when the water column is stratified and the exchanges between the bottom and surface are lower (Artegiani et al. 1993; Zavatarelli et al. 1998). Orthosilicate resuspension can be caused by natural events, such as strong winds, tidal currents and biological activities, or by anthropogenic perturbations, such as trawling and dredging (Tengberg et al. 2003; Boldrin et al. 2009).

The area upstream of the Buna-Bojana river plume (transect C, Fig. 8) shows higher concentrations of orthosilicates at the surface than the Po area, with values of Si/DIN around 5-11 (Table 2). Two hypothesis can be made to explain this nutrient structure: 1) lower uptake by diatoms and silicoflagellates in the Buna-Bojana with respect to the Po ROFI area; 2) different redistribution patterns of the phytoplankton and organic matter connected with the Buna-Bojana river plume dynamics and other rivers south of Buna-Bojana.

The presence of the bottom intensified maxima in orthosilicates in transect D shows that diatoms could be still a significant portion of the phytoplankton groups in the southeastern

Adriatic area so that hypothesis 1 seems not to be the main reason for the nutrient distribution found. The second hypothesis seems then likely to be more substantive if we admit that the phytoplankton and the organic material generated by it is rapidly exported and thus it is settling in different parts of the shelf area.

In conclusions, the Adriatic southeastern coastal area is an eutrophic area which is strongly affected by important freshwater inputs, in particular the Buna-Bojana river runoff. The Buna-Boajna plume dynamics obeys the Coriolis dynamical constraint and the current is northward, irrespective of the dominant local wind driving which is upwelling favourable and thus inducing southward currents.

The nutrient distributions are different in the Buna-Boajna ROFI area with respect to the Po while values of fluorescence are equivalent. This indicates in our opinion a strong relationship between physical transport and development of the trophic chain, in particular in the Buna-Bojana coastal strip, the organic material is settling far from the primary production area, in the offshore extension of the shelf. There, remineralization of the organic material brings about the secondary bottom intensified maximum in dissolved silicates which is typical of the eutrophic coastal areas on the northwestern Adriatic Sea.

References

Artegiani, A., M. Gacic, A. Michelato, V. Kovacevic, A. Russo, E. Paschini, P. Scarazzato, and A. Smircic. 1993. The Adriatic Sea hydrography and circulation in spring and autumn (1985-1987). Deep-Sea Res. II **40**(2): 1143-1180.

Artegiani, A., D. Bregant, E. Paschini, N. Pinardi, F. Raicich, and A. Russo. 1997a. The Adriatic Sea general circulation. Part I. Air-sea interactions and water mass structure. J. Phys. Oceanogr. **27**: 1492-1514.

Artegiani, A., D. Bregant, E. Paschini, N. Pinardi, F. Raicich, and A. Russo. 1997b. The Adriatic Sea general circulation. Part II: Baroclinic Circulation Structure, J. Phys. Oceanogr. **27**: 1515-1532.

Boldrin, A., S. Carniel, M. Giani, M. Marini, F. Bernardi Aubry, A. Campanelli, F. Grilli, and A. Russo. 2009. The effects of Bora wind on Physical and Bio-Chemical properties of stratified waters in the northern Adriatic. J. Geophys. Res. **114**, C08S92, doi:10.1029/2008JC004837.

Brzezinski, M. A., and D. M. Nelson. 1995. The annual silica cycle in the Sargasso Sea near Bermuda. Deep-Sea Res. **42**(7): 1215-1237.

Campanelli, A., P. Fornasiero, and M. Marini. 2004. Physical and chemical characterization of the water column in the Piceno Costal area (Adriatic Sea). Fresenius Environmental Bulletin. **13**(5): 430-435.

Castellari, S., N. Pinardi, and A. Coluccelli. 2006. The ADRICOSM Pilot project: a coastal and river basin prediction system for the Adriatic Sea. Acta Adriatic. **47**: 5-18.

Civitarese, G., and M. Gacic. 2001. Had the eastern Mediterranean Transient an impact on the new production in the Southern Adriatic?. Geophysical research Letters. **28**(8): 1627-1630.

Conley, D., J. Markager, S. Andersen, J. T. Ellermann, L. M. Svendsen. 2002. Coastal eutrophication and the Danish National Aquatic Monitoring and Assessment Program. Estuaries. **25**(4B): 706-719.

Cozzi, S., M. Lipizer, C. Cantoni, and G. Catalano. 2002. Nutrient balance in the ecosystem of the north western adriatic sea, Chemistry and Ecology. **18**(1-2): 1-12.

Cloern, J. 2001. Our evolving conceptual model of the coastal eutrophication problem. Mar. Ecol. Prog. Ser. **210:** 223-253.

Degobbis, D., R. Precali, N. Ivanovic, N. Smodloka, D. Fuks, and S. Kveder. 2000. Long-term chages in the northern Adriatic ecosystem related to antropogenic eutrophication. J. Environment and Pollution. **13**: 495-533.

Degobbis, D., R. Precali, C. R. Ferrari, T. Djakovac, A. Rinaldi, I. Ivancˇic´, M. Gismondi, and N. Smodlaka. 2005. Changes in nutrient concentrations and ratios during mucilage events in the period 1999–2002. Science of the Total Environment. **353**: 103-114.

Graf, G., R. Rosenberg.1997. Bioresuspension and biodeposition: a review. J. Mar. Syst. **11**: 269-278.

Grilli F., M. Marini, D. Degobbis, C.R. Ferrari, P. Fornasiero, A. Russo, M. Gismondi, T. Djakovac, R. Precali, and R. Simonetti. 2005. Circulation and horizontal fluxes in the northernAdriatic Sea in the period June 1999-July 2002. Part II: Nutrients transport. Science of the Total Environment. **353**: 115-125.

Guarnieri, A., P. Oddo, M. Pastore, and N. Pinardi. In press. The Adriatic Basin Forecasting System new model and system development. Coastal to Global Operational Oceanography: Achievements and Challenges. Eds. H. Dahlin, N.C Fleming, and S.E. Petersson. Proceeding of 5th EuroGOOS Conference, Exeter.

Hopkins, T. S., A. Artegiani, F. Bignami, and A. Russo. 1999. Water-mass modification in the Northern Adriatic: A preliminary assessment from the ELNA data set, in The Adriatic Sea, edited by T. S. Hopkins et al., Ecosyst. Res. Rep **32**: 3 – 23, Eur. Comm., Brussels.

IOCCG Report Number 3. 2000. Shubha Sathyendranath (editor) Remote Sensing of Ocean Colour in Coastal, and Other Optically-Complex,Waters Published by the International Ocean-Colour Coordinating Group, P.O.Box 1006, Dartmouth, Nova Scotia, B2Y 4A2, Canada.

