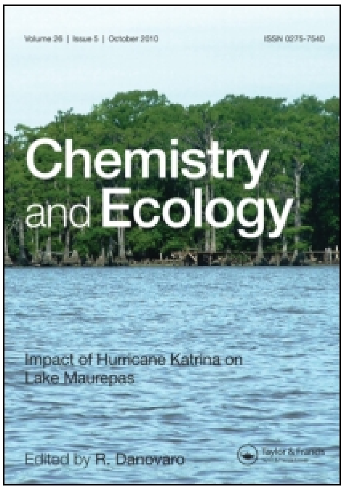


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# Particulate matter and downward flux in the Northern and Central Adriatic Sea

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# PARTICULATE MATTER AND DOWNWARD FLUX IN THE NORTHERN AND CENTRAL ADRIATIC SEA

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During four oceanographic cruises carried out in June 1996, February and June 1997, and February 1998, particulate matter characteristics and short-term downward fluxes measured with drifting sediment traps were studied in two areas of the Adriatic Sea. The investigated areas were located one south of the Po River delta, and the other in the central Adriatic between Pesaro and Ancona. In each area, a frontal system was detected and two stations inside and outside the front, *i.e.* in coastal and offshore areas, were selected.

The particulate and dissolved matter revealed a higher concentration in the coastal areas with the highest values in the central Adriatic coastal zone in both February surveys.

Total mass fluxes ranged within two orders of magnitude from 11 to 3139 mg $m^{-2}$ $d^{-1}$ in the northern area and similarly from 20 to 3864 mg $m^{-2}$ $d^{-1}$ in the southern one, with higher values in the coastal stations.

The organic carbon accounted for 3–30% of total flux in the northern coastal station with higher values in June, whereas at the offshore station it ranged from 6 to 39% in summer, decreasing to values lower than 10% in February. In the southern zone the organic carbon content was less than 2% in winter and from 3 to 33% in summer.

The organic carbon fluxes (1–82 and 6–71 mg C $m^{-2}$ $d^{-1}$ in the northern and southern area) were comparable with others measured with drifting sediment traps in the same area, though much lower with respect to those measured with long-term moored sediment traps.

The export of organic carbon from the photic layer (expressed as the percentage of primary production) in the northern area was less than 10% at the coastal station, reaching a maximum of 12% in the offshore area. In the central Adriatic area it was greater, with values reaching up to 66% at the coastal station in June 1996.

The organic carbon loss via sedimentation from the POC pool was low (*i.e.* $< 1.5\%$ per day) at both stations in the northern zone, while in the southern area the export was generally greater, exceeding 10% in the offshore area.

*Keywords*: Hydrology; circulation; Adriatic Sea; particulate matter

## INTRODUCTION

As a whole, the hydrology and circulation of the Adriatic Sea are mainly influenced by the morphology of the basin, the surface heat fluxes, and the freshwater input coming from the north-western Italian (mainly the Po River) and the south-eastern Albanian rivers. In addition, high saline water originating from the Eastern Mediterranean enters

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the Adriatic along the eastern side through the Otranto Channel (Zore-Armanda, 1969). Generally two contrasting situations occur; one characterised by the complete water column instability and mixing in winter, and the other by the stability and vertical stratification in summer (Fonda Umani *et al.*, 1992).

The Adriatic Sea is subject to horizontal and vertical discontinued thermohaline properties that lead to the development of frontal systems separating the coastal belt from the offshore water. This density gradient acts as a physical barrier that heavily influences the dissolved and particulate matter distributions and consequently the related biological and geochemical processes (Franco and Michelato, 1992).

Continental margins and shallow basins like the Adriatic Sea represent some of the most productive areas of the oceans, receiving relevant inputs from the land, both of dissolved and particulate matter. Organic fluxes in shelf and slope areas are greater than in open waters and organic matter preservation attributes to continental margins the role of preferential organic carbon deposit areas (Etcheber *et al.*, 1996).

Particulate matter settling throughout the water column is a relevant aspect in the study of biogeochemical cycles and an important source of energy for the benthic system.

Within the frame of the PRISMA II project, sub-project "Biogeochemical Cycles", the aim of this research was to study the characteristics of particulate matter, in particular the organic carbon distribution through the water column, and to evaluate the short-term transfer of biogenic material from the upper productive layers to the deeper ones, in coastal and offshore areas of the Northern and Central Adriatic Sea.



## MATERIALS AND METHODS

During four oceanographic cruises, carried out on board the R/V "U. D'Ancona" (CNR, Italy) in June 1996 (9–13, 24–25), February (7–9, 19–21) and June 1997 (6–10, 21–22), and February 1998 (3–4, 26–28), two areas of the Adriatic Sea were investigated: one located in the northern Adriatic near the Po River delta (directly influenced by the river runoff), and one in the central Adriatic between Pesaro and Ancona (Fig. 1). In each area, two stations separated by a frontal system were selected, one in the coastal diluted zone (station A and C, in the northern and central area), and the second representative of the offshore situation (station B and D in the northern and central area) outside the river plume. Due to bad weather conditions, samplings at the central Adriatic offshore station (station D) were carried out only in February and June 1997.

To estimate the export of particulate organic matter from the surface layers, short-term (12–48 h) drifting sediment trap experiments were carried out during the oceanographic cruises in each station. To assess the transformations occurring in particulate matter while settling throughout the water column, vertical particle fluxes were measured below the surface layer and near the bottom.

The drifting array consisted of two sediment traps and a Sea Bird Seacat CTD-probe coupled with the deeper trap to monitor the environmental conditions during the experiment. The sediment traps were cone-shaped with a collecting area of $0.56\,m^2$. The upper trap was deployed just below the pycnocline and/or thermocline, and the deep

