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Phytoplankton seasonality and composition along the coastal NE Adriatic Sea during the extremely low Po River discharge in 2006

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Phytoplankton composition and abundance were analyzed in the period January–September 2006, along the NE coastal Adriatic. In 2006, the Po River discharge was twice as low as the 90 year average. The maximum riverine water inflow did not appear in spring but in September, resulting in a shift of phytoplankton maximum from spring to autumn. Diatoms provided most abundant phytoplankton with an annual maximum of 6 x 10^5 cells L^{-1} in the west Istrian coastal region (in September–October). The annual average abundance of diatoms was low (5.1 x 10^4 cells L^{-1}), but bigger than that of dinoflagellates (28x), coccolithophorids (13x), cryptophytes (6x) and green nanoflagellates (9x), respectively. A comparison was made between phytoplankton seasonality in the dry year 2006, and the year 2001 characterized by greater freshwater inputs. The drought period was characterised by the small cell size diatoms *Cyclotella* and *Thalassiosira*. Po River discharge from the west, the north-westerly ingoing current (Eastern Adriatic current) and oligotrophic karstic waters discharging along the eastern coast, strongly influence phytoplankton dynamics in the NE coastal Adriatic Sea.

Key words: Phytoplankton, seasonality, abundance, Po River, discharge, Adriatic Sea

Introduction

The northern part of the Adriatic is shallow (less than 50 m deep) and relatively isolated from the central sub-basin of intermediate depth and a deep southern sub-basin, deeper than 1000 m. The northern part of the Adriatic Sea receives significant freshwater inputs, which have a marked positive impact on productivity (DEGOBBIS et al. 1986, DEGOBBIS and GILMARTIN 1990). The outflow of the Po River provides over 50% of the freshwater input to the northern Adriatic basin, making this river the most important contributor of organic matter and nutrients to the Mediterranean (PETTINE et al. 1998). The characteristics of the phytoplankton seasonal cycle depend upon input of nutrients and physical processes (ZAVATARELLI et al. 2000). Since climatological changes may impact the productivity of the Adriatic Sea, we defined phytoplankton composition and seasonality along the NE coastal Adriatic, during the extremely low Po River discharge in 2006.

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The investigated area

The northern Adriatic is the northernmost part of the Mediterranean Sea. The Adriatic Sea is a temperate sea, with temperatures almost always above 10 °C. The northern Adriatic is 8–10 °C colder than its southern part during winter. It is a shallow Adriatic sub-basin (mean depth about 30 m), with two NE extensions – the Gulf of Trieste and Rijeka Bay. In contrast to the shallow NW Adriatic which receives a large amount of freshwater from the Po River (RAICICH 1996), the NE coastal Adriatic is deeper (60–65 m in Rijeka Bay and the Vinodol Channel), and is influenced by oligotrophic karstic waters and a north-westerly ingoing Eastern Adriatic current coming from the Ionian Sea (GAČIĆ et al. 2001). The NE coastal Adriatic – Rijeka Bay and the Vinodol Channel (the area where Station Cr 001 is situated)– is isolated from the offshore sea by islands (Fig. 1) and under great continental influence, especially that of the catabatic wind the bora in winter, with gusts reaching 50 m s^{-1} surpassing speeds observed elsewhere in the Adriatic (MAKJANIĆ 1976, LEE et al. 2005). Mean daily tidal range in this area is estimated to be 30 cm (KASUMOVIĆ 1960).

The circulation in the investigated region is complex. There are generally two water masses, the less saline water mass distributed to the north-west, and the higher saline water mass distributed to the south-east of the Istrian front (LEE et al. 2005), which is commonly formed southwestward from the Istrian peninsula.

The main circulation in Rijeka Bay (an area of approximately 450 km^2) is cyclonic (ORLIĆ and KUZMIĆ 1985), as is the general Adriatic circulation (ORLIĆ et al. 1992, ARTEGIANI et al 1997). The communication with offshore waters is mainly through Kvarnerić and Kvarner, i.e the passages between the islands of Krk, Cres and the Istrian peninsula. Circulation can be modified by winds (ORLIĆ et al. 1994), especially bora (JURČEC 1981, PENZAR et al. 2001) and freshwater discharge (LEDER et al. 1998).

