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Northern Adriatic mesocosm experiment Rovinj 2003: Oceanographic conditions at the sampling station

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Key words: Po River flow, geostrophic currents, oceanographic parameters, nutrients, DOC, POC, microphytoplankton, bacteria, nanoflagellates, microparticles, northern Adriatic

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Abstract

Background and Purpose: *A mesocosm experiment with nutrient enriched seawater was performed to verify if important production of particles, considered as mucilage precursors, occur in the northern Adriatic in May, when semi-enclosed circulation is well developed and plankton growth with phosphorus limited. In this paper, the oceanographic and biological characteristics of the sampled area were described and evaluated by comparison with historical data.*

Materials and Methods: *Geostrophic currents, temperature, salinity, density, oxygen saturation, nutrients, Chla, POC, DOC, microphytoplankton, and heterotrophic bacteria and nanoflagellates were determined by methods widely used in oceanography. Surface active (SAP) and gel particle (GeP) concentrations were measured electrochemically.*

Results and Conclusions: *An anticyclonic gyre was observed in May 2003 in the open northern Adriatic, including the sampling station, in which freshened waters were retained. In these conditions nutrient, chlorophyll* a *concentrations, as well as phytoplankton and bacterial abundances did not differ essentially from long term averages, in spite of extremely low Po River discharge rates. In contrast, the content of SAP, and probably of GeP as well, was exceptionally high. All identified microphytoplankton species are often present in May at the sampling station. The diatom* Dactyliosolen fragilissimus *highly dominated the microphytoplankton community in the sea.*

INTRODUCTION

The shallow northern Adriatic is characterised by high seasonal and long-term variability of oceanographic and biological conditions, mainly due to climatic fluctuations and external nutrient input, principally from the Po River, one of the major rivers in the Mediterranean *(1)*.

Water exchange with the central Adriatic represents the main export mechanism of nutrients and other substances introduced into the northern Adriatic from external sources. In fact, northwestern Adriatic waters with higher nutrient contents are transported southwards and are replaced with oligotrophic waters from the south *(2)*.

The water mass exchange between the northern and central Adriatic is at its maximum during late autumn and winter, when a cyclonic circulation prevails, and is characterised by northward currents in the eastern part and southward currents along the western coast *(3, 4, 5)*. Due to intense heat losses at the air-sea interface, the water column of the northern Adriatic is well mixed during that period of the year. During spring and summer, semi-enclosed circulation patterns prevail in the region and thermal stratification gradually increases from spring to a maximum in August, as a result of heat accumulation in the upper layers. In these conditions, freshened surface waters, formed in the Po delta area, are generally advected eastward as far as the Istrian coast and increasing significantly the stratification of the water column.

Injections of fresh-water nutrients to the surface layer cause intense phytoplankton blooms over large areas of the northern Adriatic, particularly in spring and autumn. Generally these blooms become drastically nutrient limited (in particular with phosphorus) before other substantial nutrient discharges occur *(1)*. During such episodes of rapid bloom development and decay, an excessive accumulation and gelling of polysaccharide exudates can occur in conditions of reduced water dynamics and marked water column stratification, generating the mucilage phenomenon *(7)*. This phenomenon is characterised by the formation of macroaggregates of different shapes and dimensions (up to several meters) in the upper water column of the entire northern Adriatic. In addition, long gelatinous fronts on the sea surface and in the subsurface layer (»false bottom«; *8*), up to tens kilometres long, have been noted.

Mucilage events occurred in the past in intervals of roughly 10–60 years, as reported in scientific papers since the late 19th century *(9)*. However, in the last fifteen years the phenomenon has exploded with an unusually high frequency (1988, 1989, 1991, 1997, 2000–2003; *10–13*, CMR, unpub. data). In years when mucilage events occurred, it was noted that the Istrian Coastal Countercurrent (ICCC), a southward water flow along the Istrian coast, was well developed, particularly in summer *(12, 14, 15)*. In fact, the ICCC probably appears when the anticyclonic circulation in the northern Adriatic basin is well developed, favouring the accumulation of mucilaginous material.

