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Po River Plume Influence on Marine Biochemical Properties along the Western Adriatic Coast

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Abstract

An international research program was devoted to understanding the dynamic properties of the mesoscale circulation in the Adriatic Sea such as fronts, eddies, coastal filaments, river inflow and study the effects of forcing by winds and river run-offs. The present work focuses specifically on the impact of the Po river outflow on the biochemical properties along the western Adriatic coast under different conditions of river discharge and wind stress in winter and spring.

In the winter cruise, the satellite images show a strong front in the northern part of the Adriatic extending from the Italian coast to the Istrian Peninsula. In situ measures showed that the northern water mass was characterized by low temperature and salinity, and high nutrient and chlorophyll concentrations due to a strong Bora event which expanded the Po River plume towards the Istrian Peninsula instead of southwards in the West Adriatic Current. During the spring cruise, wind forcing was quite weak and the volume flux from the Po River was about one third of its mean discharge for this period of the year. Off the Po River, the water column was characterized by a surface layer with low salinity and high dissolved inorganic nitrogen and chlorophyll. This water mass did not extend as far eastwards as in winter because the wind forcing was not nearly as important and the alongshore plume extended southward along the Italian Coast.

1 Introduction

The Adriatic Sea is the most continental basin of the Mediterranean Sea. It lies between the Italian peninsula and the Balkans and is elongated longitudinally, with its major axis (about 800 km by 200 km) in NW-SE direction. The basin shows clear morphological differences along both the longitudinal and the transversal axes and has been divided into northern, middle and southern sub-basins [1]. The Adriatic Sea has a complicated morphology and bathymetry. The western coast is low and generally sandy, while the eastern coast is rugged, with multiple islands and coves. The northern sub-basin, extending from the northernmost coastline to the 100 m bathymetric line, is extremely shallow (mean depth ∼30 m) with a very weak bathymetric gradient along its major axis. It is characterized by strong river runoff; indeed, the Po and the other northern Italian rivers are believed to contribute about 20% of the whole Mediterranean river runoff [2]. The middle Adriatic is a transition zone between northern and southern sub-basins, with the three Jabuka depressions reaching a depth of 270 m. The southern subbasin is characterised by a wide depression about 1200 m in depth. Water exchange with the Mediterranean takes place through the Otranto Straits, which has an 800 m deep sill. The present study focuses on the northern and central continental Adriatic margin, where circulation is mainly controlled by wind stress and river discharge. Two main currents are present in Adriatic: the West Adriatic Current (WAC), that flows towards south-east, along the western coast, and the East Adriatic Current (EAC) flowing towards north-west along the eastern cost [1, 3]. Being a continental basin, the Adriatic Sea circulation and water masses are strongly influenced by atmospheric conditions, primarily winds [4, 5]. The major winds blowing over the Adriatic Sea are Bora and Sirocco. Bora winds are generally from the northeast and are associated with a high-pressure system over central Europe [6]. Bora is a cold and dry wind where air spills through gaps in the Dinaric Alps (the mountain range situated along the Adriatic's eastern shore), resulting in intense wind jets due to catabatic effects at specific points of the Adriatic eastern coast [7]. The Bora wind system causes the sea surface to rise near the western coast generating a coastal current towards the south, the western adriatic current (WAC). Historical data and numerical simulations have demonstrated that Bora winds can cause the formation of a double gyre structure consisting in a larger cyclone in front of the Po River delta and a smaller anticyclone to the South [7]. In winter, the cold, dry Bora winds cause strong heat losses in the Northern Adriatic and formation of the Northern Adriatic Deep Water (NAdDW). Another factor influencing the NAdDW formation is the water flux, mainly governed by the Po River runoff, which can lower the salinity, and hence the density, of the NAdDW. Vilibic [8] demonstrated the relationships between NadDW formation, heat fluxes and autumn Po River runoff.

The Sirocco wind is generally from the southeast, and is associated with a low pressure system over the Tyrrhenian Sea. Sirocco is a warm and humid wind and often causes flooding events in the shallow lagoons along the Adriatic coast including Venice. Coming from the southeast over the sea, the Sirocco is less subject to local variations than the Bora, but it does show some geographical variations due to the coastal orography. It tends to be southerly in the strait of Otranto and off Istrian Peninsula (Pula), and more easterly at some places along the northern Adriatic coast near Ravenna and Pesaro [7].

River runoff is particularly strong in the northern basin and affects the circulation through buoyancy input and the ecosystem by introducing large fluxes of nutrients [9]. Freshwater is discharged into the northern Adriatic from major rivers along the North and Northwest coasts. The Po River represents the major buoyancy input with an annual mean discharge rate of 1500-1700 m^3/s, accounting for about one third of the total riverine freshwater input in the Adriatic [10]. Runoff is also responsible for making the Adriatic a dilution basin. The riverine water discharged into the northern Adriatic forms a buoyant coastal layer that flows southward along the Italian coast. Since the Po River is the main source of this water, the coastal layer is predominantly south of the Po River delta and is named Western Coastal Layer (WCL, [7]). It is associated with a strong near- surface current, which flushes the nutrient rich water out of the northern Adriatic along the Italian coast [11, 12, 13]. The principal compensating inflow occurs along the eastern boundary in the EAC where warm, high salinity modified Levantine Intermediate Water (LIW) is advected northward.

Kourafalou [14] elucidated the role of the major Adriatic rivers in creating buoyancy-driven coastal currents that are essential in maintaining the cyclonic circulation.

The intent of this study is to examine the Po River plume influence on nutrients and hydrological properties along the western Adriatic coast under varying conditions of river discharge and wind stress during winter and spring.

2 Material and Methods

The data for this study were gathered in the central and northern Adriatic Sea during two oceanographic cruises aboard the R/V Knorr (Woods Hole Oceanographic Institution) during the periods from January 31 to February 24, 2003 (winter) and from May 26 to June 15, 2003 (late spring) and during a cruise aboard the R/V G. Dallaporta (ISMAR-CNR) 12-20 February, 2003. Observations were gathered using three primary modes of sampling: underway mapping of near-surface seawater utilizing the ship's uncontaminated seawater distribution system, vertical profiling with a CTD/rosette system, and three-dimensional mapping using a towed undulating vehicle equipped with a CTD. Water samples were analyzed for nutrients and chlorophyll a. The surface water samples were collected using a bucket during underway mapping, and 10 L Niskin bottles at hydrographic stations. The CTD data were collected by a SeaBrid SBE 911-plus probe equipped with a Wetlabs ECO-AFL fluorometer. The 24 Hz CTD data were processed according to UNESCO [16] standards, obtaining pressure-averaged data (0.5 db intervals). Nutrient samples were filtered (GF/F Whatman) and stored at -22 °C in polyethylene vials, or analysed on board immediately after collection (winter cruise). Nutrient concentrations (ammonium-NH4, nitrite-NO_2, nitrate-NO_3, orthophosphate-PO4 and orthosilicate-Si(OH)4) were measured using a Technicon TRAACS 800 autoanalyzer. Data analyses was carried out using the AACE software supplied by Bran+Luebbe. Nutrient analyses utilized modifications of the procedures developed by Strickland and Parsons [17]. Dissolved inorganic nitrogen (DIN) was calculated as the sum of the NH4, NO_2 and NO_3 concentrations. Chlorophyll a concentrations were measured fluorometrically. One hundred ml. samples were filtered through a 25 mm Whatman GF/F filter. Filters were extracted for 24 hours in 90% acetone at -4°C, then analyzed on a Turner Designs 10-005 fluorometer. Chlorophyll was calculated according to Holm-Hansen et al. [18]. Contoured vertical sections of the data were plotted using the kriging interpolation method (software Surfer 8.0).