Ivancˇic´, I., and D. Degobbis. 1984. An optimal manual procedure for ammonia analysis in natural waters by the indophenol blue method. Water Res. **18**: 1143-7.

Kourafalou, V. H. 1999. Process studies on the Po River plume, North Adriatic Sea. J. Geophys. Res. **104**(C12): 29963-29985.

Kourafalou, V. H. 2001. Modelling river plumes on Mediterranean shelves: Po River plume (North Adriatic Sea) and Axios River plume (North Aegean Sea). J. Marine Syst. **30**(3-4): 181-205.

Lee, C. M., F. Ascari, J. Book, S. Carniel, B. Cushman, C. K. Harris, H. Perkins, P. M. Poulen, and D. Thaler Detweiler. 2005. Northern Adriatic response to a wintertime bora wind event, Eos Trans. AGU **86**(16), 157, 163, 165.

Mann, K. H. 1985. Ed. Ecology of coastal waters, Study in Ecology; vol. **8**, 322 pp., Blackwell Scientific Publications, London, UK.

Manca, B. B., V. Kovacevic, M. Gacic, and D. Viezzoli. 2002. Dense water formation in the Southern Adriatic Sea and spreading into the Ionian sea in the period 1997-1999. J. Marine Syst. **33-34**, 133-154.

Marini, M., P. Fornasiero, and A. Artegiani. 2002. Variations of hydrochemical features in the coastal waters of Monte Conero:1982-1990. P.S.Z.N.:Marine Ecology **23**(suppl.1): 258-271.

Marini, M., B. H. Jones, A. Campanelli, F. Grilli, and C. M. Lee. 2008. Seasonal variability and Po River plume influence on biochemical properties along western Adriatic coast, J. Geophys. Res. **113**, C05S90, doi:10.1029/2007JC004370.

Oddo, P., N. Pinardi, and M. Zavatarelli. 2005. A numerical study of the interannual variability of the Adriatic Sea (2000-2002), Science of the Total Environment **353:** 39-56.

Parsons, T. R., Maita Y., and Lalli C.M. 1985. A manual of chemical and biological methods for seawater analysis. Oxford Pergamon Press. 173 pp.

Pinardi, N., E. Arneri, A. Crise, M. Ravaioli and M. Zavatarelli, 2006**.** The physical, sedimentary and ecological structure and variability of shelf areas in the Mediterranean Sea**.** The Sea Vol. **14** (A. R. Robinson and K. Brink Eds.), Harvard University Press, Cambridge, USA, 1243-1330.

Polimene, L., N. Pinardi, M. Zavatarelli, and S. Coltella. 2006. The Adriatic Sea ecosystem seasonal cycle: Validation of a three-dimensional numerical model. J. Geophys. Res. **112**: C03S19**,** doi:10.1029/2006JC003529.

Poulain, P. M., and B. Cushman-Roisin. 2001. Circulation, in Physical Oceanography of the Adriatic Sea, edited by B. Cushman-Roisin et al., pp. 67– 109, Kluwer Acad., Dordrecht, Netherlands.

Pugnetti, A., F. Acri, L. Alberighi, D. Barletta, M. Bastianini, F. Bernardi Aubry, A. Bertone, F. Bianche, G. Socal, and C. Totti. 2004. Phytoplankton photosynthetic activity and growth rates: observations in the NW Adriatic Sea. Chem. Ecol. **20**: 399-409.

Rachev, N., and R. Purini. 2001. The Adriatic response to the Bora forcing: A numerical study. Nuovo Cimento della Societa Italiana di Fisica C-Geophysics and Space Physic **24** (2): 303-311.

Raicich, F. 1996. On the fresh water balance of the Adriatic coast. J. Mar. Syst. **9**: 305-319.

Rixen, M., J. M. Beckers, S. Levitus, J. Antonov, T. Boyer, C. Maillard, M. Fichaut, E. Balopoulos, S. Iona, H. Dooley, M.J. Garcia, B. Manca, A. Giorgetti, G. Manzella, N. Mikhailov, N. Pinardi, and M. Zavatarelli. 2005. The Western Mediterranean Deep Water: A proxy for climate change Geophysical research Letters **32** (12)**:** L12608.

Ryther, J. H. and W. M. Dunstan. 1971. Nitrogen, phosphorus, and eutrophication in the coastal marine environment. Science **171**: 1008-1013.

Rönnberg, C. and E. Bonsdorff. 2004. Baltic Sea eutrophication: area-specific ecological consequences. Hydrobiologia **514**: 227-241.

Smith, V. H., B. J. Samantha, and W. R. Howarth. 2006. Eutrophication of freshwater and marine ecosystems. Limnol. Oceanogr. **51**(1, part 2): 351-800.

Tengberg, A., E. Almroth and P. Hall. 2003. Resuspension and its effects on organic carbon recycling and nutrient exchange in coastal sediments: in situ measurements using new experimental technology. J. Exp. Mar. Biol. Ecol. **285-286**: 119-142.

UNEP 1996. Mediterranean action plan (MAP), Implications of climate change for the Albanian coast, Technical Reports Series No. **98**.

UNESCO 1988. The acquisition, calibration and analysis of CTD data. A report of SCOR WG 51. Technical papers in Marine Sciences **54**: 1-59.

Vollenweider, R. A., A. Rinaldi, and G. Montanari. 1992. Eutrophication, structure and dynamics of a marine coastal system: results of ten-year monitoring along the Emilia-Romagna coast (Northwest Adriatic Sea), p. 63-106. *In* R. A. Vollenweider, R. Marchetti, R. Viviani (eds.), Marine Coastal Eutrophication, Elsevier.

Warrick, J. A., P. M. DiGiacomo, S. B. Weisberg, N. P. Nezlin, M. Mengel, B. H. Jones, J. C. Ohlmann, L. Washburn, E.J. Terrill, and K.L. Farnsworth. 2007. River plume patterns and dynamics within the Southern California Bight. Cont. Shelf Res. **27**: 2427-2448.

Zavatarelli, M., F. Raicich, A. Artegiani, D. Bregant, and A. Russo. 1998. Climatological biogeochemical characteristics of the Adriatic Sea. J. Mar. Syst. **18**: 227–263.

Zavatarelli, M., J. W. Baretta, J. G.Baretta-Bekker, and N. Pinardi, 2000. The dynamics of the Adriatic Sea ecosystem. An idealized model study. Deep-Sea Research I **47**: 937-970.

Zavatarelli, M., N. Pinardi, V. H. Kourafalou and A. Maggiore, 2002. Diagnostic and prognostic model studies of the Adriatic Sea general circulation. Part 1: The seasonal variability and the role of the forcing functions. J. Geophys. Res. **107**(C1), 4/1-4/20.