Diatoms were assumed to be the main producers of the mucilage polysaccharide matrix *(7, 9, 16)*. In particular, *Cylindrotheca closterium* has been assumed to have an important role in the mucilage formation, although conclusive evidence has not yet been obtained *(17–19)*. However, it was shown that this diatom is essential for the macroaggregate to be self-sustaining in the water column due to its high exudation capabilities and dominance in the mucilage microphytoplankton community *(11)*.

A mucilage event occurs as a result of a synergic combination of several factors *(e.g. 10)*. Among them, for example, an increased N/P ratio above 16 favours polysaccharide excretion *(20, 21)*, while fluctuations of climatic, hydrologic, and oceanographic conditions, as well as perturbations in the organic carbon flow through the plankton food webs *(24–27),* seem to have essential roles in triggering the phenomenon *(7, 22, 23)*.

The mucilage events usually start in June or early July, when the water column stratification is marked *(e.g. 9–11, 13)*. However, it was assumed that already in May, when eddy circulation in the northern Adriatic is well developed and phytoplankton blooms are at their maximum or decaying, an important production of mucilage precursors (e.g. transparent exopolymer particles and other microparticles, colloidal matter) can occur, because of drastic phosphorus limitation. To verify this hypothesis, a mesocosm experiment was performed in May 2003 by enrichment of seawater collected in a developed frontal zone between oligotrophic and eutrophic waters, where higher accumulations of mucilage were observed in previous years *(e.g. 13)*. In this paper, the oceanographic and biological characteristics of the sampled area are described and evaluated by comparison with long-term averages and variability of relevant parameters.

MATERIALS AND METHODS

Seawater samples were collected during two cruises (6 and 12 May 2003) at standard depths (0, 5, 10, 20, 30, and 35 m) of the station SJ105 (45°02.00'N, 13°09.30'E; 20 Nm W of Rovinj; Figure 1). This station was selected using satellite images (Figure 2) showing a frontal zone between oligotrophic and eutrophic waters, developed at that timer in the northern Adriatic, including the sampling area.

Temperature, salinity, oxygen, nutrients, chlorophyll *a*, heterotrophic bacteria, nanoflagellates and microphyto-