During each cruise, the sampling strategy was intended to focus on the basin response to strong physical forcing. During winter, Bora winds and the Po River freshwater input were the two major sources of forcing. The spring cruise was planned for the period when climatologically a freshet of the Po River flow occurs (Figure 1). The ships tracks / mapping grids were based on the analyses of meteorological data and on the location of specific features including the Po River plume observed from AVHRR and SeaWiFS imagery (Figures 2, 3, 5 and 6). Figure 1 shows the daily average Po River flow for the year of 2003 and the 14-year mean of the daily average flow from 1989-2002.

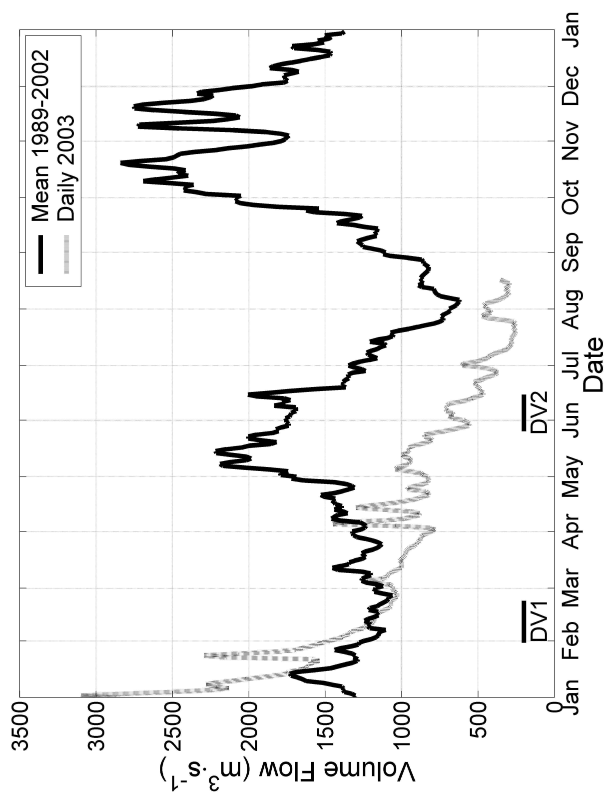


Figure 1: Daily averages of the Po River flow for the period 1989-2002. The solid line is the annual average for the period 1989-2002 and the dashed line is the daily flow for 2003 (DV1: period of the wintertime cruise, DV2: period of the springtime cruise), from [15].

3 Results

3.1 Physical characterization of the water masses

During the winter cruise (31 January – 23 February 2003) two Bora wind events occurred between 11 and 19 February resulting in distinct circulation patterns in the northern Adriatic [19, 6, 20]. Intense wind stress associated with Bora jets from Trieste and Senj drew a cold, fresh plume of Po River water across to northern basin. The Bora winds caused the plume to expand northeastward towards the Istrian coast between a northern cyclonic gyre and an anticyclonic circulation to the south ([19], Figure 1). Another front that extended westward from the southern tip of Istria separated the smaller anticyclonic gyre from a larger cyclonic gyre to the south. Remotely sensed surface temperature and ocean color showed a strong front in the northern part of the Adriatic extend-

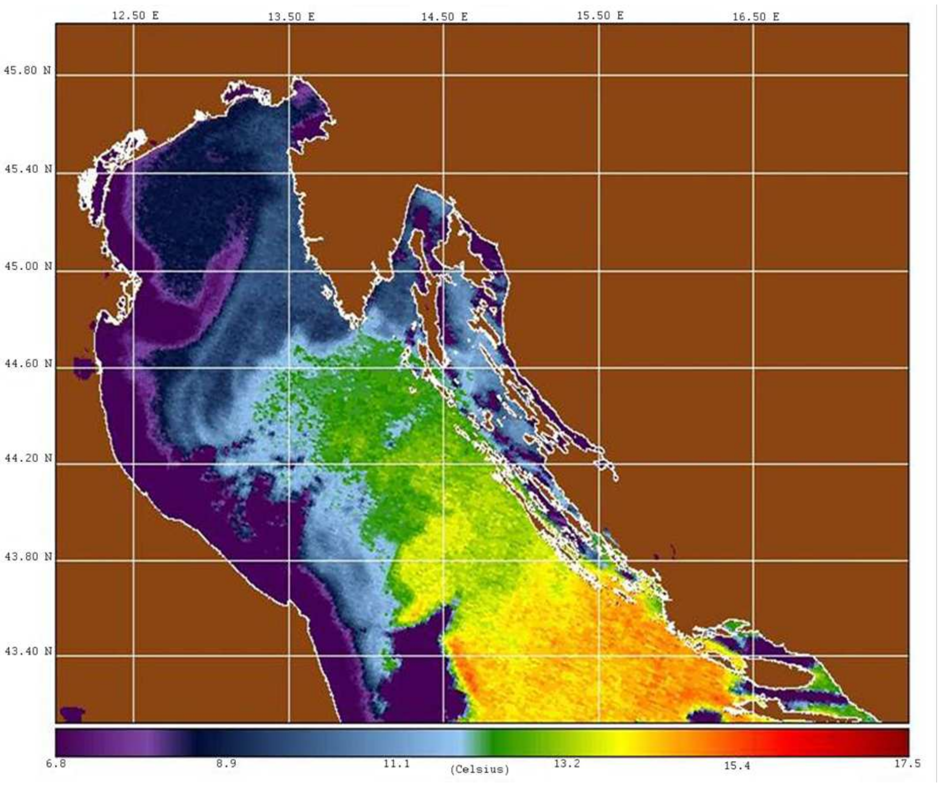


Figure 2: Sea surface temperature map from the AVHRR-NOAA-12, NRL (19 February 2003), from [15].

ing from Ravenna on the Italian coast to the northwestern corner of the Istrian Peninsula and southward along the western (Italian) boundary of the Adriatic Sea (Figures 2 and 3).In situ measurements indicated cooler, fresher water to the north and warmer, saltier water to the south of the front located southern tip of Istria (Figure 4 a and b).

During the late spring cruise (26 May – 15 June 2003), wind forcing was weak and volume flux from the Po River was about one third of its 14-year average discharge for this period (Figure 1). Despite the low discharge flux, from the river, the Po plume remained a significant feature in the northern and western Adriatic. Satellite images (Figures 5 and 6) showed a strong color front along the western boundary that divides the higher chlorophyll coastal water from the more oligotrophic mid-basin and eastern boundary Adriatic waters (Figure 6). Offshore from the mouth of the Po River, the surface layer was characterized by low salinity and high temperature (Figure 7a, b). The Po plume extended much more eastward in late spring than in winter because the vertical mixing is reduced