Zavatarelli, M., and N. Pinardi. 2003. The Adriatic Sea modelling system: a nested approach. Annales Geophysicae **21:** 345-364**.**

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	2,441	Fani Rubik (1951-1986)	87	2,753
Ishimi	673	Sukth Vendas (1968-1992)	20	624
Erzeni	760	Sallmonaj (1949-1992)	17	532
Shkumbini	2,440	Rroqzhine (1948-1991)	59	1,849
Vjosa	6,710	Mifol (1948-1987)	190	5,954
Semani	5,649	Mbrostar (1948-1987)	86	2,709
Bistrica	447	Krane (1949-1987)	32	1,011
Pavla	374	Bogaz (1951-1991)	7	210
Other river	4,028		72	2,271
Total	43,104		1,244	39,186

Table 2. Nutrient concentrations near the mouths of the Po and Buna-Bojana.

	Salinity	Si/DIN	$Si(OH)_4$, μM	DIN, μM
Northern Adriatic (Degobbis et al. 2005)	<37	1-2	-	1-15
	>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

Figure Legends

Fig. 1. MODIS image of chlorophyll *a* concentration for 23 April 2006 (provided by CNR-ISAC, Rome).

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 south-eastern coastal areas of Montenegro and Albania. The dots represent the sampling points and the rectangles indicate the position of the transects.

Fig. 3. Monthly averages of the Po and Buna-Bojana River flows for the period 1989-2002 and 1965-1985 respectively. The solid line is the annual average for the period 1989-2002 and the dashed line is the monthly flow for 2003 (thick line for Po River and thin line for the Buna-Bojana River).

Fig. 4. Horizontal distribution at 1 meters depth of temperature, salinity, fluorescence, turbidity, DIN and orthosilicate in the south-eastern coastal areas of Albanian and Montenegro in April 2006. The dots represent the sampling points.

Fig. 5. Mean horizontal surface distributions of temperature and salinity in the south-eastern coastal areas of Montenegro and Albania. The model data are averaged on the 22 and 23 of April 2006 when the samples were collected at sea . Starting from top: modelled temperature (a) and salinity (b); modelled temperature (c) and salinity (d) overlaid with currents at 2 meters.

Figure 6. Wind stress averaged on the days 21, 22, 23 and 24 of April 2006 calculated from ECMWF atmospheric forcings.

Fig. 7. Vertical sections along the Po transect for the 5th June 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 0.1). The dots represent the sampling points.

Fig. 8. Vertical sections along the transect C, shown in Fig. 2 on 23th April 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 0.1). The dots represent the sampling points.

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

Fig. 10 Vertical sections along the transect D, shown in Fig. 2, on 23th April 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 0.1). The dots represent the sampling points.