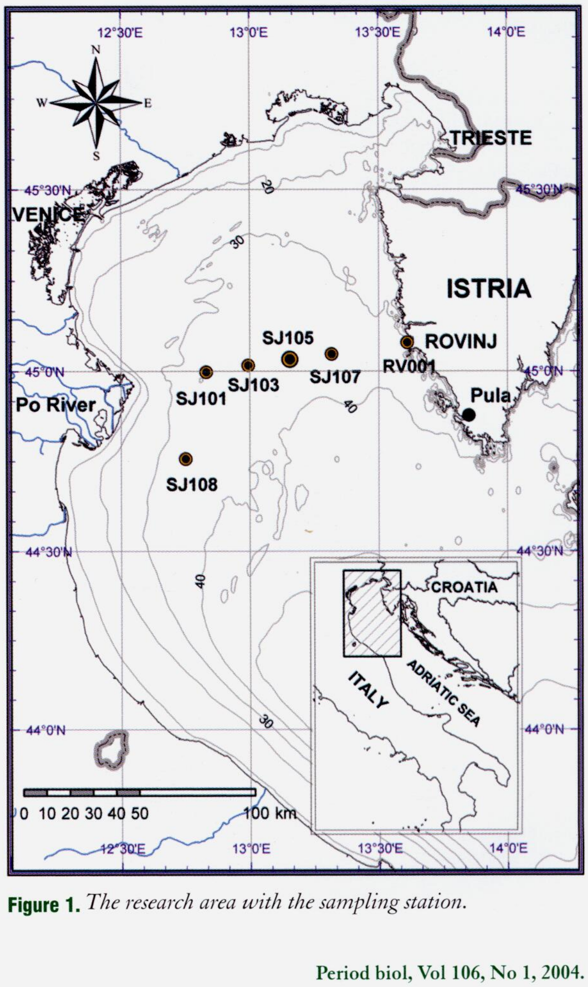

Figure 1. *The research area with the sampling station.*

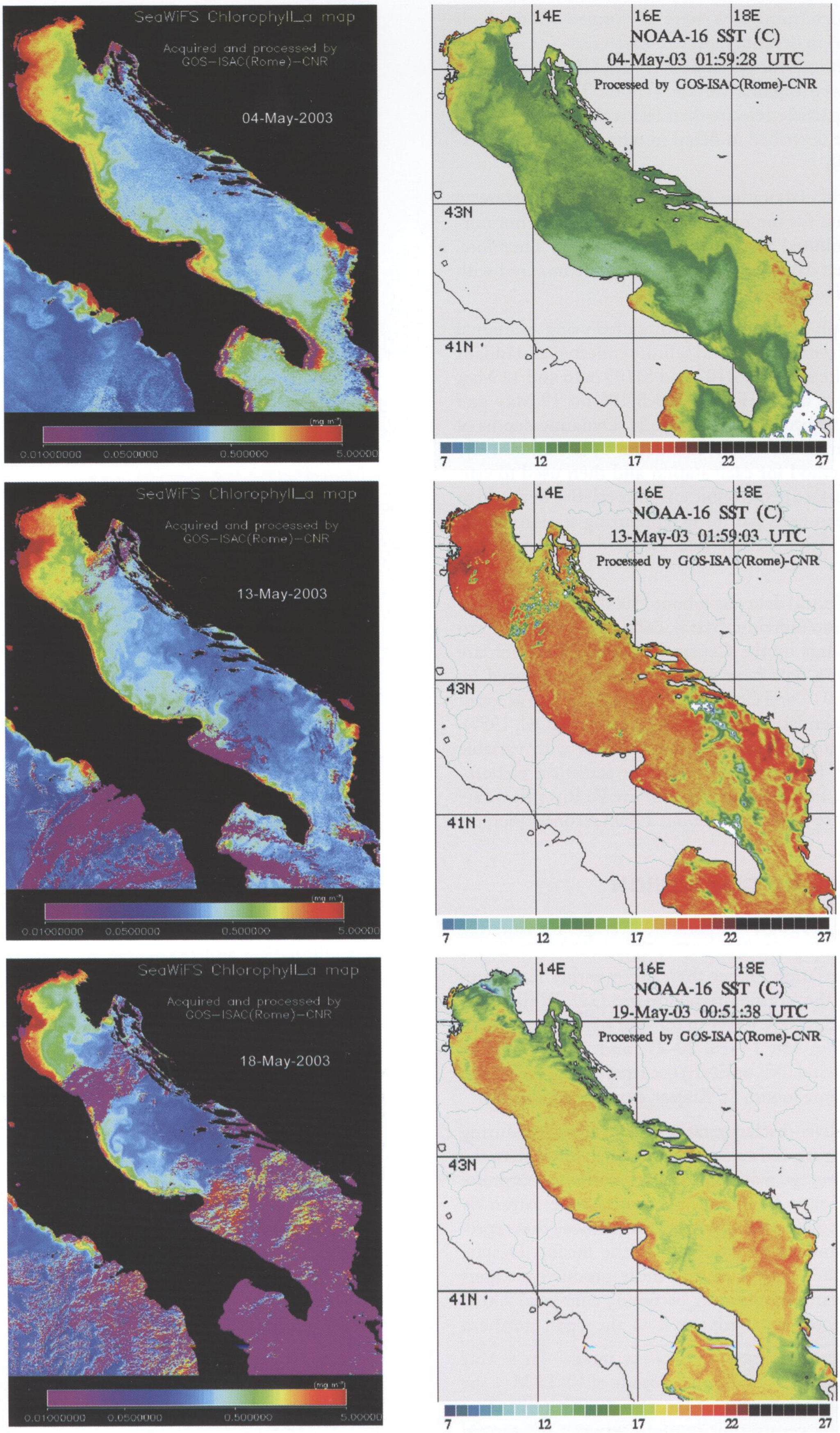

Figure 2. *Satellite images of surface chlorophyll-a (SeaWiFS) and temperature (AVHRR, NOAA-16) in May 2003.*

plankton determinations were performed by methods widely used in oceanographic research *(28–32)*. The analytical methods for particulate (POC, CHNS analyser) and dissolved organic carbon (DOC, TOC analyser), and microparticle (electrochemical technique) determinations are described in detail in other papers of this issue *(33, 34)*.

Statistical elaboration of long-term data sets showed that the data for the parameters concerned are not normally distributed around the average value. Therefore, the collected data during sampling were compared with medians of long-term values.