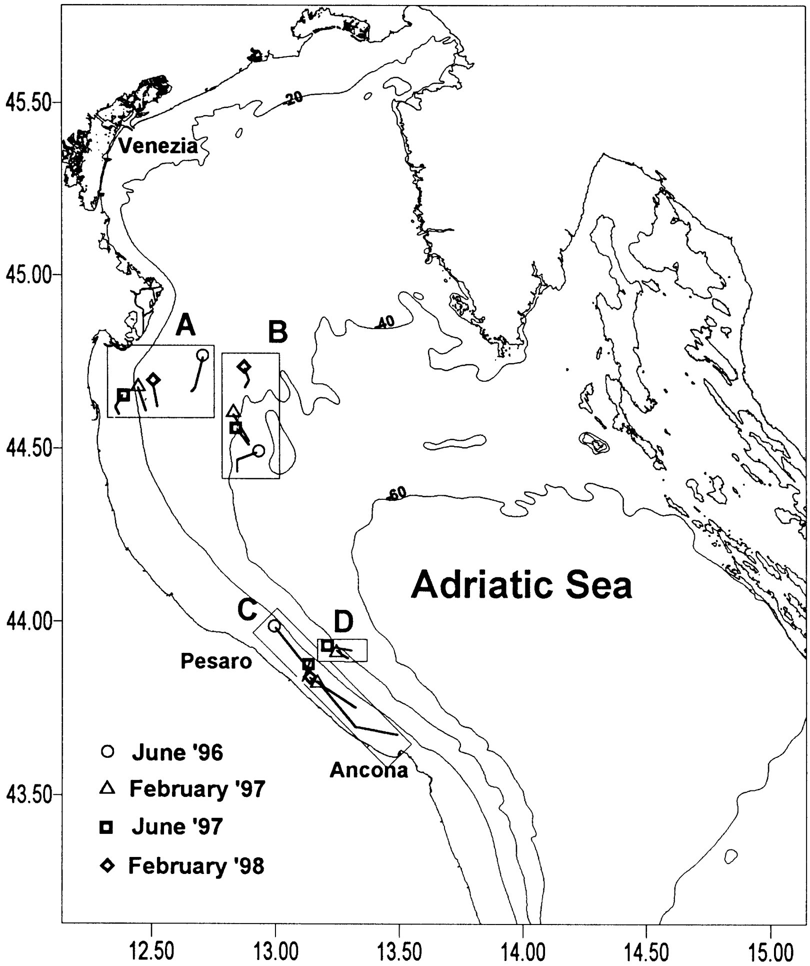


FIGURE 1 Station map and sediment trap drift tracks (symbols indicate the beginning of the track).

one was set a few metres above the sea floor. A formalin solution was added to avoid sediment trap sample degradation, after which samples were stored at 4°C.

In the laboratory, "swimmers" were removed under a dissecting microscope. Samples were then split and analysed for total mass, nitrogen, total and organic carbon content.

During these experiments, CTD vertical profiles (Idronaut Ocean Seven probe) of temperature, salinity, pH, dissolved oxygen, light transmittance and fluorescence were performed every 2 hours. Discrete water samples for Total Suspended Matter (TSM), Particulate Organic Carbon (POC), Total Particulate Nitrogen (TPN), Chlorophyll *a* concentration (CHL *a*), dissolved nutrient concentration as Dissolved Inorganic Nitrogen (DIN = ammonium + nitrite + nitrate), silicate ($Si\text{-}SiO_4$) and phosphate ($P\text{-}PO_4$), phytoplankton abundance and species composition were collected at selected depths every four to six hours. Furthermore, zooplankton net samples were collected once a day.

Samples for TSM, POC and TPN analyses were filtered on 25 mm Whatman GF/F glass fibre filters, immediately stored at −20C. TSM was determined by using a gravimetric method (Strickland and Parsons, 1972); the organic fraction was determined by the difference, after filter combustion at 480C for 4 h. POC and TPN were determined with a Perkin Elmer 2400 CHN elemental analyser. The inorganic carbon was removed from the filters by exposure to hydrochloric acid vapours (Hedges and Stern, 1984).

CHL *a* concentration was determined with a spectrophotometer after acetone extraction (Lorenzen, 1967).

Samples for nutrient analysis were immediately filtered on board with 47 mm Whatman GF/F glass fibre filters, before being deep frozen. Ammonium concentration was determined with a Technicon Autoanalyzer II; nitrite, nitrate and silicate concentrations with a Systea-Alliance mod. Integral autoanalyzer; phosphate was analysed with a Perkin Elmer Lamda 2 spectrophotometer according to Strickland and Parsons (1972).

Phytoplankton samples were fixed with a hexamethylen-tetramine buffered formalin solution; they were then counted using an inverted microscope (Utermöhl, 1958). Cell size and volume were determined according to Edler (1979) and phytoplankton carbon was obtained by multiplying cell or plasma volume by 0.11 for diatoms, coccolithophorids and flagellates and by 0.13 for thecate dinoflagellates (Smetacek, 1975).

Zooplankton was sampled with a Clarke-Bumpus net in two layers overlaying the drifting sediment traps. Samples were fixed with a 4% sodium borate buffered formalin solution. Zooplankton counting was performed under a dissecting microscope. The total zooplankton biomass was determined as dry weight and as organic carbon content (measured by a CHN analyser).

As regard the sediment trap samples, to determine the total mass flux, three subsamples were filtered on 47 mm cellulose Millipore filters (0.45 μm porosity). For total and organic carbon and total nitrogen analyses, three sub-samples were filtered on 25 mm precombusted Whatman GF/F glass fibre filters. The analyses were performed like those for suspended particulate matter; for total carbon analyses filters were not acid-treated. Inorganic carbon was obtained by difference and the carbonate content was calculated by assuming that the whole inorganic carbon content consisted of calcium carbonate considering a carbonate/inorganic-carbon ratio of 8.33.



## RESULTS

### Suspended Matter and Hydrology

#### *Northern Area*

SUMMER At the coastal station (station A), the characteristics of dissolved and suspended matter strictly depended on the Po River water input influence. In June 1996, a thin surface layer of fresh water (average salinity 28.08) supplied high nutrient concentrations (mean DIN 17 μM and Si-$SiO_4$ 16 μM, see Tab. I). TSM at the surface was on average 1.8 mg $dm^{-3}$, POC and TPN concentrations were around 600 μg $dm^{-3}$ and 90 μg $dm^{-3}$ respectively. Below this layer all values decreased, showing a further increase near the bottom.

TABLE Ia Mean values of the indicated parameters for the coastal station (st. A) of the northern Adriatic area