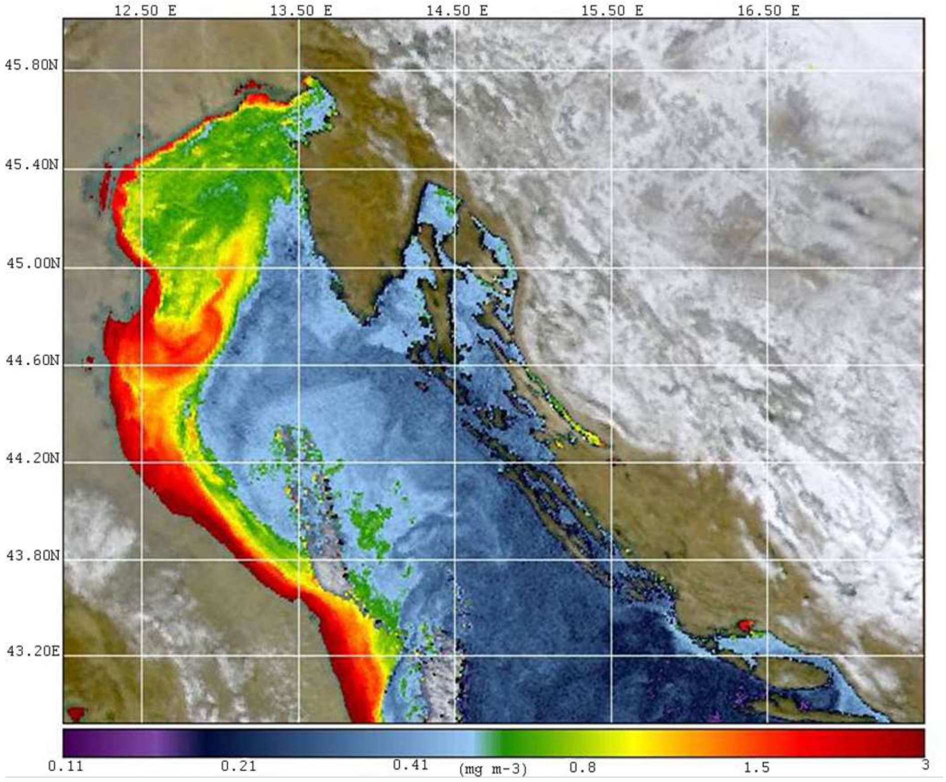


Figure 3: SeaWiFS image of chlorophyll concentration for 20 February 2003 (provide by NRL), from [15].

[7]. However, the plume extended southward along the Italian Coast.

3.2 Large Scale Surface Characterization of Biochemical properties

During the winter observations, DIN concentrations were high along the western boundary and decreased rapidly toward the east forming a strong front along the western side of the Adriatic (Figure 4c). This frontal structure extended southward from the Po River discharge consistent with the pattern of the seasonal circulation. The thermohaline circulation [7] advected the nitrate-rich river plume water southward, bound to a relatively narrow band along the Italian coast. The orthosilicate distribution was quite similar to that of nitrate (Figure 4d). On the eastern side of the basin, south of the Istrian Peninsula a strong temperature front and silicate gradient were present, resulting from the eastward extension of the Po River plume in response to the Bora winds. The phosphate distribution did not show such a clear gradient in the region south of the Istrian Peninsula (Figure 4e) because minimum concentrations were sometimes found in the coastal waters and increase toward offshore. Thus, the northern Adriatic basin tended to be phosphorus limited despite the large river input.

During late spring the temperature and salinity patterns (Figure 7a,b) showed a broader warm, low salinity river plume band extending southward along the Italian coast. The central northern basin was better sampled during the spring cruise than during the winter cruise. Relatively low nutrient concentrations were detected in the offshore and eastern boundary regions of the northern basin (Figure 7c, d).

The overall pattern was similar between winter and summer with the nutrient-rich surface waters along the western boundary advected southward. Some mixing of this coastal water with middle Adriatic surface waters was evident; in particular during the winter a nutrient grading decreased toward offshore while in late spring filaments were present.

3.3 Vertical Characterization

3.3.1 Winter

In addition to the surface mapping and towed vehicle mapping carried out on this expedition several transects with CTD/rosette profiling were obtained. Two transects each from the winter cruise and from the spring cruise are shown in Figures 8 and 9 (winter) and Figures 10 and 11 (spring). The locations for the winter transects (indicated in Figure 4f) were across Po River plume (Figure 8) and off Pesaro (Figure 9). Similarly, the spring cruise transects (locations indicated in Figure 7f) were in the Po River plume (Figure 10) and in a filament extending eastward off Vasto (Figure 11). Nutrient concentrations and chlorophyll a concentrations are shown as color shading and salinity is overlaid as contour lines.

The core of the Po River plume during the winter was indicated by the nearsurface salinity minimum midway in the section. Salinity induced stratification was very strong in the core of the plume and relatively weak at the either end of this section (Figure 8). Except for a single sample near surface in the core of the plume, chlorophyll concentrations were lower within the plume and higher at the boundaries where salinity was greater than 38. The chlorophyll distribution was confirmed by the towed vehicle mapping that showed lower chlorophyll concentrations within the plume and higher chlorophyll values in the higher-salinity water masses to either side of the plume (not shown).The role of the Po plume in providing a significant flux of nutrients into the northern basin was indicated by the high DIN (about 10 μM) and orthosilicate (about 5 μM) concentrations associated with the salinity minimum of the plume (Figure 8, top and middle panels).

The Pesaro transect was about 100 km south of the Po River delta (Figure 4). During the winter cruise, the water column was well mixed vertically at each of the four stations in the transect (Figure 9). The salinity showed that the cross-shelf section was somewhat complex with lower salinities found both near shore and at the third station (about 18 km offshore), indicating confluence of different water masses. The lowest salinities (<38.1) and high levels of suspended particulate matter (beam attenuation $>$ 5 m-1, not shown) occurred nearest to the coast indicating the influence of the river input (Figure 9). The highest chlorophyll concentrations were also observed within the lower salinity water near-shore in this transect. The chlorophyll a concentrations were vertically homogeneous in the station nearest to the coast and decreased to the east (0.5 μgl^{-1}). Nutrient values were higher (DIN $\sim$ 1.5-1.8 μM) near the coast and lowest offshore, consistent with the salinity gradient and the riverine source of the nutrients (Figure 9). Silicate concentrations were highest at the third station offshore (about 18 km in Figure 9) at middepth where salinities were less than 33.2. Nutrient values were much lower than those observed nearer the mouth of the Po River, presumably due mixing and perhaps uptake by phytoplankton.

3.3.2 Spring

During the spring cruise another section was made through the Po plume, but this time perpendicular to the coast rather than parallel to the coast. The wind forcing was much weaker during the spring cruise, and as a result stratification was much stronger. The highest chlorophyll a values from bottle samples, nearly 15 μgl^{-1}, occured near surface in the low salinity water and decreased monotonically offshore (Figure 10, bottom). The near-surface region where chlorophyll was high corresponded with the area where orthosilicate concentrations were quite low. Moderate values of 1–2 μgl^{-1} were observed near the bottom at the offshore end of the section. It was not clear from this hydrographic transect whether this near-bottom chlorophyll was the edge of a subsurface chlorophyll maximum typical of regions away from the direct influence of the Po plume.

The distribution of nutrient values (Figure 10) showed that, with strong water column stratification, DIN concentrations were highest (10-12 μM) near surface where the lowest salinities were observed. Orthosilicate distributions showed the opposite pattern with concentrations generally less than 2 μM in the surface layer and high values in the lower half of the water column (Figure 10, middle panel). The highest concentrations of $>$15 μM were observed where salinity was $>$38. The distribution of orthosilicate did not appear to be controlled by river inputs but by the active consumption by phytoplankton as reported by Cozzi et al. [21].

About 330 km southeast from the Po River delta in the southern part of the central basin, a transect was obtained through a filament distinguishable in ocean color (Figure 6) was observed extending offshore toward the east from the inshore region. A hydrographic section was obtained through the feature to determine its characteristics (Figure 7f). The filament was distinctly evident near-surface where salinities were less than 38.5, particularly near-surface at the two central stations (Figure 11). The thickness of this low salinity filament was less than 20 meters.Despite the evidence from the ocean color image, near-surface chlorophyll within the filament was low, $<$0.5 μgl^{-1} and maximum chlorophyll of up to 0.9 μgl^{-1} was observed in the chlorophyll maximum at depths of 70–75 m (Figure 11). Higher near-surface concentrations of DIN and orthosilicate values were associated with the low-salinity core of the filament. However, the highest concentrations of DIN and orthosilicate were observed below 100 m. There was some complexity to this distribution with higher DIN present near surface outside the filament in high-salinity surface at the station located at about 22 km, the southern end of the section. Below 100 m the silicate and DIN distributions also differ. Highest orthosilicate concentrations occurred at either end of the transect, whereas DIN values were lower at the southern end of the transect.