Geostrophic currents were computed using additional data sets of temperature and salinity collected at standard depths of the stations SJ107 and SJ105 on 6 and 12 May, as well as at the stations SJ103-SJ108 on 19 May and RV001-SJ105 on 20 May (Figure 1). Dynamic depths of the 30-dbar surface were calculated by a standard dynamical method for each station and then used to estimate the surface geostrophic currents relative to the 30 m level between each pair of neighbouring stations at the Rovinj-Po Delta section (see *14* for details and references).

The historical data sets (about 150000 records or more than a million individual data), collected in the northern Adriatic waters by the Center for Marine Research are available in a data base management system based on Paradox 10.0 (Corel Corp.) software, taking into account the recommendation for the GF3.2 format (IOC, 1987). These sets are organized in six modules with variable numbers of fields and are ready for statistical elaborations with a PC. Daily averages of the Po River flow rate from 1917 are also stored (about 29000 records) therein.

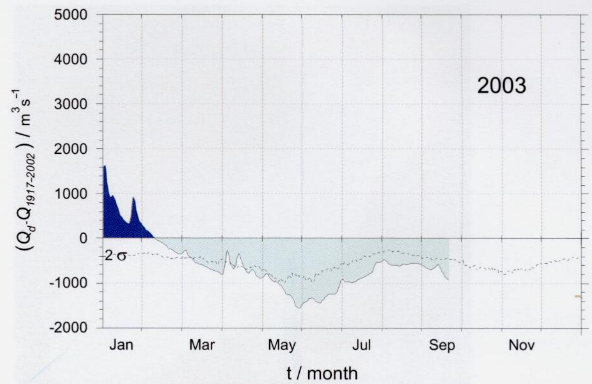

Figure 3. *Daily Po River flow rate differences (Q_d-$Q_{1917–2002}$) between 2003 values and average annual model for the period 1917–2002. Dotted line represents two standard deviations (2 σ) from the model means.*

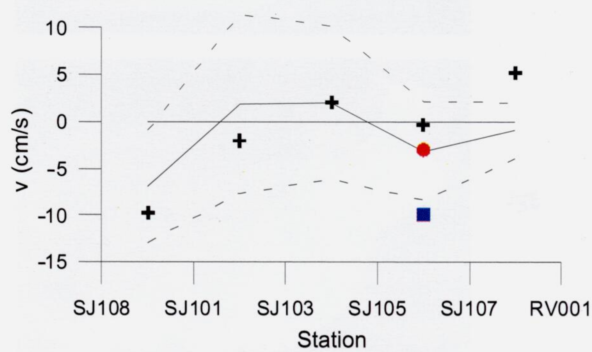

Figure 4. *Geostrophic currents relative to 30 m depth between stations of the Po Delta- Rovinj profile on 6 (●), 12 (■) and 19–20 (✚) May 2003. Solid and dashed lines represent averages and standard deviations for the period 1972–1992. Positive values indicate northwards currents (inflow into the northern Adriatic).*

RESULTS AND DISCUSSION

The May 2003 air temperature average, measured at Pula meteorological station (20.1 °C), was more than one standard deviation higher than the monthly long-term average for the northeastern Adriatic *(35)*. While daily wind velocities were lower in the first half of the month, three episodes (on 14–16, 20–21, and 27–28 May) of strong bora wind (NE or ENE) occurred during the second half of the same month (V. Krajcar, personal commun.).

The Po River discharge rates in May, as well as during the entire spring and summer, were much lower than the long-term average, without any short-term high impulse episodes (Figure 3). In fact, the values were extremely low since mid May, being even below of those that represent two standard deviations from the means. Despite these low rates, freshened and more productive waters spread eastwards significantly, becoming entrapped within a semi-enclosed circulation cell in the open northern Adriatic, as was denoted by satellite images for 4 May (Figure 2). After the NW wind episode of 10–13 May, the eastward water transport was seemingly enhanced (Figure 2). Strong geostrophic outflow between the central (SJ105) and the eastern station (SJ107), observed on the sampling dates, indicated the formation of an anticyclonic cell (Figure 4), similar to that described in the average geostrophic circulation pattern in the region for May (1911–1914 and 1947–1998; *6*). The data collected on 19 and 20 May along the Rovinj-Po Delta profile confirmed the persistence of the anticyclonic motion, in spite of the intensification of northwards water transport in the eastern part (Figure 4) and enhanced vertical mixing, due to cooling of the sea surface in the northernmost part of the region (Figure 2) after the 14–16 May bora episode. This motion (up to 2 cm/s and close to the 1972–1997 average) was much slower than in early May although still encircled a surface pool of warmer lower salinity waters including the sampling station (Figure 5).