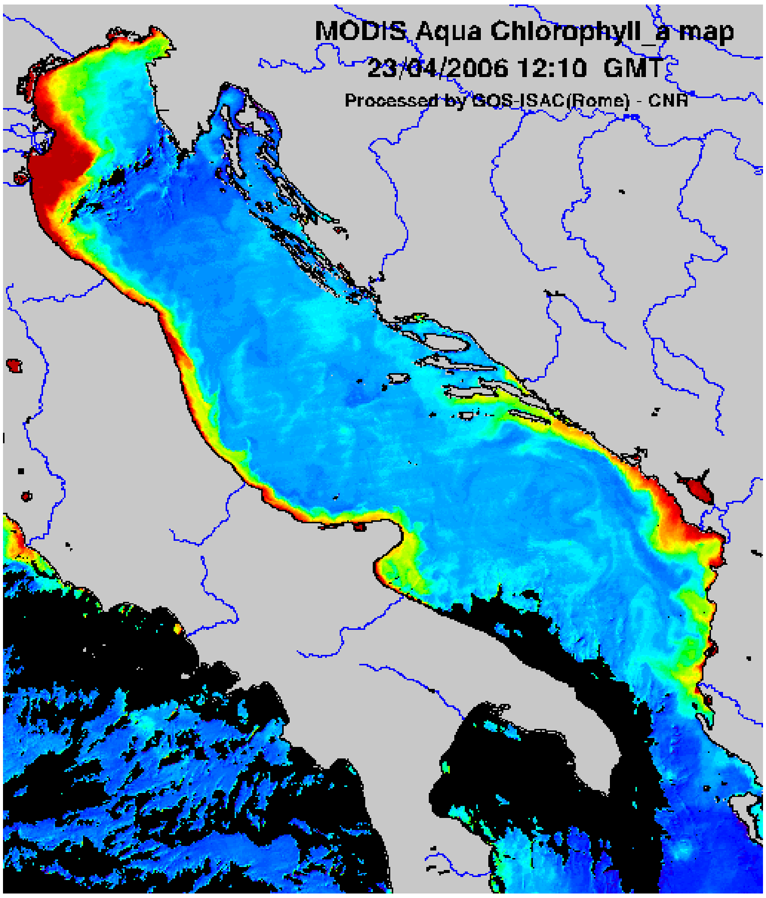
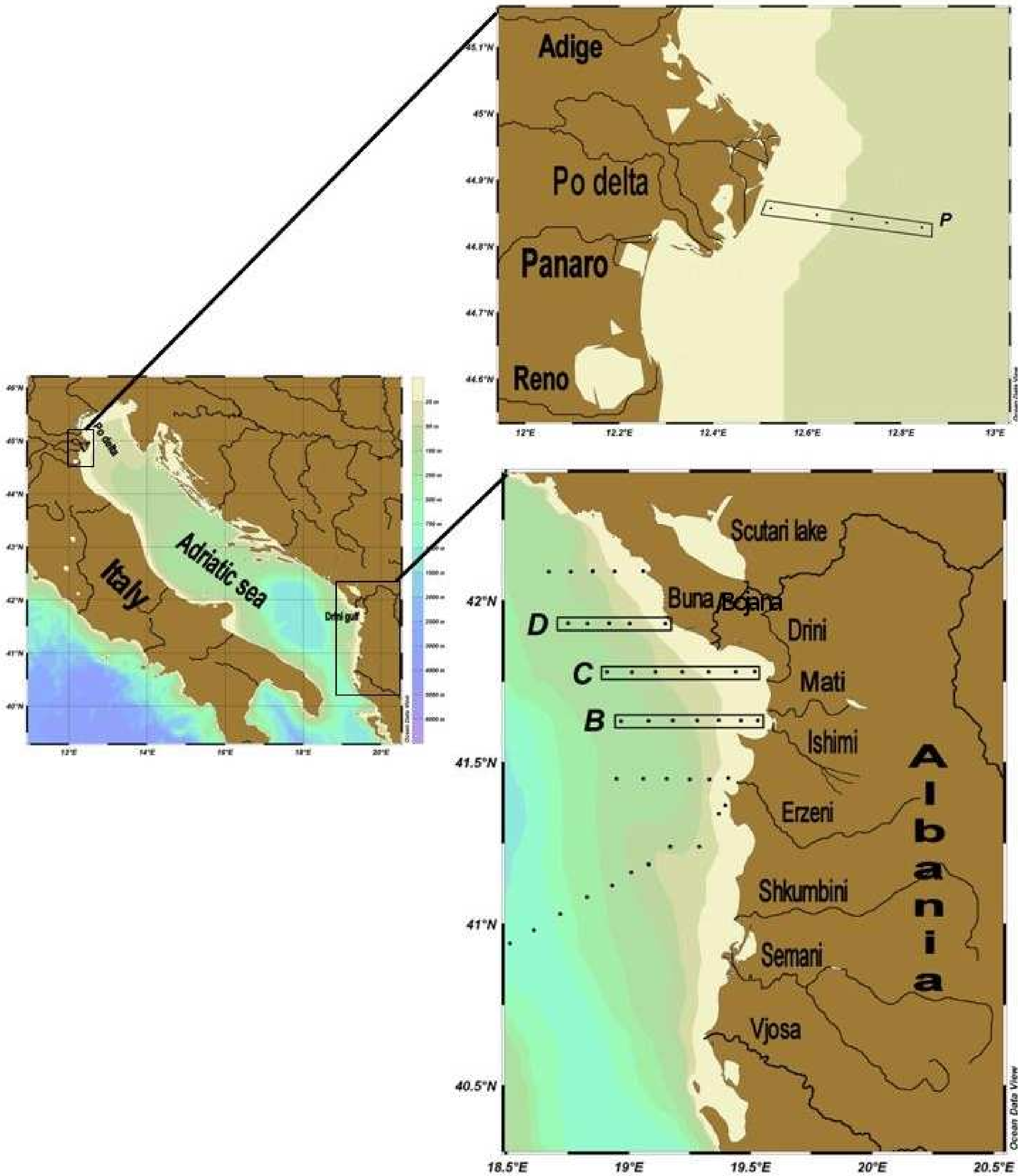
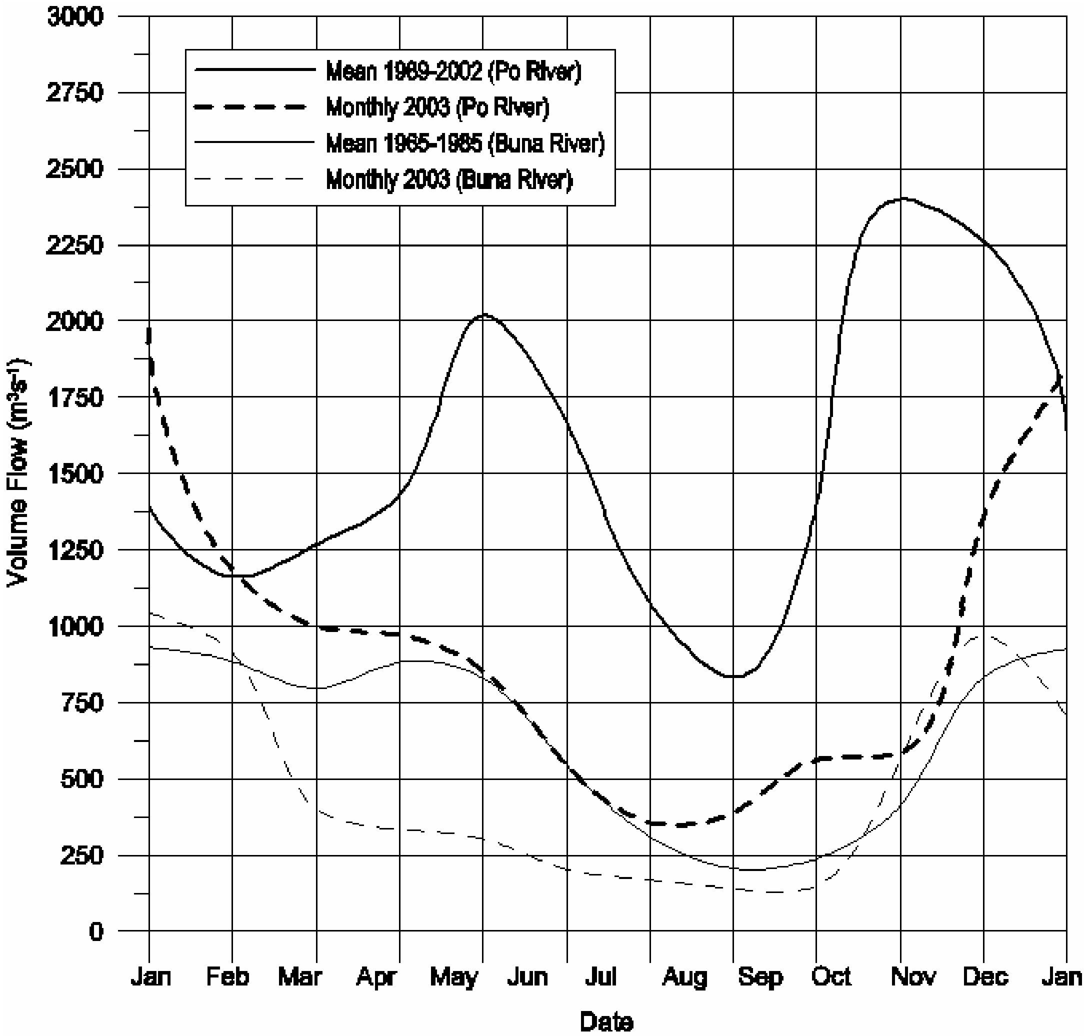

MODIS Aqua Chlorophyll_a map
23/04/2006 12:10 GMT
Processed by GOS-ISAC(Rome) - CNR

Fig. 1



Adige
Po delta
Panaro
Reno
P
Italy
Adriatic sea
Drini gulf
Scutari lake
Buna/Bojana
Drini
Mati
Ishimi
Erzeni
Shkumbini
Semani
Vjosa
Albania
D
C
B
42°N
41.5°N
41°N
40.5°N
18.5°E
19°E
19.5°E
20°E
20.5°E
Ocean Data View

Fig. 2



3000
2750
2500
2250
2000
1750
1500
1250
1000
750
500
250
0
Volume Flow (m³s⁻¹)
Mean 1969-2002 (Po River)
Monthly 2003 (Po River)
Mean 1965-1985 (Buna River)
Monthly 2003 (Buna River)
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Date