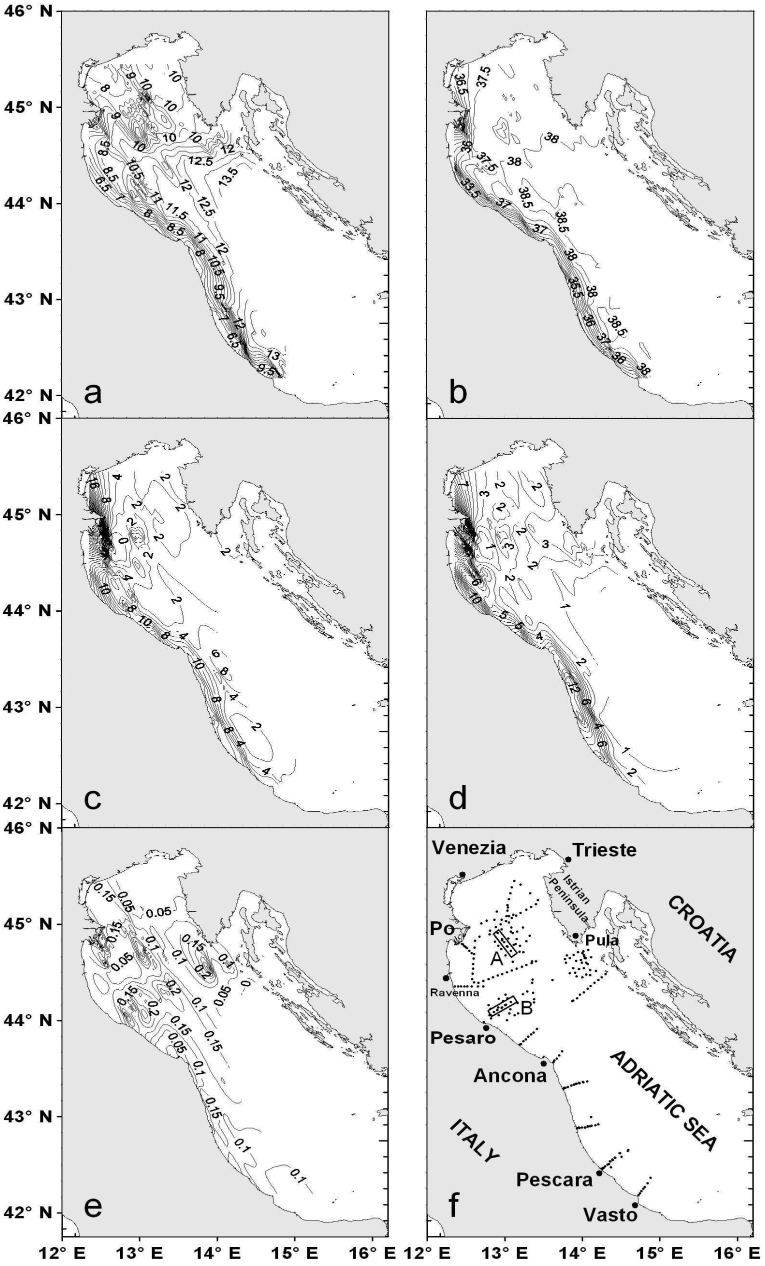


Figure 4: Winter surface field of: a) temperature (°C), contour interval is 0.5, b) salinity, contour interval is 0.5; c) DIN (μM), contour interval is 2; d) Orthosilicate (μM), contour interval is 1; e) Orthophosphate (μM), contour interval is 0.05; f) the rectangles indicate the Po (A) and Pesaro (B) transects. The dots represent the sampling points, from [15].

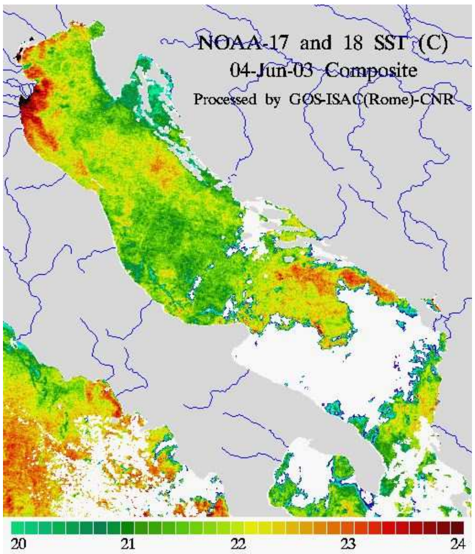


Figure 5: Sea surface temperature map from the NOAA-16, GOS-ISAC-CNR (04 June 2003), from [15].

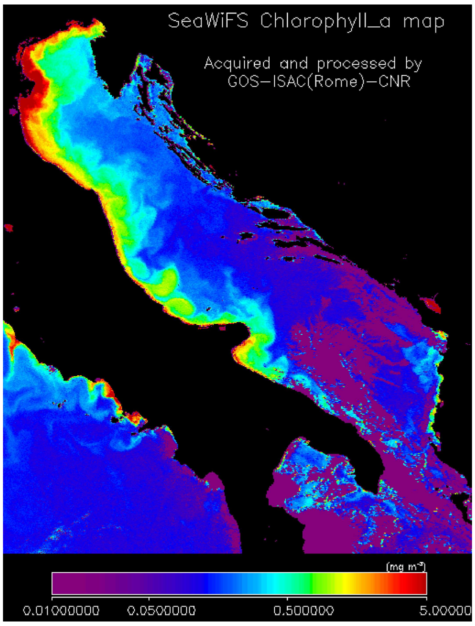


Figure 6: SeaWiFS image of chlorophyll concentration for 4 June 2003 (provide by GOS-ISAC-CNR), from [15].