Despite the drastic reduction of the freshwater input, surface salinity and density were lower (6 May) or not very different (12 May) compared with their respective long-term medians (1972–2002) for May, while the values for temperature were higher, especially during the first sampling (Figure 6). At 5 m and 10 m depths, salinity and density were higher, while the temperature was lower than (6 May) or close to (12 May) the average, implying an increased inflow of central Adriatic waters. Intrusions of unusually high salinity waters in spring and than in the subsurface layer, probably due to increased orthophosphate availability.

Among nutrients, only orthophosphate concentrations varied significantly between the two sampling days (Figure 6). The values in the upper water column on 6 May were similar to the long-term medians, but they were higher in the deeper layers. In contrast, on 12 May the concentrations decreased substantially, approximating the medians only in the lower water column. The vertical distribution of total inorganic nitrogen (TIN) during both samplings was characterised by higher concentrations than on average at the surface, but lower in the bottom layer (Figure 6). In the major part of the water column values close to the long-term medians were measured. Orthosilicate concentrations (SiO_4) were higher than the medians in the upper water column, and slightly increased to-

TABLE 1

Microphytoplankton abundances (cells L^{-1}) on two performed cruises in May 2003 with minimum, median and maximum values for May in the period 1981–2002.

Depth/m	06.05.2003.	12.05.2003.	May (1981–2002)		
			Min.	Median	Max.
0	45880	27010	3772	94454	6211800
5	11100	1850	–	–	–
10	5550	740	3330	21275	624560
35	3700	–	920	13690	594220

TABLE 2

Abundances of identified microphytoplankton species at the sampling station (SJ105) on 6 and 12 May 2003. B=*Bacillariophyceae*, D=Dinoflagellates.

Species	Abundance (cells L^{-1})						
	06.05.2003.				12.05.2003		
	0m	5m	10m	35m	0m	5m	10m
Chaetoceros sp.			740				
Dactyliosolen fragilissimus (Bergon) Hasle	37740	5180	4810		24790	1480	740
Diploneis sp.				740			
Leptocylindrus danicus Cleve	370	370					
Navicula sp.				740			
Nitzschia tenuirostris Mer. S.l.				1850			
Pleurosigma normanii Ralfs				370			
Undeterm. *Bacillariophyceae* (one pennate species)	4440	4440			2220		
Ceratium furca (Ehrenberg) Claparède & Lachmann	2590	370					
Glenodinium sp.		370					
Noctiluca scintilans (Macartney) Kofoid et Swezy	370	370				370	
Prorocentrum micans Ehrenberg	370						

TABLE 3

Bacterial (bact.) and heterotrophic nanoflagellates (HNF) abundances at the sampling station (SJ105) on 6 May 2003 and minimum, average and maximum values for May in the period 1990–2002.

Depth/m	C(bact.)/ 10^8 L^{-1}	C(HNF)/ 10^6 L^{-1}	May (1990–2002)					
			C(bact.) / 10^8 L^{-1}			C(HNF) / 10^6 L^{-1}		
	06.05.2003.		Min.	Average	Max.	Min.	Average	Max.
0	11.9	10.2	4.6	15.8 ± 12.2	49.0	1.5	5.2 ± 2.7	10.5
5	9.1	0.8	4.5	13.5 ± 9.8	36.0	1.1	6.1 ± 3.4	11.3
10	9.5	0.4	3.5	9.8 ± 4.9	18.4	0.3	4.0 ± 3.5	13.4
20	8.3	0.03	3.5	10.7 ± 5.4	21.4	0.3	2.9 ± 1.6	5.5
35	9.6	0.09	4.2	12.3 ± 6.4	22.8	0.1	1.8 ± 1.4	4.9