Fig. 3

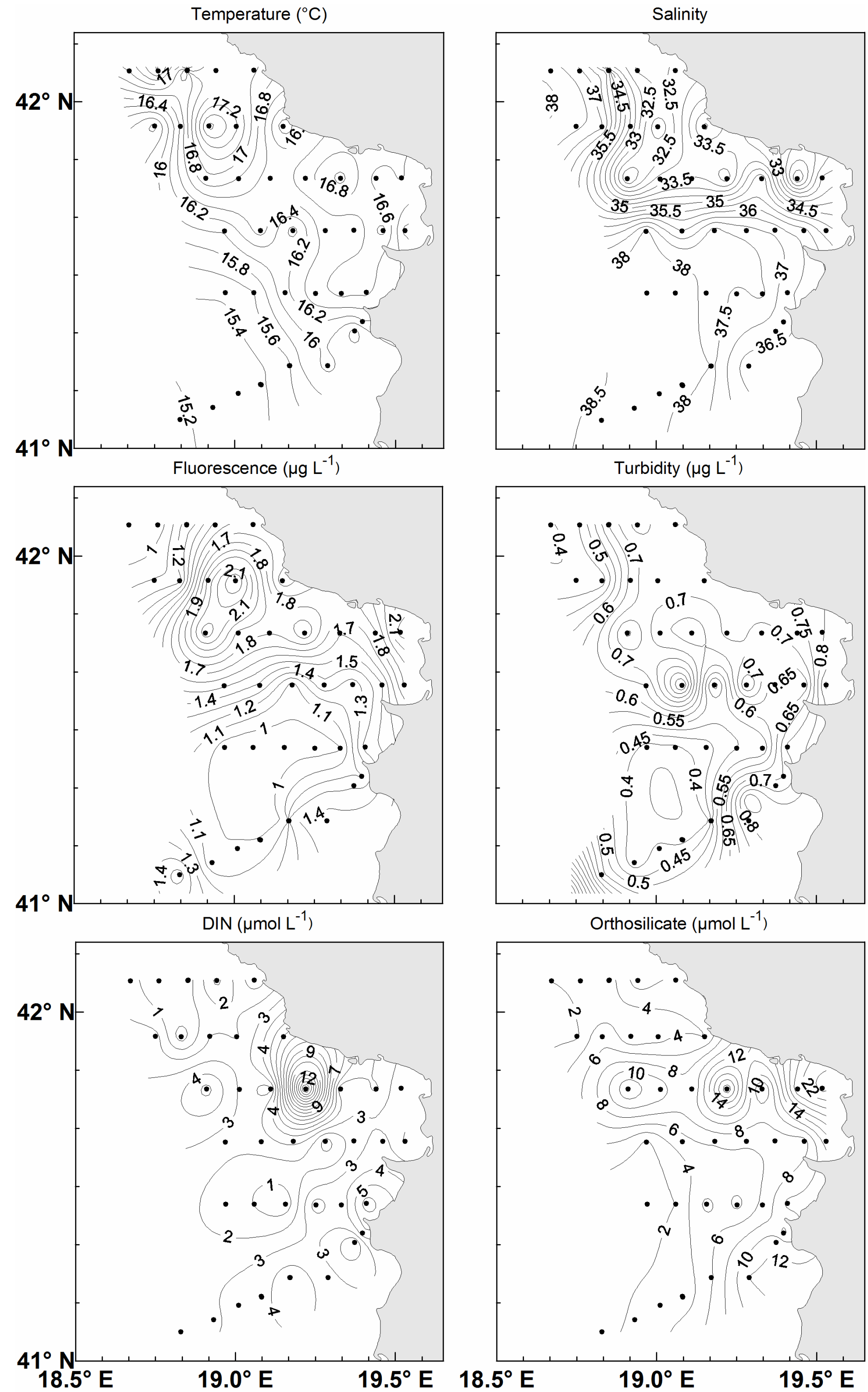

Temperature (°C)
Salinity
Fluorescence (μg L-1)
Turbidity (μg L-1)
DIN (μmol L-1)
Orthosilicate (μmol L-1)
42° N
41° N
18.5° E
19.0° E
19.5° E