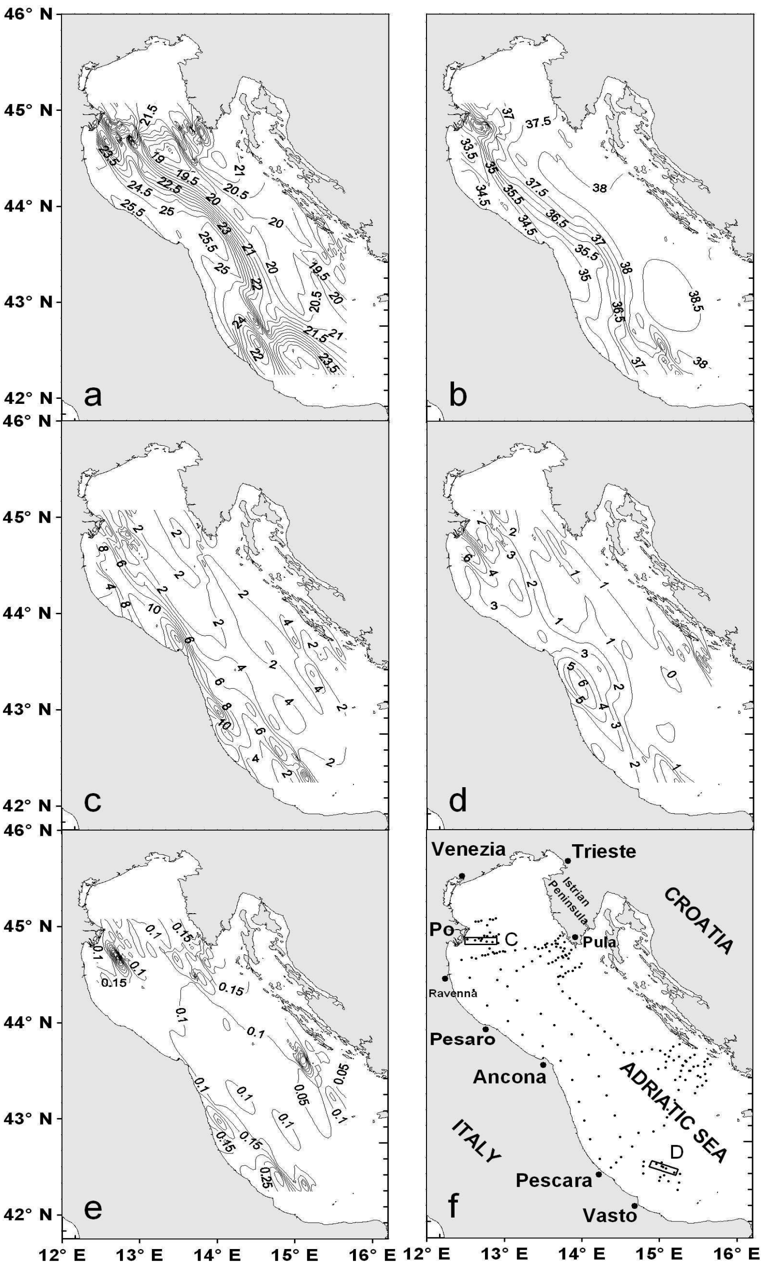


Figure 7: Late spring surface field of: a) temperature (°C), contour interval is 0.5, b) salinity, contour interval is 0.5; c) DIN (μM), contour interval is 2; d) Orthosilicate (μM), contour interval is 1; e) Orthophosphate (μM), contour interval is 0.05; f) the rectangles indicate the Po (C) and Vasto (D) transects. The dots represent the sampling points, from Marini et al. [15].

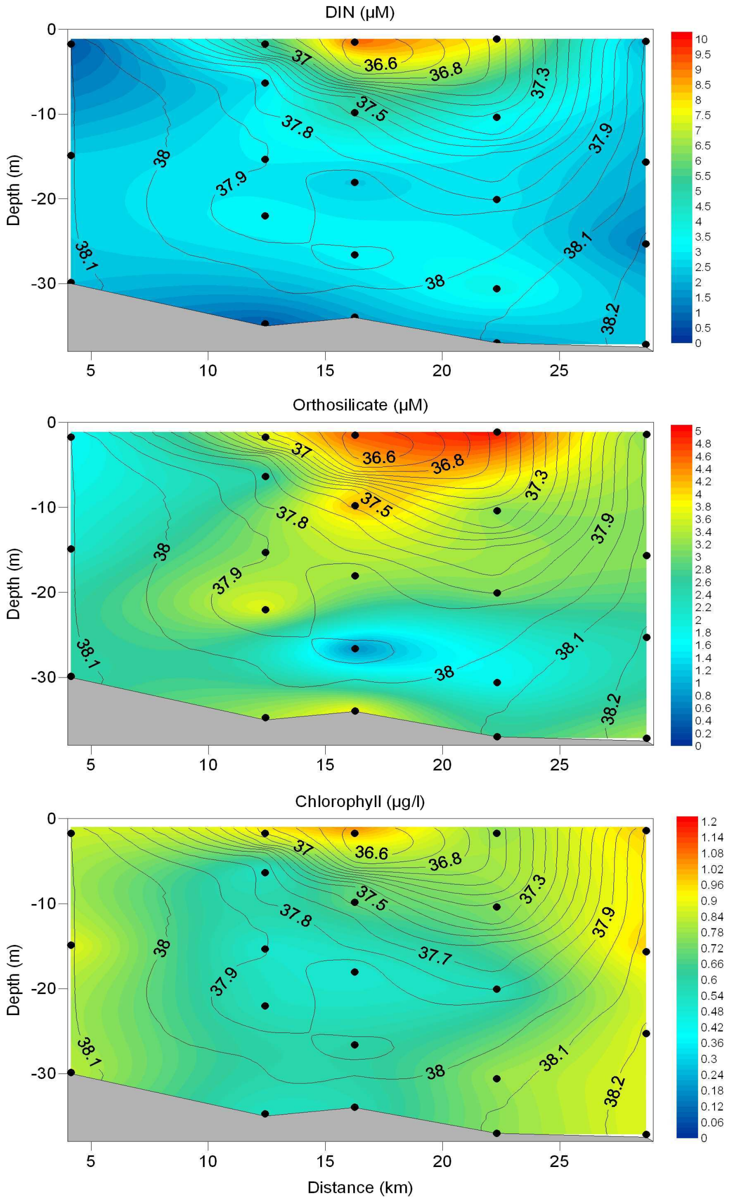


Figure 8: Po transect during winter cruise (February 21, 2003) of DIN, Orthosilicate and chlorophyll a concentration (colored shading). The black contours represent the salinity (contour interval 0.1) and the dots represent the sampling points. The position of the transect is plotted in Figure 4f, from Marini et al. [15].