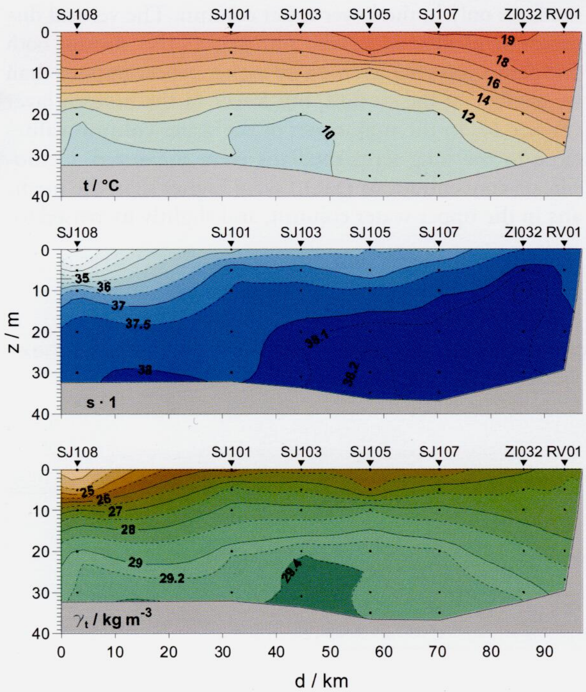

Figure 5. *Temperature (t), salinity (s) and density (γ_t) distribution along the Po Delta-Rovinj profile on 19–20 May 2003.*

early summer, affecting the northern Adriatic intermediate layers, were observed since the late eighties in correspondence to mucilage events *(23)*. The lower water column (≥ 20 m depth) was well mixed and the values for these parameters did not differ significantly from the long-term medians.

The vertical profiles of the oxygen saturation ratio were typical for May, characterised by a moderate supersaturation in the upper water column, with values (110–115 %) very close to the long-term medians, and a slight undersaturation in the lower water column (~ 95 %), although significantly less marked than on average (Figure 6).

The chlorophyll *a* concentrations did not differ to a great extent from the medians (Figure 6). However, it should be highlighted that the surface value on 12 May was lower than during the first sampling (6 May). This change was in agreement with a salinity increase, and particularly with the depletion of orthophosphate. Orthophosphate assimilated during the spring bloom could not be replaced by Po River discharges, because of extremely low flow rates during mid- and late May (Figure 3). This supports the hypothesis that, at least in spring, phosphorus is the principal element limiting primary production in the northern Adriatic *(1, 36, 37)*. In deeper layers, chlorophyll *a* concentration was slightly higher