Fig. 4

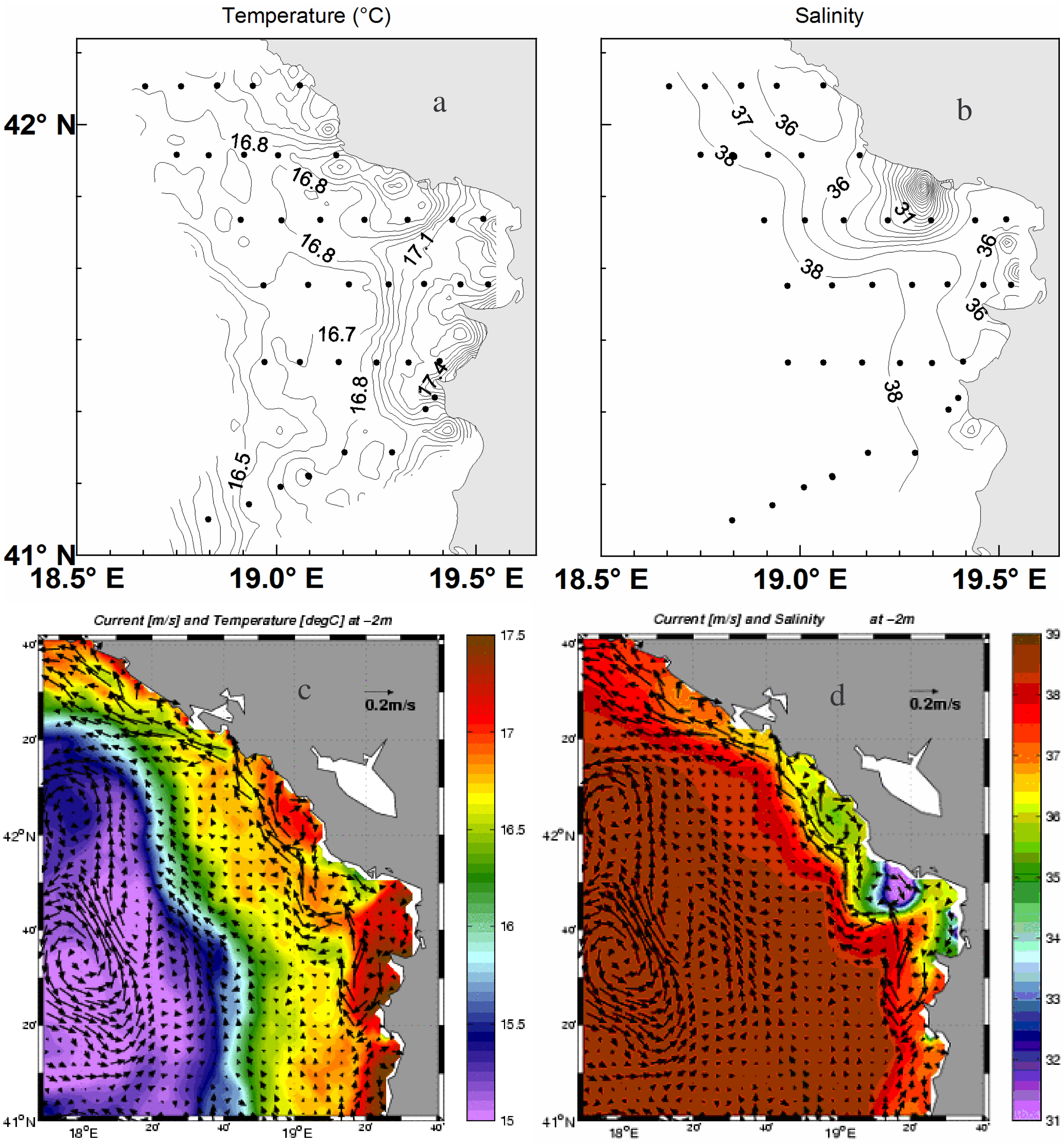

Temperature (°C)
Salinity
a
b
c
d
42° N
41° N
18.5° E
19.0° E
19.5° E
16.8
16.7
17.1
17.4
16.5
37
36
38
31
Current [m/s] and Temperature [degC] at −2m
Current [m/s] and Salinity at −2m
0.2m/s
17.5
17
16.5
16
15.5
15
39
38
37
36
35
34
33
32
31
42°N
41°N
18°E
19°E
20'
40'

Fig. 5

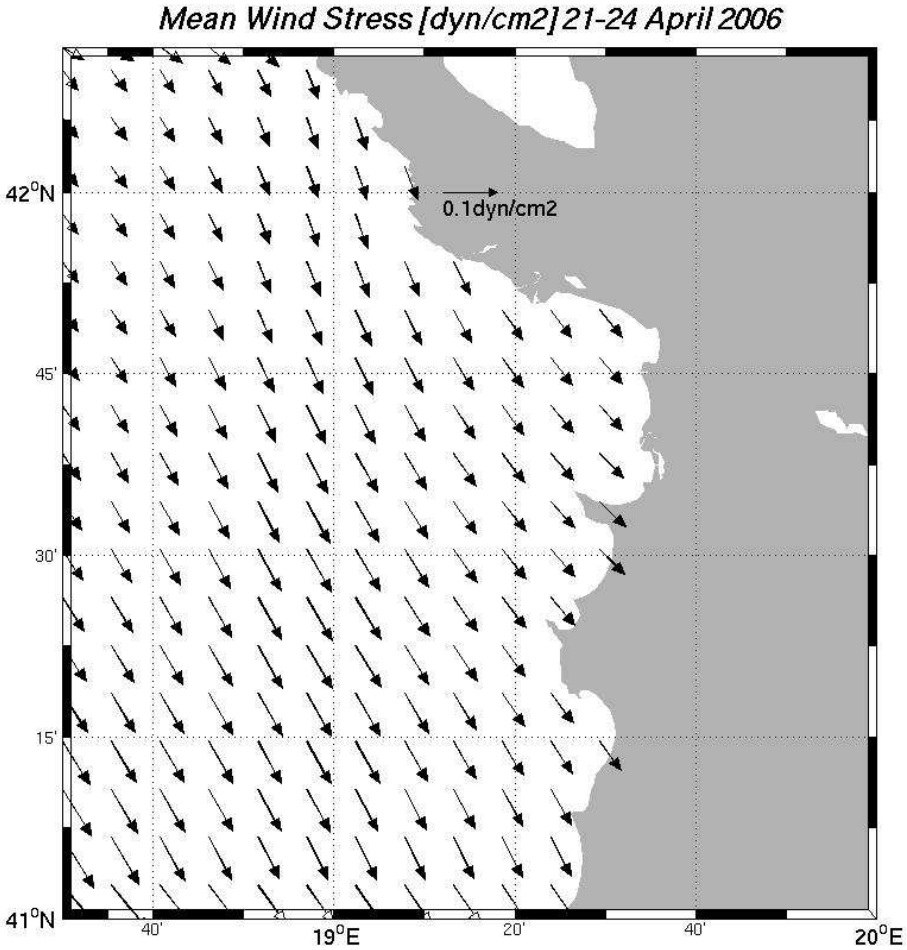

Mean Wind Stress [dyn/cm2] 21-24 April 2006
0.1dyn/cm2
42°N
45'
30'
15'
41°N
40'
19°E
20'
40'
20°E