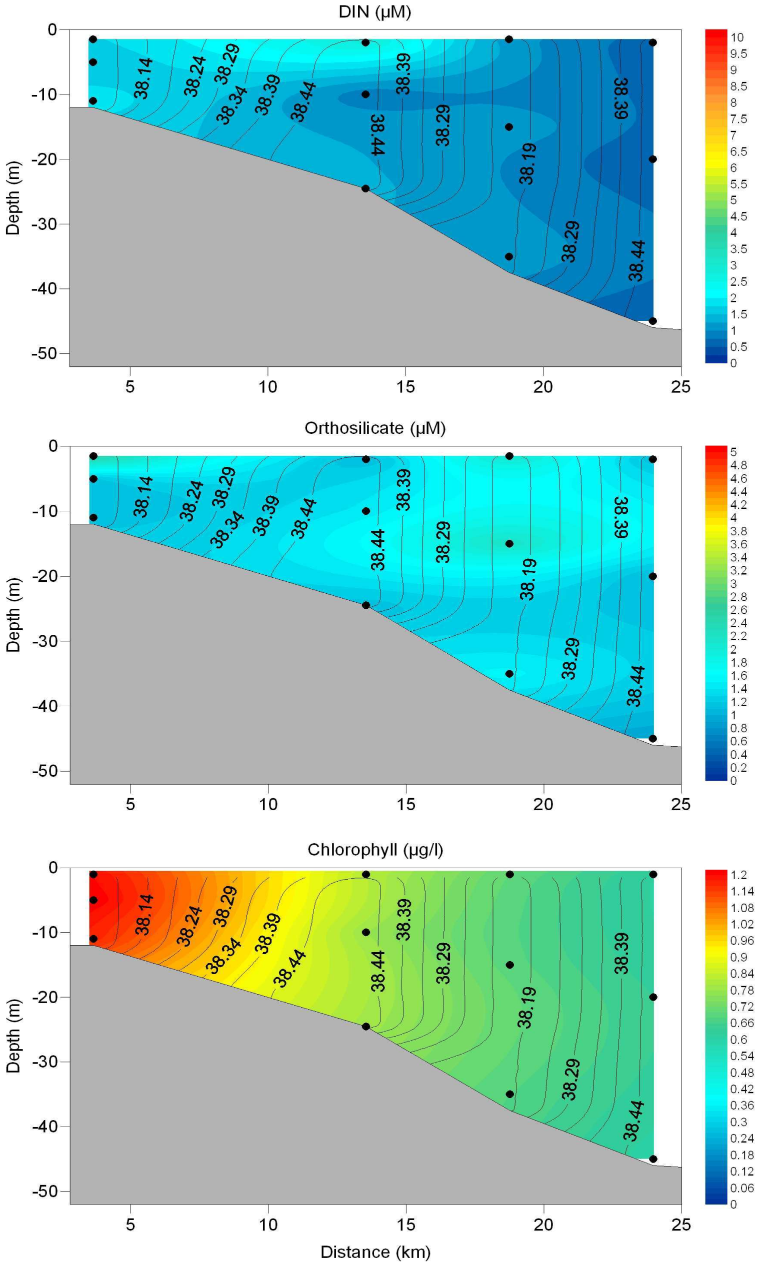


Figure 9: Pesaro transect during winter cruise (February 18, 2003) of DIN, Orthosilicate and chlorophyll a concentration (colored shading). The black contours represent the salinity (contour interval 0.1) and the dots represent the sampling points. The position of the transect is plotted in Figure 4 f, from [15].

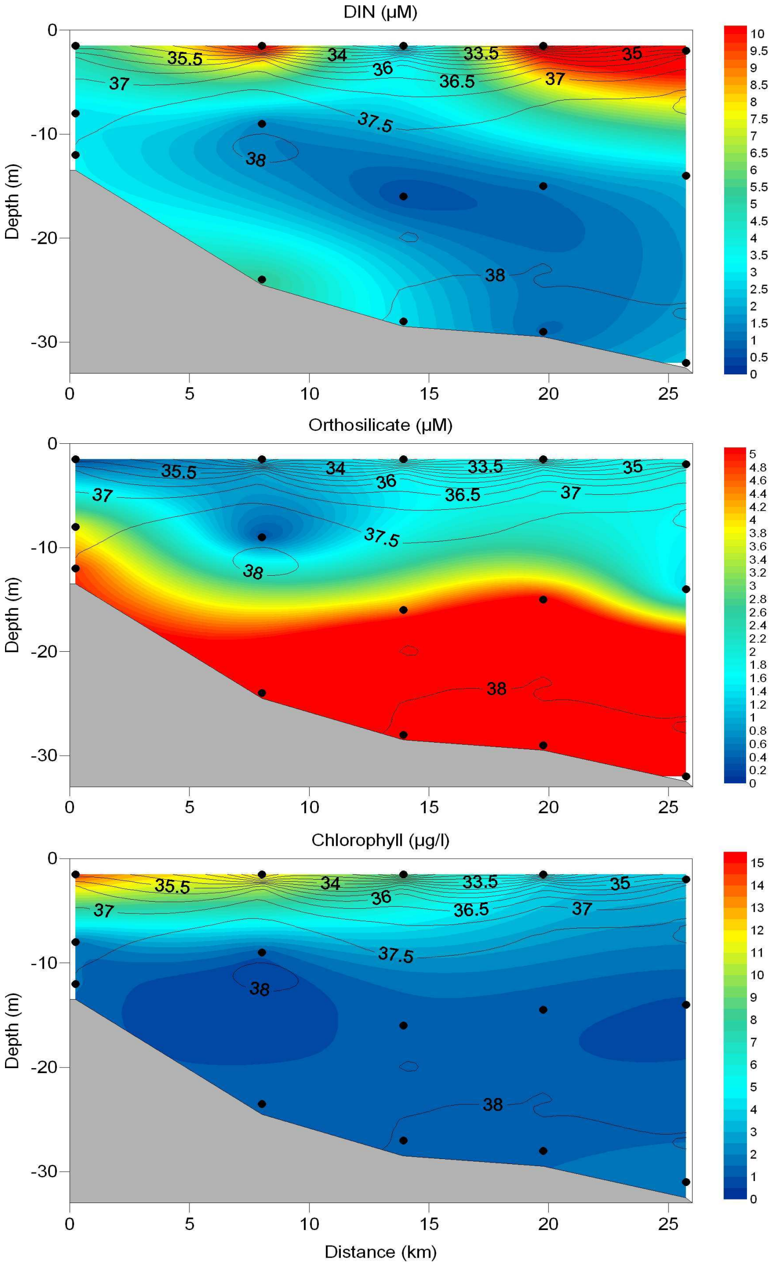


Figure 10: Po transect during late spring cruise (June 08, 2003) of DIN, Orthosilicate and chlorophyll a concentration (colored shading). The black contours represent the salinity (contour interval 0.1) and the dots represent the sampling points. The position of the transect is plotted in Figure 7f, from Marini et al. [15].

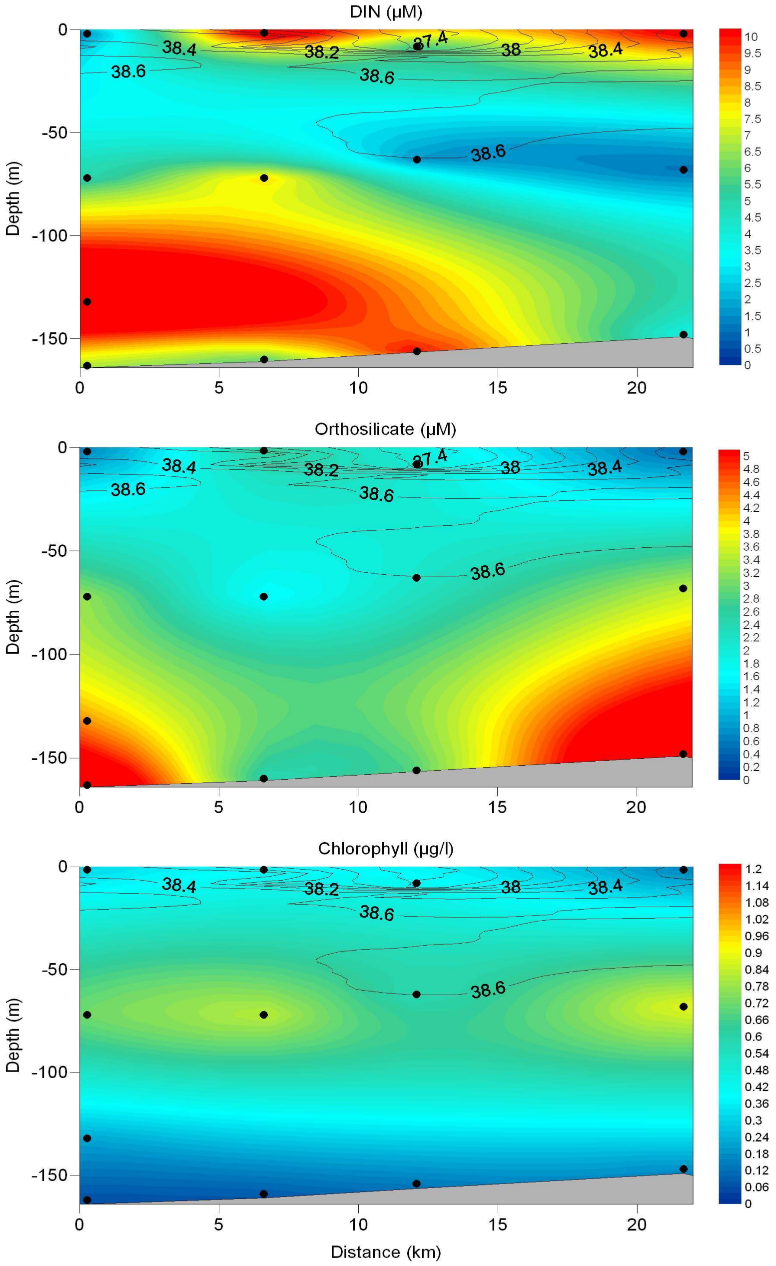


Figure 11: Vasto transect during late spring cruise (June 13, 2003) of DIN, Orthosilicate and chlorophyll a concentration (colored shading). The black contours represent the salinity (contour interval 0.1) and the dots represent the sampling points. The position of the transect is plotted in Figure 7f, from Marini et al. [15].