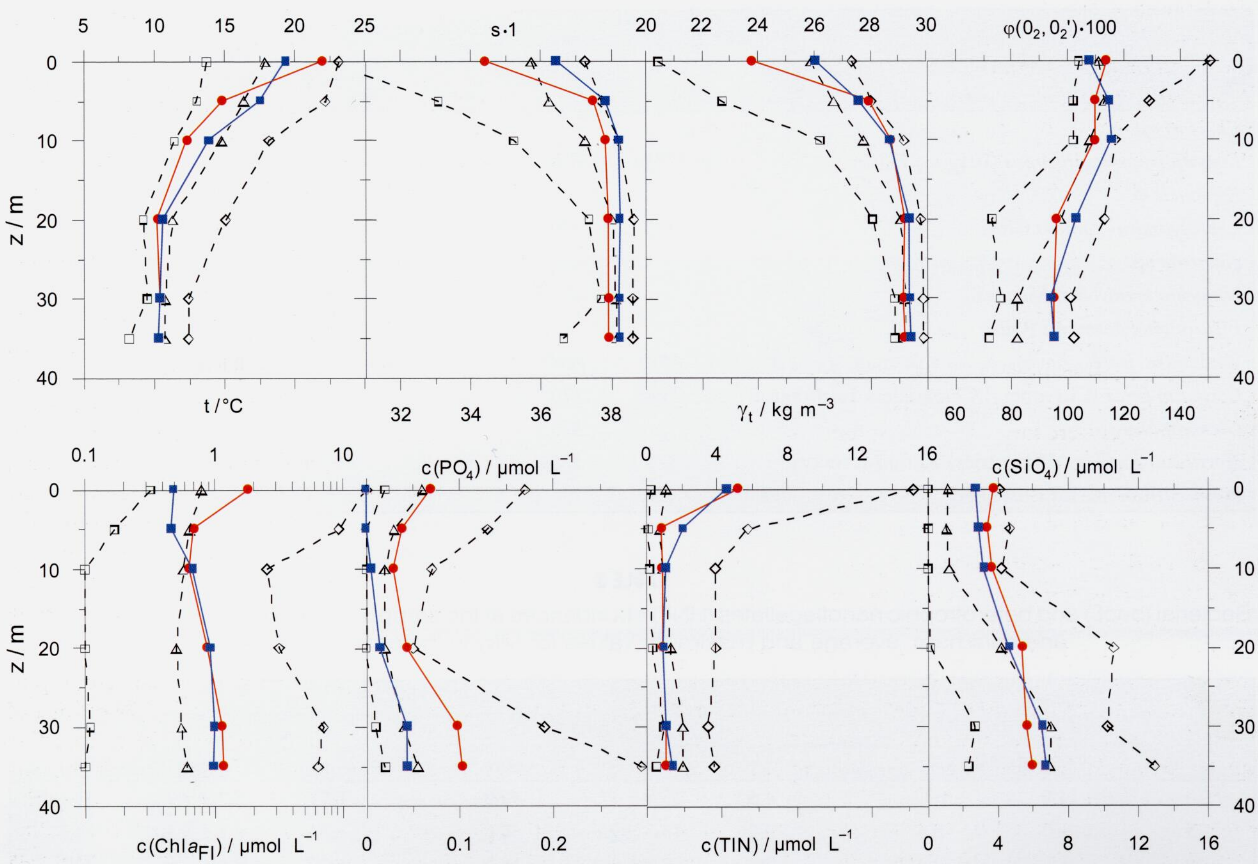

Figure 6. *Temperature (t), salinity (s), density (γ_t), oxygen saturation [$\varphi(O_2,O_2')$], chlorophyll* a *($Chla_{Fl}$), orthophosphate (PO_4), total inorganic nitrogen (TIN) and orthosilicate (SiO_4) distribution at the sampling station (SJ105) on 6 (●) and 12 (■) May 2003. Dashed lines represent minimum (□), median (-) and maximum (◇) values for May in the period 1972–2002.*

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35	9.6	0.09	4.2	12.3 ± 6.4	22.8	0.1	1.8 ± 1.4	4.9

TABLE 4

Particulate organic carbon (POC), total particulate nitrogen (TPN) and dissolved organic carbon (DOC) at the sampling station (SJ105), on 6 and 12 May 2003.

Depth/m	06.05.2003.			12.05.2003.	
	POC / µmol L^{-1}	TPN / µmol L^{-1}	DOC / µmol L^{-1}	POC / µmol L^{-1}	TPN / µmol L^{-1}
0	31.1	4.5	199	20.7	2.0
5	12.3	1.7	153	14.2	2.3
10	15.2	2.1	139	12.7	1.4
20	18.4	2.6	160	18.0	2.9
30	15.5	1.6	119	9.8	1.3
35	10.2	1.7	143	18.6	2.4

wards the bottom, approximating the usual values for the deeper layers (Figure 6). The fact that TIN and SiO_4 concentrations did not change between the two samplings, despite the salinity increase, indicates that, as a difference of PO_4, N and Si regeneration processes dominated over their assimilation by phytoplankton.

Microphytoplankton abundances were up to four times lower than the medians for this month (period 1981–2002), or even more in the intermediate layer on 12 May (Table 1). As usual, the surface values were much higher than in the rest of the water column, decreasing gradually by at least one order of magnitude towards the bottom. All identified species are often present in May at the sampling station (SJ105; Table 2). *Dactyliosolen fragilissimus* (Berghon) Hasle (syn. *Rhizosolenia fragilissima* Berghon) highly dominated the microphytoplankton community in May 2003. Other well represented species were *Cerataulina pelagica*, *Pseudo-nitzschia delicatissima* and *Nitzschia tenuirostris*. Other species, identified in much smaller abundances, are usually present either often (*Ceratium furca, Ceratium fusus, Pyrophacus horologicum, Glenodinium sp., Gonyaulax sp.*) or rarely (*Thalassiosira sp., Ceratium candelabrum, Ceratium longirostrum*), but always in low abundances. The dinoflagellate *Noctiluca scintilans*, generally considered as a heterotrophic species, was also present, but in very low abundance (Table 2).