Figure 6

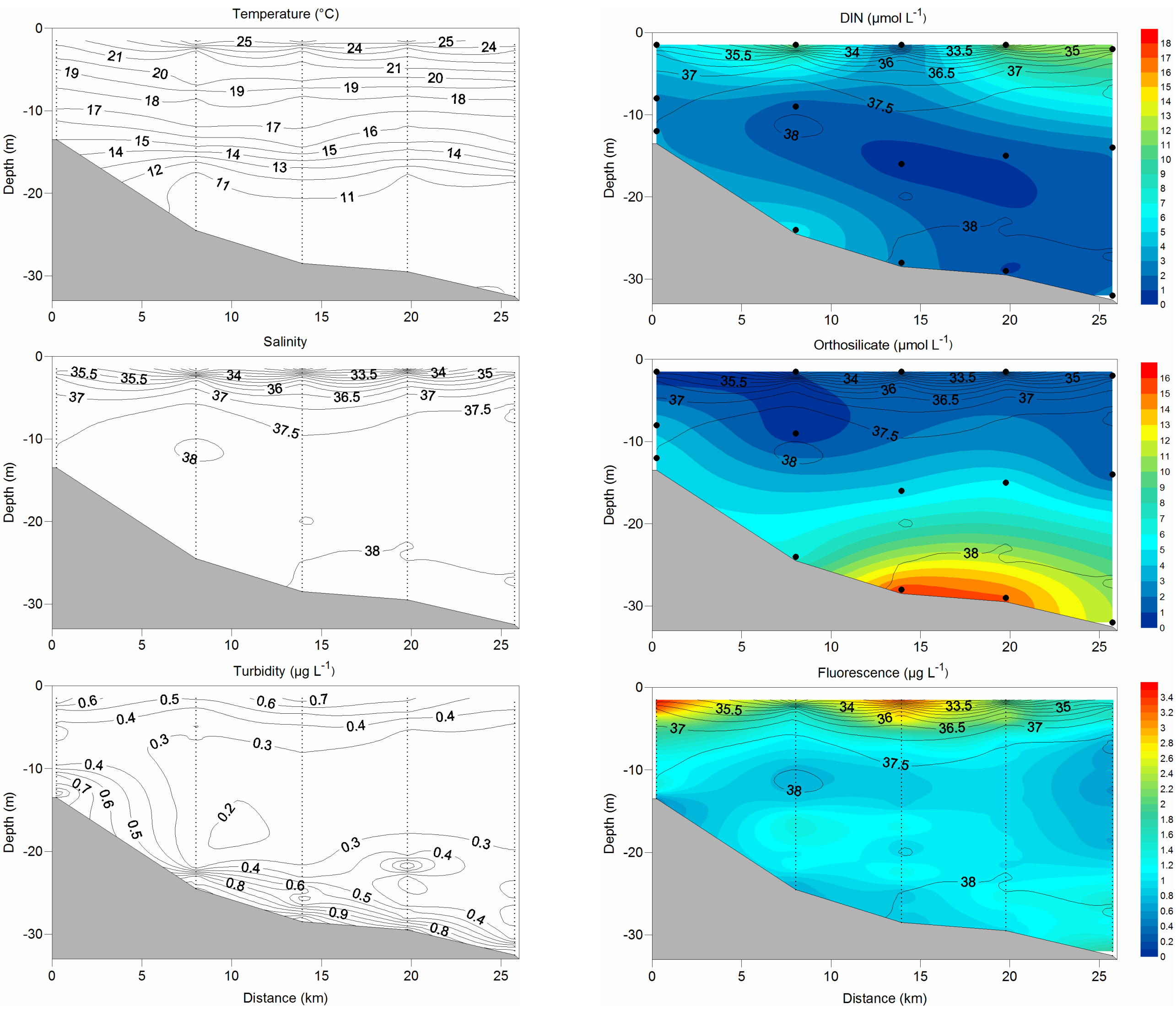

Temperature (°C)
DIN (µmol L-1)
Salinity
Orthosilicate (µmol L-1)
Turbidity (µg L-1)
Fluorescence (µg L-1)
Depth (m)
Distance (km)

Fig. 7

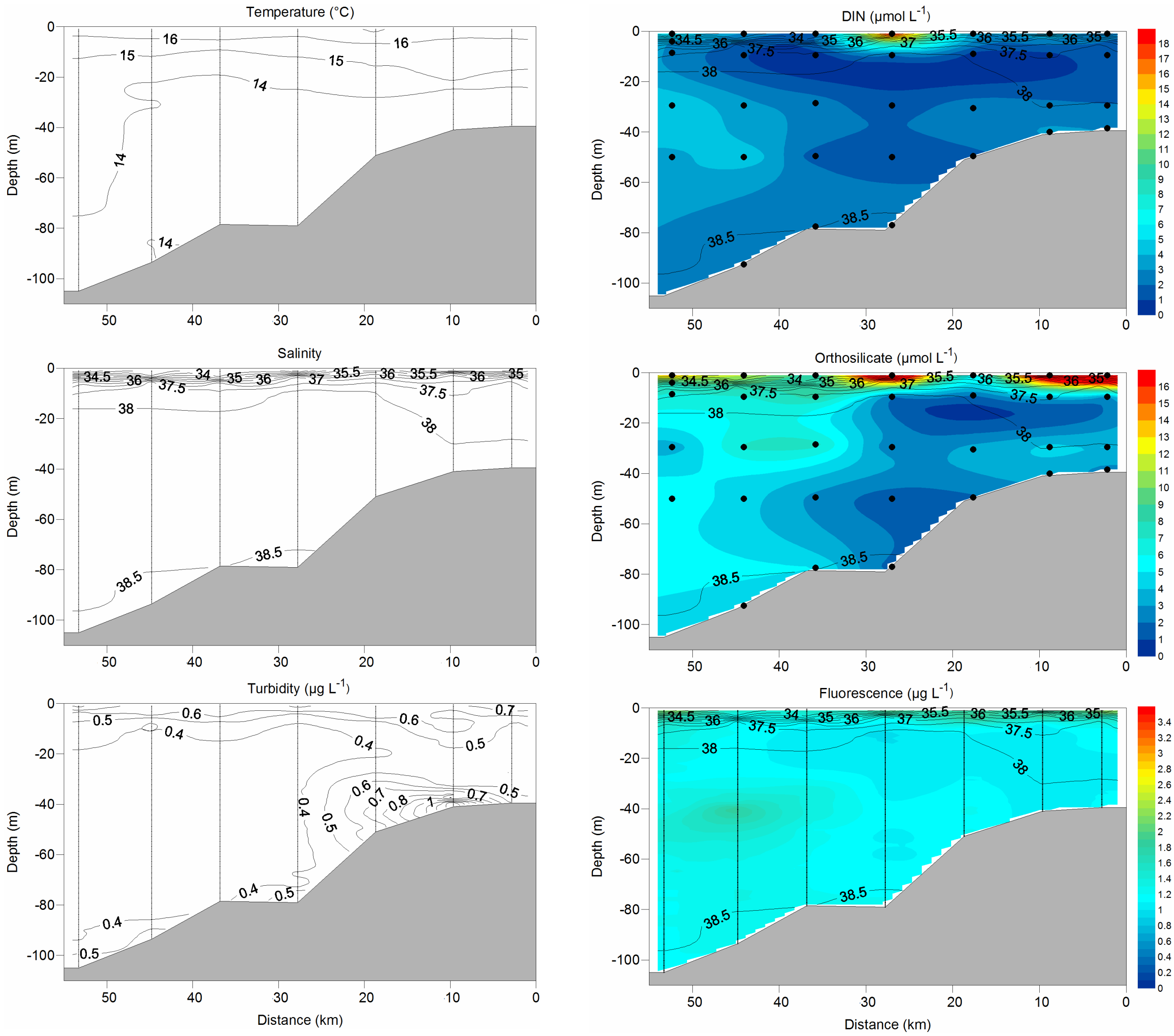

Temperature (°C)
DIN (µmol L-1)
Salinity
Orthosilicate (µmol L-1)
Turbidity (µg L-1)
Fluorescence (µg L-1)
Depth (m)
Distance (km)