*Station A*

| *Cruise* | *Depth m* | *TSM mg dm$^{-3}$* | *TPN µg dm$^{-3}$* | *POC µg dm$^{-3}$* | *CHL a µg dm$^{-3}$* | *DIN µM* | *Si-SiO$_4$ µM* | *P-PO$_4$ µM* | *Temp C* | *Salinity* |
|---|---|---|---|---|---|---|---|---|---|---|
| June 1996 | 0 | 1.79 | 87.5 | 596.3 | 3.64 | 16.99 | 15.61 | 0.09 | 26.73 | 28.08 |
| | 5 | 0.95 | 49.5 | 307.9 | 1.98 | 2.90 | 5.51 | 0.09 | 22.88 | 34.85 |
| | 10 | 0.36 | 33.2 | 193.7 | – | – | – | – | 17.48 | 36.76 |
| | 20 | 0.16 | 13.4 | 77.0 | 1.00 | 0.91 | 3.15 | 0.09 | 11.64 | 37.81 |
| | 30 | 0.70 | 13.7 | 80.8 | – | – | – | – | 9.88 | 37.90 |
| February 1997 | 0 | 4.35 | 106.4 | 689.9 | 7.24 | 31.75 | 6.73 | 0.05 | 8.51 | 30.23 |
| | 5 | 4.15 | 87.0 | 494.3 | 5.75 | 25.03 | 2.33 | 0.05 | 8.78 | 32.25 |
| | 10 | 2.53 | 43.1 | 304.1 | – | 16.43 | 4.25 | 0.04 | 10.26 | 36.98 |
| | 15 | 2.91 | 27.3 | 168.6 | 1.20 | 7.41 | 8.28 | 0.07 | 10.35 | 37.08 |
| | 21 | 5.20 | 40.6 | 217.8 | – | 6.58 | 8.88 | 0.04 | 10.45 | 37.15 |
| June 1997 | 0 | 1.55 | 82.1 | 438.6 | 3.47 | 6.56 | 11.73 | 0.11 | 19.76 | 31.31 |
| | 5 | 0.69 | 43.7 | 230.3 | 1.56 | 2.42 | 4.61 | 0.14 | 18.53 | 35.21 |
| | 10 | 0.32 | 29.5 | 157.1 | 1.71 | 2.35 | 4.26 | 0.10 | 17.53 | 35.83 |
| | 13 | 2.58 | 30.1 | 164.4 | – | 2.34 | 8.55 | 0.10 | 17.09 | 35.91 |
| February 1998 | 0 | 2.24 | 74.4 | 450.3 | 5.52 | 15.74 | 3.26 | 0.04 | 9.84 | 34.04 |
| | 5 | 1.25 | 57.0 | 326.7 | 3.22 | 6.47 | 0.17 | 0.03 | 9.70 | 36.10 |
| | 10 | 1.48 | 36.9 | 225.3 | – | 2.53 | 0.14 | 0.03 | 9.78 | 37.29 |
| | 18 | 4.14 | 22.4 | 136.4 | 1.16 | 2.94 | 6.28 | 0.05 | 10.77 | 37.95 |
| | 23 | 8.09 | 30.1 | 176.9 | – | 3.02 | 6.90 | 0.08 | 10.81 | 37.97 |

TABLE Ib Mean values of the indicated parameters at the offshore station (st. B) of the northern Adriatic area

*Station B*

| *Cruise* | *Depth m* | *TSM mg dm$^{-3}$* | *TPN µg dm$^{-3}$* | *POC µg dm$^{-3}$* | *CHL a µg dm$^{-3}$* | *DIN µM* | *Si-SiO$_4$ µM* | *P-PO$_4$ µM* | *Temp C* | *Salinity* |
|---|---|---|---|---|---|---|---|---|---|---|
| June 1996 | 0 | 0.53 | 41.5 | 266.2 | – | 1.11 | 3.21 | 0.08 | 25.66 | 33.38 |
| | 5 | 0.53 | 31.8 | 213.2 | 1.58 | – | – | – | 23.09 | 35.22 |
| | 10 | 0.22 | 16.6 | 102.5 | 0.85 | 2.98 | 5.86 | 0.11 | 15.16 | 37.52 |
| | 30 | 0.11 | 9.0 | 57.5 | 0.57 | 1.23 | 3.10 | 0.09 | 11.04 | 37.98 |
| | 40 | 2.17 | 20.5 | 136.7 | – | – | – | – | 10.00 | 37.95 |
| February 1997 | 0 | 0.68 | 36.0 | 357.3 | 1.93 | 14.77 | 1.67 | 0.04 | 9.02 | 33.87 |
| | 5 | 0.54 | 28.1 | 232.4 | – | 9.50 | 1.82 | 0.03 | 9.59 | 35.74 |
| | 10 | 0.73 | 22.6 | 204.5 | 2.14 | 5.15 | 2.07 | 0.04 | 10.16 | 36.80 |
| | 30 | 1.09 | 15.3 | 117.2 | 1.58 | 2.56 | 3.64 | 0.03 | 10.78 | 37.52 |
| | 41 | 2.58 | 21.7 | 182.7 | – | 2.66 | 3.48 | 0.03 | 11.06 | 37.65 |
| June 1997 | 0 | 0.19 | 22.5 | 136.4 | – | 2.26 | 3.69 | 0.11 | 21.05 | 36.08 |
| | 5 | 0.18 | 20.3 | 115.4 | 0.45 | 1.36 | 3.45 | 0.14 | 18.73 | 36.41 |
| | 10 | 0.25 | 16.4 | 111.7 | 0.50 | 1.04 | 3.17 | 0.13 | 18.20 | 36.64 |
| | 30 | 0.21 | 15.9 | 89.9 | 0.86 | 0.68 | 3.77 | 0.28 | 12.16 | 37.63 |
| | 39 | 1.11 | 16.6 | 86.5 | – | 1.98 | 7.34 | 0.17 | 12.05 | 37.73 |
| February 1998 | 0 | 1.10 | 32.3 | 159.2 | 0.86 | 1.00 | 1.42 | 0.02 | 10.81 | 37.60 |
| | 10 | 0.84 | 20.7 | 106.8 | 0.64 | 0.68 | 2.04 | 0.04 | 10.96 | 37.84 |
| | 20 | 0.43 | 17.5 | 81.9 | – | 0.54 | 2.62 | 0.03 | 11.01 | 37.94 |
| | 28 | 0.93 | 13.7 | 59.8 | 0.75 | 0.60 | 2.95 | 0.06 | 11.00 | 37.97 |
| | 33 | 2.71 | 24.9 | 131.3 | – | 0.85 | 3.69 | 0.04 | 11.03 | 37.99 |

TABLE Ic Mean values of the indicated parameters for the coastal (st. C) and offshore (st. D) stations of the central Adriatic area