DV1 January 31, 2003 - February 24, 2003							
	Temperature (*degree C*)	Salinity (*PSU*)	$Si(OH)_4$ (μM)	DIN (μM)	PO_4 (μM)	DIN/Si (μM)	Chl *a* ($\mu g/l$)
Po Survey (surface) S < 37.5	7.06 ± 0.34	37.02 ± 0.32	4.03 ± 1.12	6.51 ± 3.69	0.17 ± 0.12	1.51 ± 0.59	0.88(12) ± 0.20
Po Survey (surface) S > 37.5	8.71 ± 0.54	37.91 ± 0.11	2.20 ± 0.90	1.50 ± 0.83	0.11 ± 0.06	0.74 ± 0.42	0.79(20) ± 0.19
Istria Survey (Surface) S < 38.15	10.08 ± 0.46	37.84 ± 0.14	3.77 ± 0.51	1.97 ± 1.07	0.18 ± 0.12	0.53 ± 0.31	0.63(13) ± 0.05
Istria Survey (Surface) S > 38.15	12.17 ± 0.27	38.32 ± 0.03	1.95 ± 0.24	0.97 ± 0.29	0.15 ± 0.11	0.50 ± 0.15	0.45(13) ± 0.04
Pesaro Survey (Surface) S < 38.2	9.62 ± 0.76	37.94 ± 0.18	2.30 ± 0.94	2.17 ± 1.22	0.24 ± 0.07	1.07 ± 1.05	0.91(15) ± 0.32
Pesaro Survey (Surface) S > 38.2	11.39 ± 0.55	38.38 ± 0.07	1.60 ± 0.52	1.06 ± 0.60	0.22 ± 0.07	0.76 ± 0.61	0.63(13) ± 0.13

Table 1: The winter cruise (January 31- February 24, 2003) parameters for distinguished two water masses in three areas, in brackets number of data ± Standard Deviation.

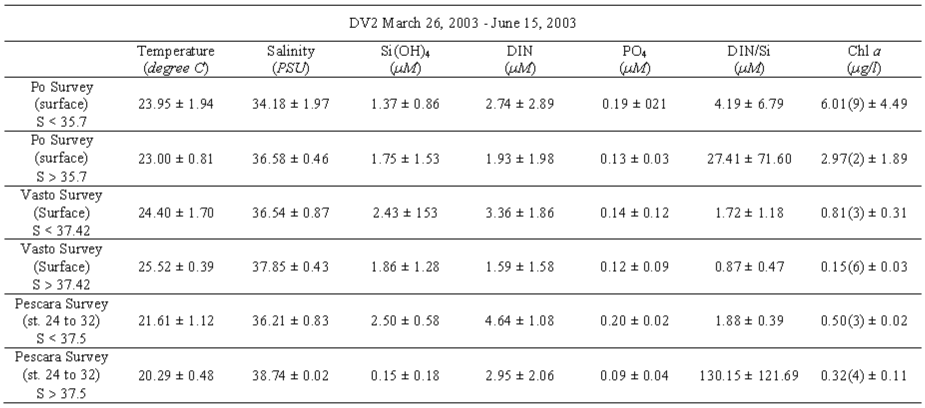
4 Discussion

4.1 Winter characterization of northern and western Adriatic Sea

In the northern Adriatic Sea, during winter period, Bora winds are frequent, intense, narrow sea surface wind jets coming from the northeast through the mountain passages along the eastern side (e.g., [7]). During the winter cruise, two sequential Bora events occurred during 11-19 February [19, 6, 20].

In order to describe the simultaneous influence of Bora wind and Po plume on the distribution of the water masses in the northern and western part of the Adriatic Sea, three areas have been compared: Po plume area, Pula area and Pesaro area.

Some biochemical characteristics of the water masses have been described in this period. Salinity was used to discriminate water masses in the three areas investigated and two different water masses in each regions were found (Table 1). Water unaffected by river runoff generally had salinities equal to or greater than 38.5, which characterizes North Adriatic DeepWater (e.g., [3]). The water mass influenced by river runoff was fresher, colder, richer in chlorophyll a, orthosilicates, DIN, and DIN/orthosilicates ratio, and confined to the northern Adriatic, between the Po Delta and the Istrian peninsula, and along the western Adriatic coast. Farther offshore a more saline water mass was warmer and less nutrient-rich. The two water masses, always present in the three surveys, were compared and the results were summarized in Table 1. The northern region where salinity was less than 37.5 was strongly impacted by Po River runoff, in particular high concentrations of DIN, orthosilicates and DIN/orthosilicates ratio were found. A DIN/orthosilicate ratio close to 1 is good for diatom phytoplankton growth as examined by Redfield et al. [22] and Brzezinski [23]. High surface values of nutrients were evident in vertical transect across the Po river plume (Figure 8) concurrent with low salinity down to 20 m depth in the



	DV2 March 26, 2003 - June 15, 2003						
	Temperature (*degree C*)	Salinity (*PSU*)	Si(OH)$_4$ (*μM*)	DIN (*μM*)	PO$_4$ (*μM*)	DIN/Si (*μM*)	Chl *a* (*μg/l*)
Po Survey (surface) S < 35.7	23.95 ± 1.94	34.18 ± 1.97	1.37 ± 0.86	2.74 ± 2.89	0.19 ± 021	4.19 ± 6.79	6.01(9) ± 4.49
Po Survey (surface) S > 35.7	23.00 ± 0.81	36.58 ± 0.46	1.75 ± 1.53	1.93 ± 1.98	0.13 ± 0.03	27.41 ± 71.60	2.97(2) ± 1.89
Vasto Survey (Surface) S < 37.42	24.40 ± 1.70	36.54 ± 0.87	2.43 ± 153	3.36 ± 1.86	0.14 ± 0.12	1.72 ± 1.18	0.81(3) ± 0.31
Vasto Survey (Surface) S > 37.42	25.52 ± 0.39	37.85 ± 0.43	1.86 ± 1.28	1.59 ± 1.58	0.12 ± 0.09	0.87 ± 0.47	0.15(6) ± 0.03
Pescara Survey (st. 24 to 32) S < 37.5	21.61 ± 1.12	36.21 ± 0.83	2.50 ± 0.58	4.64 ± 1.08	0.20 ± 0.02	1.88 ± 0.39	0.50(3) ± 0.02
Pescara Survey (st. 24 to 32) S > 37.5	20.29 ± 0.48	38.74 ± 0.02	0.15 ± 0.18	2.95 ± 2.06	0.09 ± 0.04	130.15 ± 121.69	0.32(4) ± 0.11

Table 2: The late spring cruise (March 26 - June 15, 2003) parameters for distinguished two water masses in three areas, in brackets number of data ± Standard Deviation.

core of the plume. South of the Po plume and east of Pesaro, DIN and orthosilicate values decrease and temperature and salinity increase (Table 1). In Figure 9, DIN, orthosilicates and chlorophyll a concentrations decrease from the cost toward offshore while the salinity increased. The influence of Po River discharge is quite evident in the northern Adriatic area and along the western coast in front of Pesaro (Figures 2, 3, and 4). DIN concentrations decrease threefold from north to south and orthosilicates decrease approximately twofold. Both temperature and salinity increase eastward and southward from the Po delta, whereas orthosilicates and DIN concentrations decrease (Table 1). South of the Istrian Peninsula, a strong front separated colder, fresher, and more DIN-rich water on the north from warmer, saltier, less DIN-rich water south of the front (Table 1). This front marks the eastern extension of the Po plume driven by strong Bora winds on either side of the plume.