Fig. 8

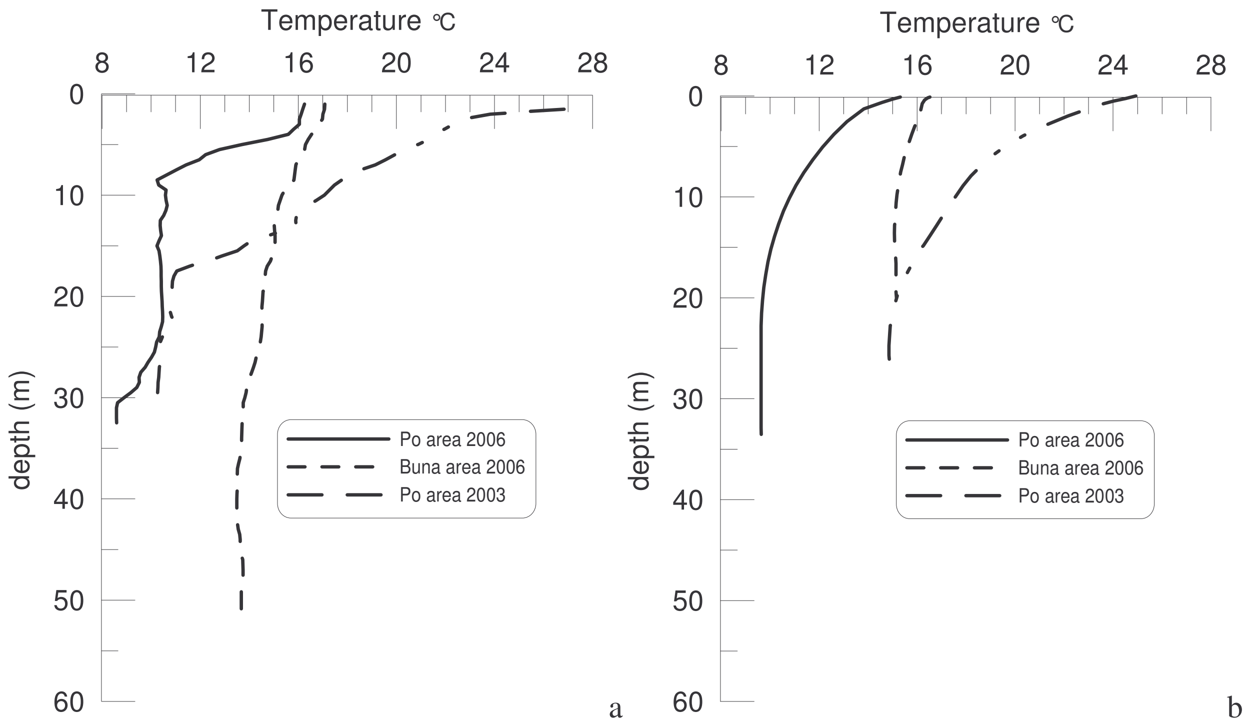

Temperature °C
8
12
16
20
24
28
0
10
20
30
40
50
60
depth (m)
Po area 2006
Buna area 2006
Po area 2003
a
Temperature °C
8
12
16
20
24
28
0
10
20
30
40
50
60
depth (m)
Po area 2006
Buna area 2006
Po area 2003
b

Fig. 9

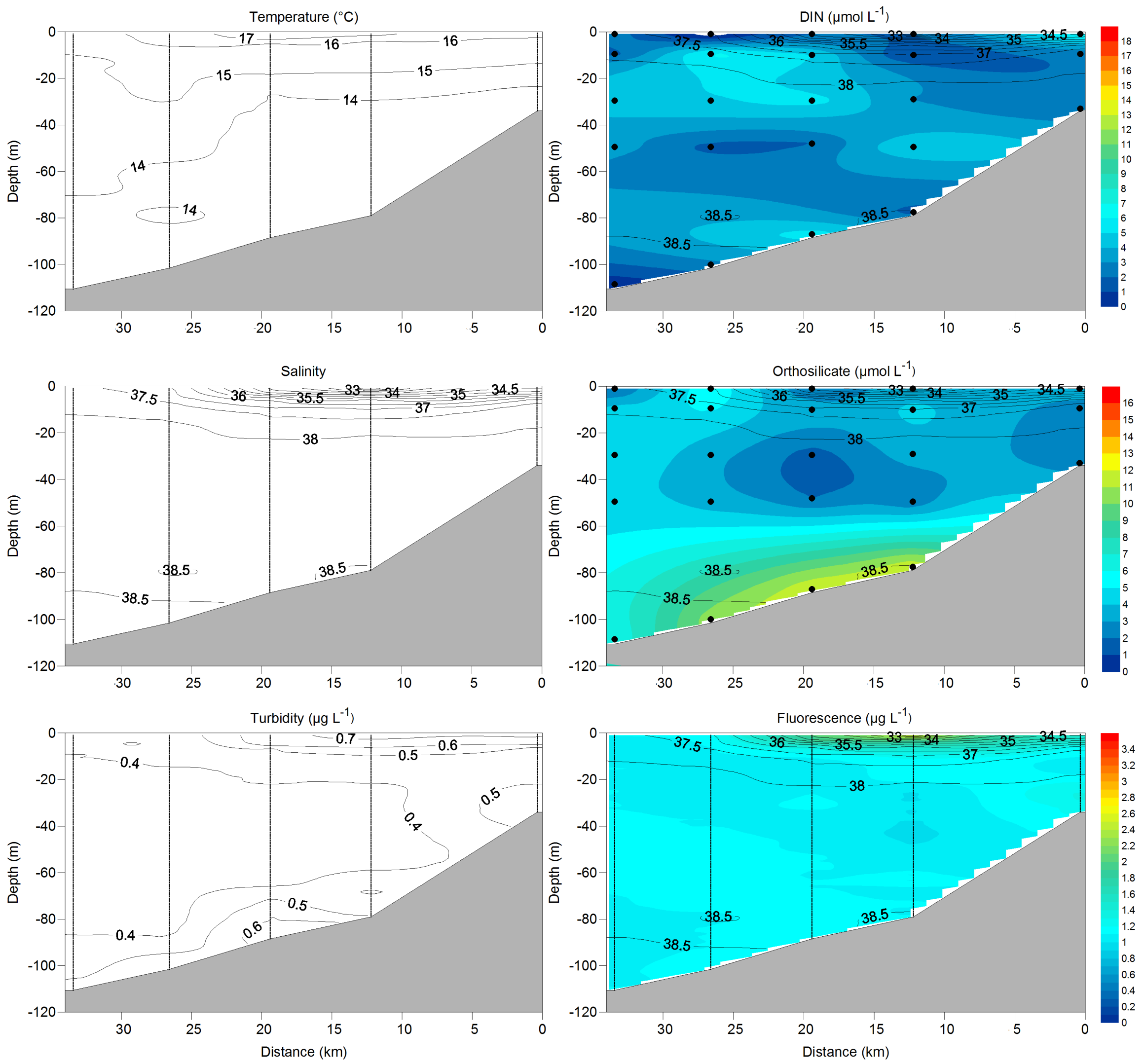

Temperature (°C)
DIN (μmol L-1)
Salinity
Orthosilicate (μmol L-1)
Turbidity (μg L-1)
Fluorescence (μg L-1)
Depth (m)
Distance (km)

Fig. 10