Bacterial abundances on 6 May (~10^9 L^{-1}) were moderately lower than the average values for the period 1990–2002 (Table 3). These differences were somewhat larger in the surface layer. In this layer the heterotrophic nanoflagellate abundance almost reached the maximum for the period 1990–2002, although in the most part of the water column the values were close to historical minima (Table 3).

Surface active particles (SAP) were measured at the station SJ105 since February 1998, while gel microparticles (GeP) determination started only recently. SAP values on 6 May 2003 were close to or even higher than the maxima for the period 1998–2003 (Figure 7). However, on 12 May the values were reduced to average levels in the most part of the water column except at 10 m depth that was at the bottom of the main pycnocline layer (Figure 6). GeP concentrations were significantly lower than SAP values, particularly during the second sampling. Previous measurements indicated that GeP concentrations generally account for less than 10% of SAP concentrations *(38)*. However, on 6 May the GeP values accounted for up to 40 % of SAP values (Figure 7).

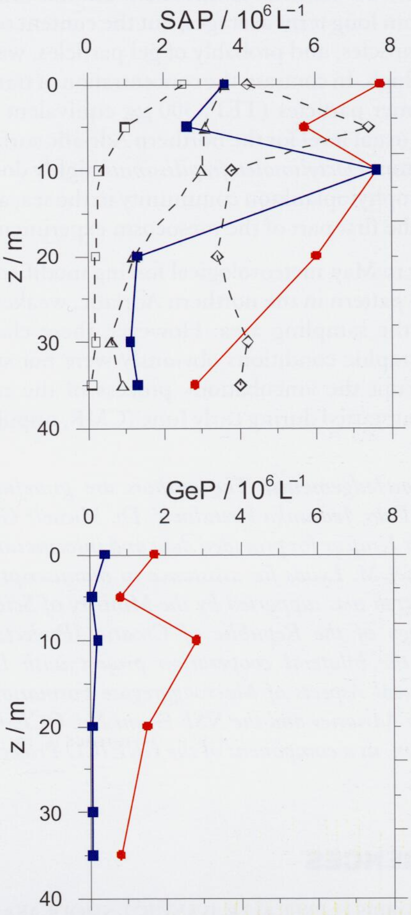

Figure 7. *Surface active (SAP) and gel (GeP) microparticles distribution at the sampling station (SJ105) on 6 (●) and 12 (■) May 2003. Dashed lines represent minimum (□), median (-) and maximum (◇) values for May in the period 1998–2003.*

Particulate organic carbon (POC), total particulate nitrogen (TPN) and dissolved organic carbon (DOC) concentrations were significantly higher at the surface than in lower layers (Table 4). Remarkably, surface POC and TPN values on 12 May were lower than on 6 May, in accordance with changes of related parameters (e.g. salinity increase and decrease of microphytoplankton abundance as well as chlorophyll *a*, ortohophosphate and microparticle concentration).

CONCLUSIONS

Despite the extremely low Po discharge rate, freshened surface waters were transported eastwards and entrapped in a gyre (probably anticyclonic), in which frontal area seawater for the mesocosm experiment was collected on 6 May 2003 (station SJ105; Figure 1). Nutrient and chlorophyll *a* concentrations, as well as microphytoplankton and bacterial abundances did not differ especially from long term averages, but the content of surface active particles, and probably of gel particles, was exceptionally high. In contrast, the concentration of transparent exopolymer particles (TEP; 300 μg equivalent L^{-1}; *39*) was at a usual level for the northern Adriatic surface *(40)*. The diatom *Dactyliosolen fragilissimus* highly dominated the microphytoplankton community in the sea, as well as during the first part of the mesocosm experiment *(41)*.

Later in May, meteorological forcing modified the circulation pattern in the northern Adriatic, weakening the gyre in the sampling area. However, these changes in oceanographic conditions obviously were not sufficient to interrupt the »incubation« process of the mucilage event that started during early June (CMR, unpub. data).

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