*Station C*

| *Cruise* | *Depth m* | *TSM mg dm$^{-3}$* | *TPN μg dm$^{-3}$* | *POC μg dm$^{-3}$* | *CHL a μg dm$^{-3}$* | *DIN μM* | *Si-SiO$_4$ μM* | *P-PO$_4$ μM* | *Temp C* | *Salinity* |
|---|---|---|---|---|---|---|---|---|---|---|
| June 1996 | 0 | 0.38 | 17.0 | 108.4 | 1.54 | 0.54 | 3.03 | 0.11 | 21.92 | 34.60 |
| | 5 | 0.37 | 20.4 | 132.0 | 1.44 | 0.45 | 2.99 | 0.10 | 21.70 | 34.57 |
| | 10 | 0.52 | 15.4 | 102.4 | – | – | – | – | 21.62 | 34.58 |
| | 15 | 1.14 | 22.8 | 135.1 | 1.71 | 2.39 | 4.74 | 0.11 | 21.02 | 34.64 |
| February 1997 | 0 | 9.79 | 102.1 | 836.9 | 16.25 | 14.71 | 0.84 | 0.03 | 8.20 | 34.10 |
| | 5 | 9.62 | 115.1 | 985.4 | 12.83 | 11.33 | 0.87 | 0.03 | 8.66 | 35.01 |
| | 10 | 7.88 | 82.4 | 687.8 | 8.95 | 7.65 | 1.32 | 0.02 | 9.02 | 35.71 |
| June 1997 | 0 | 0.67 | 24.1 | 151.2 | 0.53 | 0.38 | 3.53 | 0.29 | 22.59 | 35.73 |
| | 5 | 0.50 | 30.4 | 166.0 | 0.50 | 0.23 | 3.40 | 0.28 | 21.42 | 36.07 |
| | 9 | 0.97 | 26.8 | 151.8 | 0.77 | 0.47 | 3.56 | 0.24 | 18.94 | 36.87 |
| | 13 | 1.42 | 29.3 | 148.1 | – | 0.67 | 3.24 | 0.29 | 18.86 | 36.91 |
| February 1998 | 0 | 7.66 | 65.3 | 339.2 | 4.02 | 14.91 | 4.10 | 0.01 | 8.11 | 34.79 |
| | 4 | 7.14 | 62.1 | 327.5 | 5.40 | 12.13 | 3.95 | 0.01 | 8.26 | 35.02 |
| | 7 | 7.41 | 64.8 | 341.4 | 6.43 | 11.69 | 3.92 | 0.02 | 8.51 | 35.34 |
| | 13 | 7.64 | 52.3 | 279.6 | – | 9.90 | 3.59 | 0.04 | 8.83 | 35.83 |
| *Station D* | | | | | | | | | | |
| February 1997 | 0 | 0.73 | 8.0 | 52.5 | 0.40 | 1.58 | 3.04 | 0.06 | 11.67 | 37.86 |
| | 5 | 0.70 | 8.4 | 50.3 | 0.12 | 1.81 | 3.20 | 0.06 | 11.62 | 37.87 |
| | 15 | 0.76 | 9.4 | 53.0 | – | 1.48 | 2.89 | 0.05 | 11.58 | 37.87 |
| | 25 | 0.78 | 12.0 | 61.3 | 0.35 | 1.82 | 3.17 | 0.04 | 11.56 | 37.87 |
| | 35 | 1.50 | 8.9 | 50.3 | – | 1.66 | 3.10 | 0.06 | 11.56 | 37.87 |
| June 1997 | 0 | 0.19 | 16.4 | 121.3 | – | 0.27 | 3.01 | 0.28 | 21.52 | 36.39 |
| | 5 | 0.20 | 28.8 | 149.0 | 0.32 | 0.22 | 3.05 | 0.20 | 21.33 | 36.40 |
| | 15 | 0.10 | 10.8 | 66.2 | 0.08 | 0.23 | 1.76 | 0.19 | 17.01 | 37.33 |
| | 30 | 0.61 | 18.8 | 94.4 | 0.74 | 0.58 | 4.54 | 0.31 | 12.72 | 37.71 |
| | 38 | 1.37 | 23.3 | 81.1 | – | 0.70 | 4.88 | 0.30 | 12.50 | 37.74 |



The high nutrient concentration at the surface led to a large phytoplankton growth, with a maximum CHL *a* concentration of 3.6 μg dm$^{-3}$, an abundance of up to $14 \times 10^6$ cells dm$^{-3}$ and a relative biomass of 645 μg C dm$^{-3}$ (Tab. II). The community was dominated by small flagellates, nanoflagellates, naked dinoflagellates (mainly at the surface), cryptophyceans and centric diatoms like *Chaetoceros* sp., *Thalassiosira* sp. and *Skeletonema* sp. Zooplankton abundance and biomass revealed high values ($11 \times 10^3$ ind. m$^{-3}$, and 22 mg C m$^{-3}$) at the surface layer, whereas in the deep layer they decreased to values lower than $5 \times 10^3$ ind. m$^{-3}$ and 10 mg C m$^{-3}$ (Tab. III). The community consisted mainly of copepods, accounting for approximately 80% of the population, whereas cladocerans represented only 15%.

In June 1997, the hydrological conditions were considerably different: the surface layer was colder and less diluted (*i.e.* salinity was 31.31) with lower nutrient concentrations; in particular the nitrate was on average about 3 fold lower. The average TSM, POC, TPN and CHL *a* concentrations were similar to those of the previous year, whereas the phytoplankton abundance at the surface was around $3 \times 10^6$ cells dm$^{-3}$ with a respective biomass of 48 μg C dm$^{-3}$.

TABLE IIa Phytoplankton abundance and phytoplankton carbon (PPC) in the northern area.

| *Cruise* | *Depth m* | *Phytoplankton cells* $\times 10^6\,dm^{-3}$ | *PPC* $\mu g\ C\ dm^{-3}$ | *Cruise* | *Depth m* | *Phytoplankton cells* $\times 10^6\,dm^{-3}$ | *PPC* $\mu g\ C\ dm^{-3}$ |
|---|---|---|---|---|---|---|---|
| | | | *Northern area* | | | | |
| | *Station A* | | | | *Station B* | | |
| June 1996 | 0 | 14.86 | 644.5 | June 1996 | 5 | 5.74 | 65.3 |
| | 5 | 7.13 | 92.3 | | 10 | 1.79 | 10.7 |
| | 20 | 2.20 | 16.7 | | 30 | 1.04 | 16.1 |
| February 1997 | 0 | 12.67 | 202.7 | February 1997 | 0 | 7.44 | 99.5 |
| | 5 | 12.46 | 189.4 | | 10 | 7.58 | 93.2 |
| | 15 | 3.44 | 32.8 | | 30 | 4.78 | 58.6 |
| June 1997 | 0 | 3.06 | 48.4 | June 1997 | 5 | 0.70 | 17.5 |
| | 5 | 2.58 | 55.8 | | 10 | 1.24 | 70.1 |
| | 10 | 0.79 | 27.2 | | 30 | 0.43 | 17.3 |
| February 1998 | 0 | 7.45 | 149.2 | February 1998 | 0 | 1.26 | 52.3 |
| | 5 | 2.81 | 84.5 | | 10 | 0.50 | 23.3 |
| | 18 | 0.20 | 7.9 | | 28 | 0.13 | 4.9 |

TABLE IIb Phytoplankton abundance and phytoplankton carbon (PPC) in the southern area.