Furthermore, Bignami et al. (2007) suggest that the Bora is the only wind capable of generating extensive offshore jets off the Po delta. Orthophosphate concentrations do not show much difference between the zones, indicating little or no contribution from the Po River runoff. The maximum of chlorophyll was at the edge of the plume owing to higher chlorophyll concentrations in waters outside the plume. The lower chlorophyll values within the plume may be due to cold temperature and low light concentrations within the plume, inhibiting growth of phytoplankton within the plume.

4.2 Late spring characterization of western Adriatic coast

During the late spring cruise strong stratification characterized the water column of the northern Adriatic (Figure 10). A SeaWiFS image of chlorophyll from June 4 showed the southward extension of the Po plume along the western boundary within the flow of the WAC (Figure 6). Despite the below average flow from the Po River, the buoyancy driven flow was evident along the western boundary of the basin consistent with results from models and observations (e.g., [14, 24]).

In order to evaluate the influence of Po River runoff on biochemical properties of surface waters from three areas along the western Adriatic were compared: the Po plume area and the coastal regions off Pescara and Vasto (Figure 7). As in winter, salinity was used to distinguish between the different water masses. Two water masses were identified from the late spring cruise: fresher water where salinity was generally less than about 38.2 was indicative of the influence of river inputs along the western boundary, and more saline water, greater than 38.2, was present offshore. Water mass structure showed gradient from western coast to offshore. As in winter, salinity increased toward the east, but because of the strong vertical stratification, this gradient was confined mainly to the surface layer, in contrast to the winter situation. In the fresher water of the Po plume (salinity < 35.7, Table 2) nutrient concentrations were variable. The highest concentrations of nutrients were found at intermediate salinities where $S > 35.7$. The region of the Po plume where $S>35.7$, did not show marked differences in nutrient values from the fresher water where $S<35.7$. However, DIN/orthosilicate ratios were much higher in summer than in winter period when DIN/ Si ratios were nearly all less than 2.5. The much larger DIN/ Si ratios in the spring were most likely due to higher consumption of orthosilicate by diatom phytoplankton groups in response to high light availability near the surface and stratification. Diatoms were a dominated the phytoplankton community of the Po plume (I. Cetinic, personal communication, 2005). In the bottom plot in Figure 10 the maximum surface chlorophyll a of about 15 $\mu\mathrm{gl}^{-1}$ corresponded to a minimum of orthosilicate concentration as observed by Socal et al. [25].

The Pescara region showed larger differences in the water properties between the surface coastal water and the surface offshore water (Table 2). Orthosilicate and DIN concentrations decreased from near the coast toward offshore and DIN/orthosilicates ratio increased. In contrast to winter when concentrations of nutrients decreased southward from the Po River plume, concentrations off Pescara were greater than concentrations in the Po plume area.

In the most southern region off Vasto, a filament extending from the coast toward offshore was evident in the SeaWiFS image (Figure 6). In situ measurements across the filament (Figure 11) indicated that it included less saline surface water than the water into which it advected (Table 2, average $S = 36.54 \pm 0.87$). Though the filament was generally characterized by water less than saline than 38.55, the salinity of hydrographic samples from the filament were <37.42. Outside of the filament where the salinity was greater and temperatures warmer; the mean concentrations of orthosilicates and DIN decreased (Table 2).

In all regions chlorophyll a concentration was greater in the lower salinity coastal water than in the more saline water offshore and decreased from the area of Po plume southward along the coast. A deep chlorophyll a maximum at about 70–75 m depth was present in the offshore higher salinity water where deep penetration of the light field coincided with the top of the nutricline [26].

4.3 Characterization of the Seasonal Biochemical Variations

In general the basin was characterized by decreasing nutrient gradient in the surface layer from the western boundary eastward. Nutrient values in the northern Adriatic resulted from river input not only from the Po River, but from other smaller rivers along the Italian coast. Wintertime DIN and orthosilicates values were on average twice as high as late spring concentrations in the same region (Table 1 and 1). This could be due also to both low Po River discharge and high phytoplankton uptake of nutrients during the spring, indicated by the relatively high chlorophyll concentrations within the Po plume.

During the winter cruise the Po plume was more clearly defined extending northeastward toward the Istrian Peninsula in response to strong Bora winds from Trieste and Senj, and higher, but typical, river discharge rates. During the late spring cruise, although the Po plume spread more broadly, the area south of the Istrian Peninsula appeared less influenced by the Po plume (Figures 7c and 7d) perhaps because of below average river discharge rates and the absence of strong wind forcing. The middle Adriatic showed less influence from the Po River. During springtime local river inputs contributed to the nutrient concentrations along the coast [8, 13]; in particular the Pescara and Vasto regions were characterized by nutrient concentrations similar to the Po plume region (Table 2). Nutrient and chlorophyll values were highest in the western coastal areas of the Adriatic during both seasons.

5 Conclusions

The biochemical characteristics of water masses in the northern Adriatic and the western boundary of the Adriatic have been showed. Because temperature was very non-conservative in the shallow northern region of the Adriatic, salinity was a better discriminator of water mass variability.

During winter the extent and shape of the Po plume appeared to respond to Bora winds, extending northeastward toward the Istrian Peninsula carrying highs concentrations of DIN and orthosilicate. In general, nutrient concentrations were negatively correlated with salinity, nutrients increasing with decreasing salinity. Little accumulation of phytoplankton biomass was observed within the Po plume, and nutrient values tended to be transported offshore with the freshwater. The Western Coastal Layer, observed in the Pesaro section, showed a decreasing nutrient concentrations and an increasing salinity in the offshore direction. Coastal advection transported freshwater, nutrients, and suspended material southward, dominated by physical mixing, and with limited phytoplankton growth.

In late spring, the western boundary coastal waters were characterized by lower salinity water near the coast and saltier water offshore, as in winter period. However, unlike the winter period, the onshore-to-offshore gradient is confined vertically mainly to the surface layer because of the strong stratification. During the spring cruise, low Po River runoff ($\sim$625 m^3/s) and weak wind forcing resulted in a broad spreading, vertically stratified river plume, where high phytoplankton abundance contributed to a rapid depletion of nutrients. In the central part of the Adriatic basin a filament extended offshore from the coast. In situ measurements showed that this filament is characterized by lower salinity and temperature, and higher concentrations of orthosilicates and DIN compared to the surrounding water. Alongshore advection of the plume does occur, but because of the weak mixing, relatively slow advection, nutrients are relatively low in the advected plume, phytoplankton biomass is high relative to the offshore water, but decreases rapidly alongshore and in offshore filaments because of the lack of nutrients to sustain phytoplankton growth.

DIN/orthosilicate ratios were much typically less than 2–3 during the winter when phytoplankton growth was small. Low phytoplankton growth rates were probably the result of cold temperatures, low incident light, high attenuation of light in the plume, and deeper mixing than in spring. During the late spring the DIN/orthosilicate ratios were much higher. This higher ratio in spring is indicative of enhanced phytoplankton uptake in higher illumination and stratification conditions.

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