The catchment area of the Istrian peninsula and the surrounding Rijeka Bay is composed of permeable carbonate rocks (BIONDIĆ et al. 1996). Precipitation in the Rijeka Bay hinterland (above 1000 m above sea level) is higher than 3000 mm (GAJIĆ-ČAPKA et al. 2003) with short-term precipitation possibly up to 46 mm per hour (GAJIĆ-ČAPKA 1991). The annual precipitation maximum is usually in November (PENZAR and PENZAR 1980). The surrounding coast abounds with coastal and submarine springs (BENAC et al. 2003).

Materials and methods

Water samples were collected along the permanently monitored profile along the Istrian peninsula; from the Slovenian border on the North, to Vinodol Channel in the East (where Station Cr 001 is situated)(Fig. 1), at approximately monthly intervals, in the period January–November 2006.

Samples for the determination of phytoplankton abundance were taken with a 5 L Niskin sampler. Samples were preserved in a 2 per cent (final concentration) neutralized formaldehyde solution. The phytoplankton abundance (cells per liter) was determined using the inverted microscope method (UTERMÖHL 1958; HASLE 1978a, b; VENRICK 1978). Sub-samples of 50 mL were analyzed using a Zeiss Axiovert 200 microscope, after a sedimentation time of 24 h, within one month after the cruise. Recognizable nanoplankton cells (longer than 5 µm) and abundant microphytoplankton cells (longer than 20 µm) were counted and identified at a magnification of 400x. Usually one transect was scanned with 400X and two transects with 200X, with a phase contrast. At 100X a total bottom count was completed for taxa greater than 30 μm. The minimum concentration that can be detected by this method is 20 cells L^{-1}.

The entire phytoplankton community was identified to species or genus according to recent keys, as described elsewhere (VILIČIĆ et al. 2002).

Results

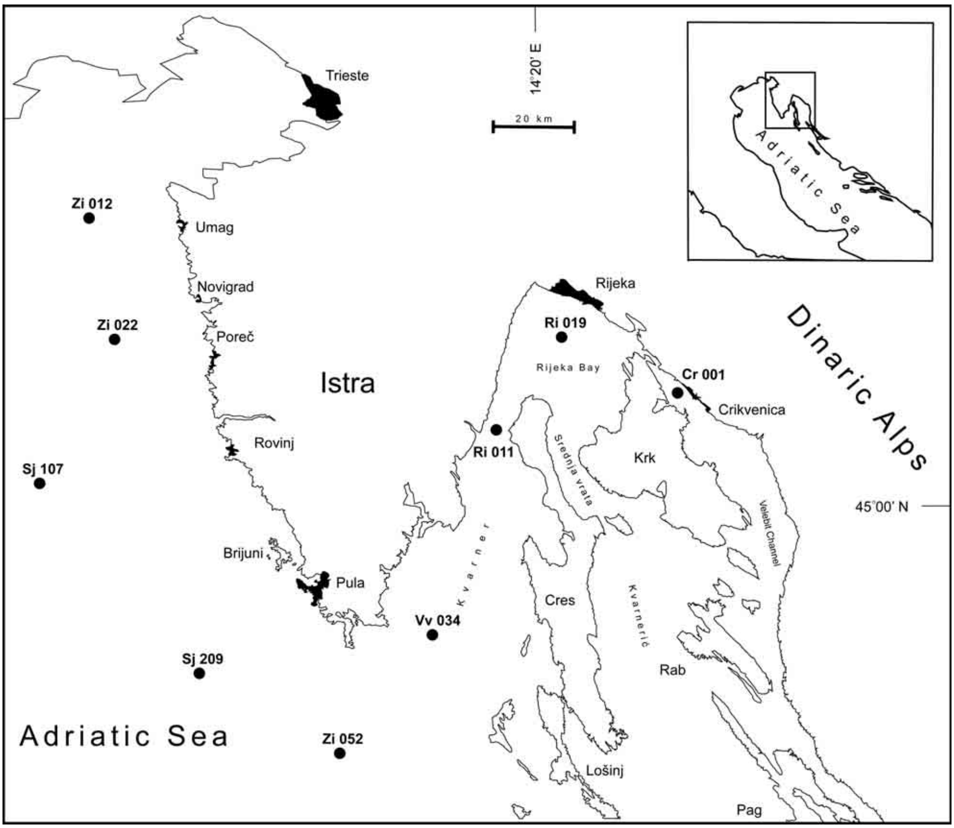

Fig. 1. Map and position of stations along the »Istrian profile« in the NE Adriatic Sea.