| *Cruise* | *Depth m* | *Phytoplankton cells* $\times 10^6\,dm^{-3}$ | *PPC* $\mu g\ C\ dm^{-3}$ | *Cruise* | *Depth m* | *Phytoplankton cells* $\times 10^6\,dm^{-3}$ | *PPC* $\mu g\ C\ dm^{-3}$ |
|---|---|---|---|---|---|---|---|
| | | | *Northern area* | | | | |
| | *Station C* | | | | *Station D* | | |
| June 1996 | 0 | 1.76 | 210.9 | June 1996 | – | – | – |
| | 5 | 2.24 | 241.8 | | – | – | – |
| | 15 | 1.19 | 74.8 | | – | – | – |
| February 1997 | 0 | 13.30 | 187.8 | February 1997 | 0 | 0.07 | 5.9 |
| | 5 | 24.84 | 320.1 | | 5 | 0.08 | 1.2 |
| | 10 | 15.02 | 165.9 | | 25 | 0.08 | 1.5 |
| June 1997 | 0 | 0.65 | 60.9 | June 1997 | 5 | 0.29 | 9.3 |
| | 5 | 0.35 | 53.5 | | 15 | 0.20 | 3.6 |
| | 9 | 0.92 | 77.5 | | 30 | 0.30 | 49.0 |
| February 1998 | 0 | 7.68 | 112.8 | February 1998 | – | – | – |
| | 4 | 7.89 | 109.0 | | – | – | – |
| | 7 | 7.48 | 142.9 | | – | – | – |



The zooplankton showed lower abundance (7 and $1.3 \times 10^3$ ind. $m^{-3}$ at the surface and bottom layers), and more than 75% of the community consisted of copepods.

At the offshore station (station B), the dilution gradient determined decreasing values in the dissolved and particulate components.
Nutrient concentrations were particularly low (in June 1996, DIN1–2.3 µM, Si-$SiO_4$ 3–3.7 µM) and TSM was almost half that of the coastal area. In June 1997, the highest TSM and phytoplankton abundance were found at intermediate depth (10 m), with a maximum of $1.2 \times 10^6$ cell $dm^{-3}$. The community consisted mainly of nanoflagellates, dinoflagellates and cryptophyceans; coccolithophorids were mainly found in the deeper layer.

The zooplankton population in the offshore area showed lower abundance ($5.6 \times 10^3$ ind. $m^{-3}$ on average in the surface layer), in the deeper layer values decreased to

TABLE III Zooplankton averaged abundance and biomass (as Dry Weight and Organic Carbon content)

| *Cruise* | *Depth m* | *Zooplankton ind. dm*$^{-3}$ | *DW mg m*$^{-3}$ | *C org mg m*$^{-3}$ | *Cruise* | *Depth m* | *Zooplankton ind. dm*$^{-3}$ | *DW mg m*$^{-3}$ | *C org mg m*$^{-3}$ |
|---|---|---|---|---|---|---|---|---|---|
| *Northern area* | | | | | | | | | |
| | | *Station A* | | | | | *Station B* | | |
| June 1996 | 4–8 | 11,230 | 35.8 | 21.6 | June 1996 | 4–8 | 6,444 | 35.9 | 12.6 |
| | 14–18 | 4,733 | 16.8 | 9.8 | | 20–24 | 3,058 | 41.2 | 19.8 |
| February 1997 | 3–7 | 312 | – | 1.5 | February 1997 | 5–10 | 1,541 | 9.9 | 5.2 |
| | 14–18 | 551 | 28.9 | 11.3 | | 12–19 | 789 | 12.2 | 4.1 |
| June 1997 | 1–6 | 6,938 | 51.7 | 24.3 | June 1997 | 5–10 | 5,614 | 25.7 | 10.1 |
| | 6–11 | 1,338 | 15.2 | 4.3 | | 25–30 | 2,241 | 13.8 | 5.3 |
| February 1998 | 2–6 | 3,382 | 28.2 | 11.2 | February 1998 | 6–10 | 2,571 | 37.6 | 13.8 |
| | 14–18 | 2,348 | 23.4 | 9.6 | | 24–28 | 2,043 | 19.0 | 8.5 |
| *Southern area* | | | | | | | | | |
| | | *Station C* | | | | | *Station D* | | |
| June 1996 | 3–7 | 17,485 | 67.6 | 36.7 | June 1996 | – | – | – | – |
| | 8–12 | 47,325 | 68.4 | 33.9 | | | | | |
| February 1997 | 3–7 | 818 | 5.2 | 2.1 | February 1997 | 3–7 | 152 | – | 0.8 |
| | | | | | | 21–25 | – | – | – |
| June 1997 | 4–8 | 5,067 | 24.0 | 6.2 | June 1997 | 5–9 | 6,986 | 12.1 | 5.5 |
| | 8–12 | 6,168 | 82.7 | 8.3 | | 26–30 | 1,295 | 66.0 | 5.4 |
| February 1998 | 3–7 | 1,330 | 16.4 | 6.1 | February 1998 | – | – | – | – |

$2.2 \times 10^3$ ind. m$^{-3}$, copepods accounted for 44–58% and cladocerans increased up to 46–24% of the total at the surface and bottom layers.

WINTER During the February cruises, suspended matter showed higher concentrations than in summer, especially in the coastal area, though with lower organic fraction. In particular, in February 1997 the diluted surface waters found both at the coastal and the offshore stations contained high nutrient concentrations (DIN 32 $\mu$M and 14 $\mu$M) that sustained large phytoplankton blooms (with abundance of $12 \times 10^6$ and $7.5 \times 10^6$ cell dm$^{-3}$ at station A and B) dominated by the centric diatom *Skeletonema costatum*.

In February 1998 the bloom was less extensive, with an abundance at the surface of $7.4 \times 10^6$ and $1.2 \times 10^6$ cell dm$^{-3}$, the species composition was represented together with *Skeletonema costatum*, by *Pseudonitzschia pseudodelicatissima* and *Chaetoceros* sp. at the coastal station.

As expected, in winter zooplankton abundance was much lower than in summer ($< 3.5 \times 10^3$ ind. m$^{-3}$) and the population consisted mainly of copepods.

## *Central Adriatic Area*

SUMMER In summer 1996, temperature and salinity were quite homogeneous within the water column at the coastal station (station C), with values around 21–22C and 34.6 respectively.

Average TSM, POC and TPN values were lower with respect to the northern area and increased downward (Tab. Ib). Nutrient concentrations were also low, DIN was less than 1 μM and Si-$SiO_4$ around 3 μM at the surface, following the same vertical pattern. CHL *a* concentration ranged from 1.4 to 1.8 μg $dm^{-3}$ and phytoplankton abundance was around 1–2 × $10^6$ cells $dm^{-3}$, with biomass ranging from 75 to 242 μg C $dm^{-3}$. The phytoplankton population consisted of nanoflagellates and centric diatoms mostly represented by *Cerataulina pelagica*. A high zooplankton abundance was found in the deeper layer (47 × $10^3$ ind. $m^{-3}$, about 34 mg C $m^{-3}$), where cladocerans were the dominant group.

In June 1997, particulate matter and nutrient concentration values were similar to those found in June 1996, whereas CHL *a* and phytoplankton abundance values were much lower (0.5 μg $dm^{-3}$ and 0.65 × $10^6$ cells $dm^{-3}$ at the surface, with a peak of 0.9 × $10^6$ cells $dm^{-3}$ at 9 m depth) and the community consisted mainly of nanoflagellates, dinoflagellates and cryptophyceans.

Zooplankton abundance was up to one order of magnitude lower than in 1996, with values around 5–6 × $10^3$ ind. $m^{-3}$ (6–8 mg C $m^{-3}$), again constituted mainly by cladocerans (87%) at the surface layer.

In June 1997 at the offshore station, TSM, POC and TPN concentration values were lower with respect to the coastal station and comparable to those of the northern offshore area. TSM, nutrients, CHL *a* concentration and phytoplankton abundance showed a minimum at intermediate depth (around 15 m at the thermocline level), whereas POC and TPN concentrations were greater at the surface. The phytoplankton community consisted mainly of nanoflagellates (50–67%) followed by dinoflagellates and diatoms. Coccolithophorids showed an increasing abundance with depth. Zooplankton abundance at the surface layer was similar to that of the coastal station, while in the bottom layer it showed a consistent decrease. The community at the surface was mainly dominated by cladocerans, whereas copepods prevailed towards the bottom.



WINTER In February 1997, the inshore station showed the highest TSM ($>$9 mg $dm^{-3}$), POC (985 μg $dm^{-3}$), TPN (115 μg $dm^{-3}$) and CHL *a* (16.2 μg $dm^{-3}$) concentrations, together with the highest phytoplankton abundance (24 × $10^6$ cells $dm^{-3}$) in the subsurface layer, related with a bloom consisting of more than 90% of *Skeletonema costatum*.

At the surface and subsurface layer, nitrate concentration was higher than 10 μM, whereas silicate, probably depleted by the diatom bloom, reached values lower than 1 μM.

In winter 1997, the offshore station showed higher temperature and salinity values, with low and fairly homogeneous particulate matter, nutrient and CHL *a* concentrations. TSM was around 0.7 mg $dm^{-3}$ throughout the water column with an increase of up to 1.5 mg $dm^{-3}$ near the bottom. POC and TPN showed the lowest absolute values found (POC 50–60 μg $dm^{-3}$ and TPN 8–12 μg $dm^{-3}$). Phytoplankton showed very low abundance ($<$8 × $10^4$ cells $dm^{-3}$), the population being mainly composed of coccolithophorids and nanoflagellates.

In February 1998, the inshore area showed again high TSM and nutrient concentrations comparable to those of the previous year, whereas POC, TPN, chlorophyll, phytoplankton abundance and biomass were lower (7.4–7.8 × $10^6$ cells $dm^{-3}$ and 109–143 μg C $dm^{-3}$). Like in the northern area, the community was composed of 56% of *Pseudonitzschia pseudodelicatissima* and 32% of *Skeletonema costatum*.

Throughout both winters, zooplankton abundance was low, never exceeding $1.5 \times 10^3$ ind. $m^{-3}$ (1–6 mg C $m^{-3}$), and the populations were dominated by copepods.

## Particle Flux

In the northern Adriatic area, total mass flux observed in all situations ranged within two orders of magnitude from 11 to 3139 mg $m^{-2}$ $d^{-1}$ (Tab. IVa). Fluxes were higher at the coastal station, related to the high particle concentration in the water column; they were greater near the bottom especially in winter, when lateral advection and re-suspension processes were most likely the main particle sources. On the contrary, in summer, fluxes were higher at the surface due to the higher productivity of this layer and to the water column stratification. The composition of the flux is reported in Table IVa. Organic carbon fluxes ranged from 1 to 82 mg C $m^{-2}$ $d^{-1}$ at the coastal station, accounting for 10–30% of total flux in June, whereas in February it decreased to 3–10% with a relatively greater percentage at the surface level. Total nitrogen flux varied between 0.1 and 11 mg N $m^{-2}$ $d^{-1}$ ranging from 1.5% to 5% of the total flux in summer and from 0.4% to 1.6% in winter, following the same pattern as that of the organic carbon flux. Carbonate flux ranged from 0.4 to 652 mg $m^{-2}$ $d^{-1}$, representing on average 4.3% and 25% of total flux in the surface and bottom traps.

At the offshore station, the organic carbon flux varied from 4.9 to 29.4 mg C $m^{-2}$ $d^{-1}$ with a percentage up to 39% in summer, decreasing in February to values $< 10\%$ in the deep layer; total nitrogen flux ranged between 0.9–4 mg N $m^{-2}$ $d^{-1}$, whereas the percentage of total flux was similar throughout both seasons (0.9%–5.6% in June and 0.2%–4% in February). Carbonate presented an average higher percentage (30%) respect to the coastal station with not much difference between the surface and bottom trap.

In the Central Adriatic area, total mass fluxes ranged from 20 to 3864 mg $m^{-2}$ $d^{-1}$, the highest values were measured in February 1997 (Tab. IVb). Bottom fluxes were generally greater than those measured below the surface layer in summer. The organic

TABLE IVa Particle fluxes measured in the coastal (station A) and offshore (station B) stations of the northern Adriatic area