In the period January–September 2006, there was extremely low Po discharge, providing an annual discharge twice as low as the 90 year average. The seasonal distribution of the inflow was characterized by a shift of maximum values from spring to autumn (Fig. 2). Diatoms provided most the abundant phytoplankton along the investigated profile (Istrian profile). The maximum annual abundance of diatoms was 4–5 x 10^5 cells L^{-1} in the west Istrian coastal region, September–October (Fig. 3, 4). The annual average abundance of di-

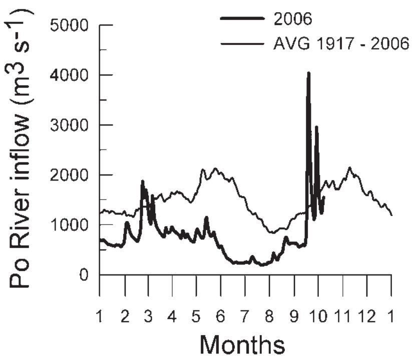

Fig. 2. Daily discharge of the Po River in 2006 at the station Pontelagoscuro.

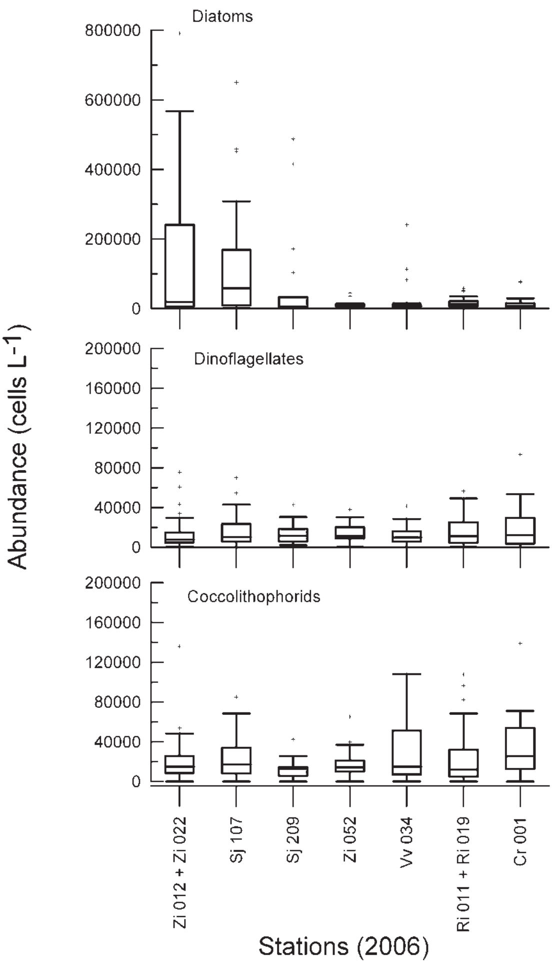

Fig. 3. Distribution of diatoms, dinoflagellates and coccolithophorids along the Istrian profile, presented by Box Whisker plots in 2006.

atoms was low (5.1 x 10^4 cells L^{-1}), but bigger than that of the dinoflagellates (28x), the coccolithophorids (13x), cryptophytes (6x) and green nanoflagellates (9x). Maximum abundance of diatoms appeared neither in spring nor at station Sj107 which is generally the mostly influenced by the Po River. In spring, diatom abundance increased as compared to Rijeka Bay, where the maximum abundance of 10^5 cells L^{-1} was registered.

The maximum abundance of dinoflagellates (Fig. 4) and coccolithophorids (Fig. 5) appeared in June, of cryptophytes in May (at the eastern stations, Fig. 6), and green nanoflagellates in May and September (at the northern stations)(Fig. 6).