| Station | Depth m | Cruise | Total mass flux mg $m^{-2}$ $d^{-1}$ | *Org. C* | | *Tot. N* | | *Carbonates* | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | mg $m^{-2}$ $d^{-1}$ | % | mg $m^{-2}$ $d^{-1}$ | % | mg $m^{-2}$ $d^{-1}$ | % |
| A | 8 | Jun-96 | 109 | 29.9 | 27.4 | 3.0 | 2.7 | | |
| A | 26 | Jun-96 | 48 | 14.9 | 31.3 | 2.4 | 4.9 | 9.8 | 20.5 |
| A | 5 | Feb-97 | 474 | 48.5 | 10.2 | 7.6 | 1.6 | 31.8 | 6.7 |
| A | 18 | Feb-97 | 3139 | 81.8 | 2.6 | 11.1 | 0.4 | 651.5 | 20.8 |
| A | 5 | Jun-97 | 466 | 47.4 | 10.2 | 7.1 | 1.5 | 8.6 | 1.8 |
| A | 10 | Jun-97 | 99 | 15.0 | 15.2 | 2.4 | 2.5 | 0.4 | 0.4 |
| A | 6 | Feb-98 | 11 | 1.2 | 11.2 | 0.1 | 1.1 | – | – |
| A | 18 | Feb-98 | 223 | 12.2 | 5.5 | 2.3 | 1.1 | 128.9 | 57.9 |
| B | 8 | Jun-96 | 54 | 14.8 | 27.2 | 3.1 | 5.6 | 24.4 | 45.2 |
| B | 31 | Jun-96 | 16 | 6.1 | 38.7 | 0.9 | 5.5 | 7.6 | 48.2 |
| B | 11 | Feb-97 | 22 | 4.9 | 21.8 | 0.9 | 3.9 | 6.4 | 28.6 |
| B | 33 | Feb-97 | 1002 | 29.4 | 2.9 | 4.1 | 0.4 | 295.9 | 29.5 |
| B | 10 | Jun-97 | 56 | 7.8 | 13.9 | 1.2 | 2.1 | 1.1 | 1.9 |
| B | 30 | Jun-97 | 204 | 12.8 | 6.3 | 1.9 | 0.9 | 26.9 | 13.1 |
| B | 28 | Feb-98 | 1333 | 20.6 | 1.5 | 2.9 | 0.2 | 554.9 | 41.6 |

TABLE IVb Particle fluxes measured in the coastal (station C) and offshore (station D) stations of the central Adriatic area

| Station | Depth m | Cruise | Total Mass Flux $mg\ m^{-2}\ d^{-1}$ | Org. C $mg\ m^{-2}\ d^{-1}$ | Org. C % | Tot. N $mg\ m^{-2}\ d^{-1}$ | Tot. N % | Carbonates $mg\ m^{-2}\ d^{-1}$ | Carbonates % |
|---|---|---|---|---|---|---|---|---|---|
| C | 5 | Jun-96 | 90 | 15.7 | 17.4 | 2.9 | 3.3 | 40.2 | 44.7 |
| C | 12 | Jun-96 | 2081 | 71.1 | 3.4 | 13.2 | 0.6 | 722.9 | 34.7 |
| C | 5 | Feb-97 | 3864 | 55.4 | 1.4 | 7.2 | 0.2 | 1046.4 | 27.1 |
| C | 5 | Jun-97 | 89 | 14.9 | 16.7 | 2.0 | 2.2 | 10.7 | 12.0 |
| C | 9 | Jun-97 | 851 | 51.4 | 6.0 | 6.6 | 0.8 | 184.7 | 21.7 |
| C | 7 | Feb-98 | 313 | 5.5 | 1.7 | 0.9 | 0.3 | 114.7 | 36.6 |
| D | 5 | Feb-97 | 3298 | 47.0 | 1.4 | 7.0 | 0.2 | 833.1 | 25.3 |
| D | 5 | Jun-97 | 20 | 6.6 | 33.7 | 0.5 | 2.6 | – | – |
| D | 30 | Jun-97 | 607 | 22.6 | 3.7 | 3.3 | 0.5 | 159.3 | 26.2 |

carbon content (flux range 6–71 $mg\,C\,m^{-2}\,d^{-1}$) was less then 2% of total flux in February, and varied from 3 to 33% in June, with higher values at the surface level. The nitrogen content of fluxes resulted slightly lower (0.2–3.3%) than in the northern area. Carbonate was on average 30% and 26% of total mass flux at the coastal and offshore stations.

In both sampling areas the organic carbon and total nitrogen percentages resulted inversely correlated ($r = -0.6$, $p < 0.05$) with total mass flux.

The trapped material during summer appeared mucilaginous and sticky, with a large number of mollusc (gastropods and bivalves) larvae, while in winter several fecal pellets, mostly cylindrical and some oval shaped, were found.



## Organic Carbon Compartments and Export

The particulate organic carbon standing stock (as POC integrated on the whole water column) was generally higher in the northern area and relatively greater in the coastal diluted zone, with maximum values ($>6000\,mg\,C\,m^{-2}$) in February 1997 (Tab. V). The contribution of the phytoplankton carbon to the organic carbon poo1 ranged from 18 to 52%, with a peak of 68% found in the surface layer of the coastal area in summer, whereas in the offshore station it was only slightly lower, with a maximum of 40% in February 1997, when a diatom bloom was observed (Tab. V). In the central Adriatic area, the organic carbon pool was lower with respect to the northern part, and showed an opposite seasonal trend: it was higher at the offshore area in summer, while in winter this occurred at the coastal zone. The percentage of organic carbon due to phytoplankton showed a strong difference between the coastal and the offshore areas, with values on average 6 times higher in the former.

The percentage of organic carbon removal from the standing stock through sedimentation was always less than 2% per day in the northern area; higher values were observed in the central area, particularly at the inshore station in the summer periods (3.6–5% per day).

Organic carbon export estimates, expressed as a percentage of primary production rates measured in the same areas and in the same periods (Socal, personal comm.), were less than 10% at the inshore station in the northern area (Tab. V), reaching a

TABLE V Values integrated at the indicated depths of particulate organic carbon (POC), of primary production (PP). Organic carbon flux, phytoplankton carbon (PPC) % with respect to POC. PP export, as % of primary production and export of POC from the standing stock

| *Northern Adriatic* | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| *Area* | *Inshore* | | | | *Offshore* | | | |
| *Cruise* | *June 1996* | *June 1997* | *Feb 1997* | *Feb 1998* | *June 1996* | *June 1997* | *Feb 1997* | *Feb 1998* |
| Integrated depth, m | 0–26 | 0–10 | 0–18 | 0–18 | 0–31 | 0–30 | 0–33 | 0–28 |
| POC, mg $m^{-2}$ | 5336 | 2640 | 6680 | 4769 | 3588 | 3213 | 6163 | 2841 |
| PP, mg C $m^{-2}d^{-1}$ | 192 | 499 | – | 856 | 102 | 183 | 1527 | 170 |
| Org C flux, mg $m^{-2}$ $d^{-1}$ | 15 | 15 | 82 | 12 | 6 | 13 | 29 | 21 |
| PPC/POC, % | 52 | 18 | 31 | 25 | 22 | 34 | 40 | 22 |
| Export PP, % | 7.8 | 3 | – | 1.4 | 6 | 7 | 2 | 12 |
| Export POC, % per day | 0.3 | 0.6 | 1.2 | 0.3 | 0.2 | 0.4 | 0.5 | 0.7 |
| *Central Adriatic* | | | | | | | | |
| *Area* | *Inshore* | | | | *Offshore* | | | |
| *Cruise* | *June 1996* | *June 1997* | *Feb 1997* | *Feb 1998* | *June 1997* | *June 1997* | *Feb 1997* | *Feb 1998* |
| Integrated depth, m | 0–12 | 0–9 | 0–5 | 0–7 | 0–30 | – | 0–5 | – |
| POC, mg $m^{-2}$ | 1405 | 1429 | 4556 | 2337 | 2956 | – | 1466 | – |
| PP, mg C $m^{-2}$ $d^{-1}$ | 108 | 348 | 1492 | 774 | 374 | – | 611 | – |
| Org C flux, mg $m^{-2}$ $d^{-1}$ | 71 | 51 | 55 | 5.5 | 22.6 | – | – | – |
| PPC/POC, % | – | 38 | 28 | 35 | 8 | – | 3 | – |
| Export PP, % | 66 | 15 | 3.7 | 0.7 | 6 | – | – | – |
| Export POC, % per day | 5 | 3.6 | 1.2 | 0.2 | 0.8 | – | 11 | – |

maximum of 12% in the offshore waters in February 1998, while in the southern zone it was almost always greater, with a maximum of 66% at the coastal station in summer.

## DISCUSSION

In the study areas, the river outflow and its spread, together with the thermohaline conditions and circulation pattern were the main forcing factors that affected the distribution and settling of particulate material.

Total suspended matter was particularly high at the coastal stations, inside the front originated by the Po River discharge. The freshwater input from rivers was mainly evident in both February situations, showing low salinity and high particulate matter and nutrient loads at the surface layers. These conditions favoured the development of phytoplankton blooms. The southern inshore area showed high values of suspended matter in February, related to coastal transport driven by strong currents present in this area as highlighted by the long distance drift of the trap array.

Most of the situations examined showed an increase of suspended particulate matter near the bottom, indicating the almost constant presence of a benthic nepheloid layer related with frequent occurrence of resuspension processes and advective transport.

POC concentrations resulted in the range reported for the northern Adriatic by Gilmartin and Revelante (1991), with a horizontal decreasing trend from the coast outwards, and comparable to the results of the PRISMA I ("Cicli biogeochimici ed indagini ecofisiologiche") project (Giani *et al.*, 2000).

The phytoplankton abundance and community structure observed were in agreement with results reported by Socal and Bianchi (1989), Socal *et al*. (1992), Fonda Umani *et al*. (1992), Alberighi *et al*. (1997) for the northern Adriatic and by Zoppini *et al*. (1995) for the central Adriatic area. In June, in the stratified period, nanoplankton was the prevailing fraction, whereas in February diatoms were the dominant group. Coccolithophorids were found mainly at the offshore stations and sometimes in the deeper layer of the coastal areas. In February 1997, a large bloom of *Skeletonema costatum* was observed, while in February, 1998, the prevailing species of the bloom were *Pseudonitzschia pseudodelicatissima*, together with *Skeletonema costatum* and *Chaetoceros* sp.

The mesozooplankton abundance was within the range of data reported for the northern Adriatic by Fonda Umani *et al*. (1992), and Comaschi *et al*. (1997), with higher values in summer, when cladocerans were the prevailing group.

Zooplankton biomass resulted comparable with the values reported by Benovic *et al*. (1984), Fonda Umani *et al*. (1992), Fonda Umani (1996) for the northern and central Adriatic.

The organic carbon fluxes measured with the drifting sediment traps were of the same order of magnitude as those reported by Miquel *et al*. (1999), observed near the Po river outflow utilising the same sampling method.



They appear much lower if compared with those reported from studies carried out in the northern Adriatic (Delta Po river area) with moored sediment traps. The latter ranged, in fact, on average from 100–560 $mg\,m^{-2}\,d^{-1}$ near the bottom and around 60–70 $mg\,m^{-2}\,d^{-1}$ immediately below the surface layer (Boldrin and Rabitti, 1992; Puskaric *et al*., 1992; Matteucci and Frascari, 1997).

It must be considered that in these long-term fluxes, collected with moored sediment traps, the resuspension and lateral transport components could be an important fraction of the measured flux, especially in the winter period, when it can reach 80% of the total flux (Matteucci and Frascari 1997, Puskaric *et al*., 1992).

Otherwise, if we compare the organic carbon fluxes measured with primary organic carbon fluxes (*i.e.* fluxes corrected by subtracting the organic carbon fraction due to resuspension and lateral advection) measured in northern Adriatic during the PRISMA I project (Giani *et al*., 2001), they appear more similar, mainly in the winter season, whereas in summer the discrepancy still exists, though considerably lower.

The organic carbon content exported from the euphotic zone, expressed as a percentage of primary production, did not show a clear pattern. In the northern area, this content was always less than 10%, relatively higher in the offshore station particularly during the second year of sampling, though lower than expected for shallow environments (Eppley and Peterson, 1979).

These low values are comparable to those found by Miquel *et al*. (1999), and similar to those estimated in the northern Adriatic (Giani *et al*., 2001).

In the central Adriatic, the coastal area showed high values in summer (40% on average), while at the offshore station the export was around 6%.

The export of organic carbon with respect to the POC standing stock was always less than 1.5% per day near the bottom in the northern area, and quite similar in both the diluted and non diluted zones, (the coastal station showing slightly higher values). These values were lower than those found in the PRISMA I project.

In the central Adriatic zone, the export in the coastal area was greater than 4% per day on average in summer, whilst in winter it exceeded 10% per day at the offshore station.

The low carbon export values found, especially in the northern area, suggest a high carbon recycling and consumption efficiency within the water column.

Particulate matter settlement can be quite heterogeneous in this kind of environment, occurring through pulse episodes, alternating high fluxes to very low particle transfer. The majority of biogenic material sinks through large amorphous aggregates and faecal pellets in spot-like events that short-term measurements may miss.

When considering downward flux measurements in a shallow environment such as that of the northern and central Adriatic Sea, the sampling strategy has to be very carefully considered, as it is possible to obtain contrasting information with different sampling methods.

## CONCLUDING REMARKS

The coastal areas showed higher suspended particulate matter and particle fluxes, in particular the southern area showed the highest concentrations in winter.

Although the range of particle fluxes was similar in both the northern and southern areas, on average fluxes were higher in the southern area near the bottom.

In general, the fluxes measured below the surface layer displayed a greater organic fraction; the northern coastal area exhibited a different trend with higher organic fractions in the bottom fluxes in summer.

The organic carbon export, expressed as a percentage of primary production and of the POC standing stock, was greater in the southern area, particularly in the coastal station in summer.

Although the northern area showed higher POC concentrations, the organic carbon transfer to the deep layer was greater in southern one.



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