In the spring-summer oligotrophic conditions, small dinoflagellates also appeared in small abundances (average 10^4 cells L^{-1}), increasing in the direction of Rijeka Bay. Coccolithophorids, cryptophytes and green flagellates played an important role in the pelagic

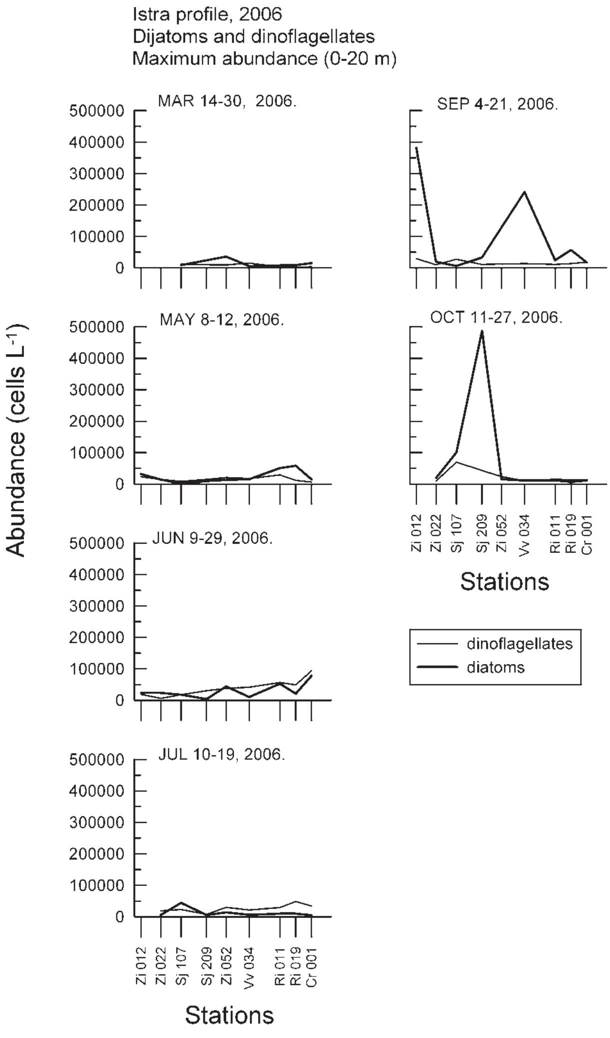

Fig. 4. Distribution of diatoms and dinoflagellates along the Istrian profile in 2006.

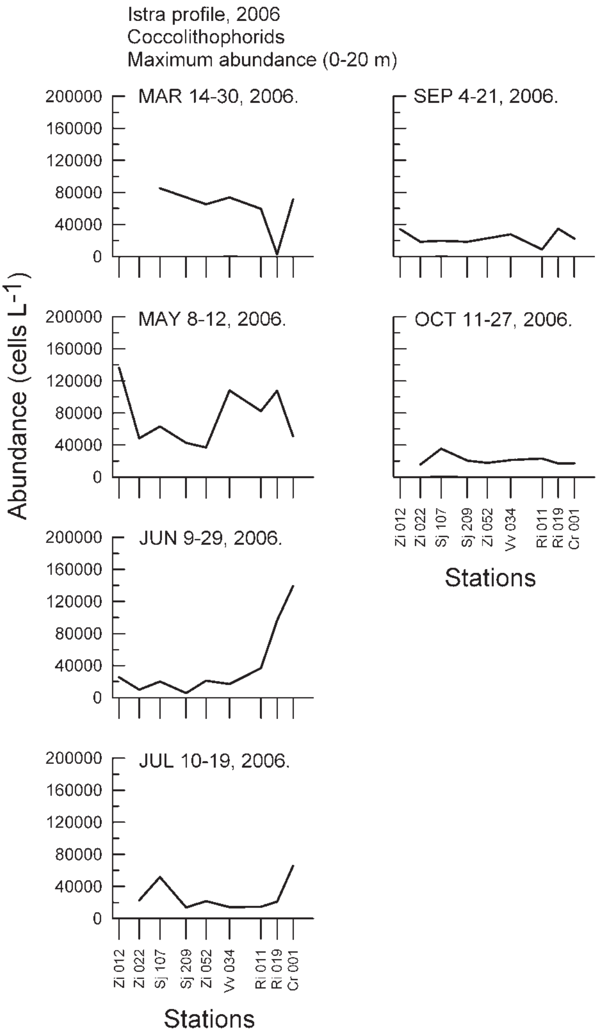

Fig. 5. Distribution of coccolithophorids along the Istrian profile in 2006.

community, with a similar horizontal trend of distribution. North Adriatic oligotrophication was most considerable in June 2006, with a minimum abundance at Station Sj107.

In September and October, high influxes of fresh water resulted in the enrichment of the Northern Adriatic with nutrients, and the development of phytoplankton at western stations of the profile. In the October 2006, increased diatom abundance was also found in the region around the tip of the Istrian peninsula.

The minimum phytoplankton abundance was most frequently found around the tip of the Istrian peninsula, at Stations Zi052 and Vv 034.

Taxonomic composition of microphytoplankton revealed the dominance of diatoms, the most abundant genera being those of *Chaetoceros* and *Pseudo-nitzschia* (Fig. 7) which

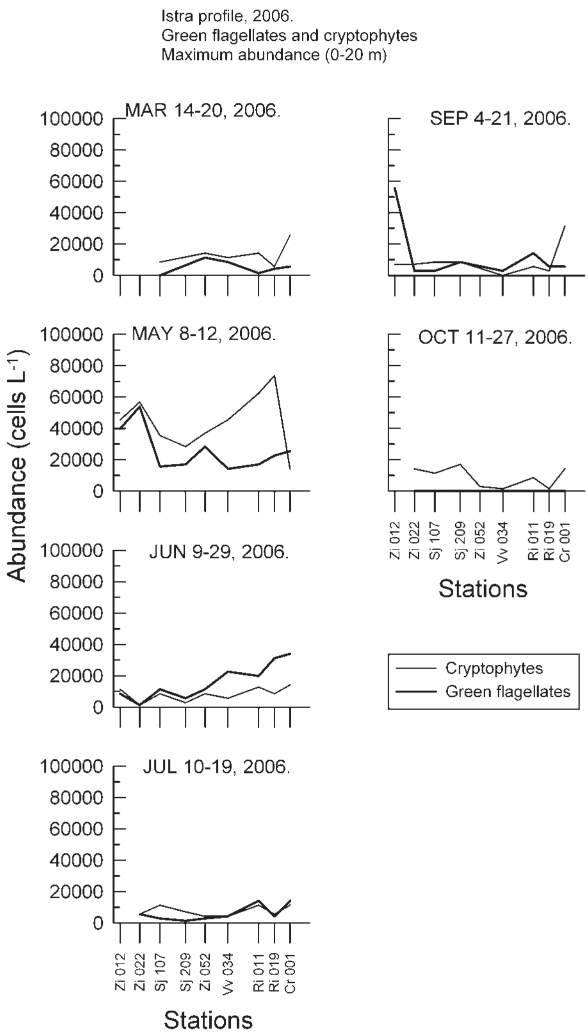

Fig. 6. Distribution of cryptophytes and green nanoflagellates along the Istrian profile in 2006.

reached 6 x 10^5 and 1.2 x 10^5 cells L^{-1} in autumn 2006, respectively (Tab. 1) Microdinoflagellates were scarce throughout the year (maximum 1.7 x 10^4 cells L^{-1}).

Among dinoflagellates, toxic dinoflagellates are of economic interest and human health. Five toxic dinoflagellates were registered along the Istrian profile in 2006 (*Dinophysis acuminata, D. caudata, D. forti, D. rotundata, Lingulodinium polyedricum* i *Prorocentrum minimum*) (Tab. 2). Toxic *Dinophysis* species were found in up to 2.8 % of the analyzed samples. The most frequent species *Dinophysis caudata* appeared in the period July–October, with maximum abundance of 240 cells L^{-1} in September. Among other toxic dinoflagellates, *Prorocentrum minimum* was found in 7.8 % of samples, with the maximum abundance of 8.5 x 10^3 stanica L^{-1} in February 2006. *Lingulodinium polyedricum* was found in small abundances, up to 380 cells L^{-1}.

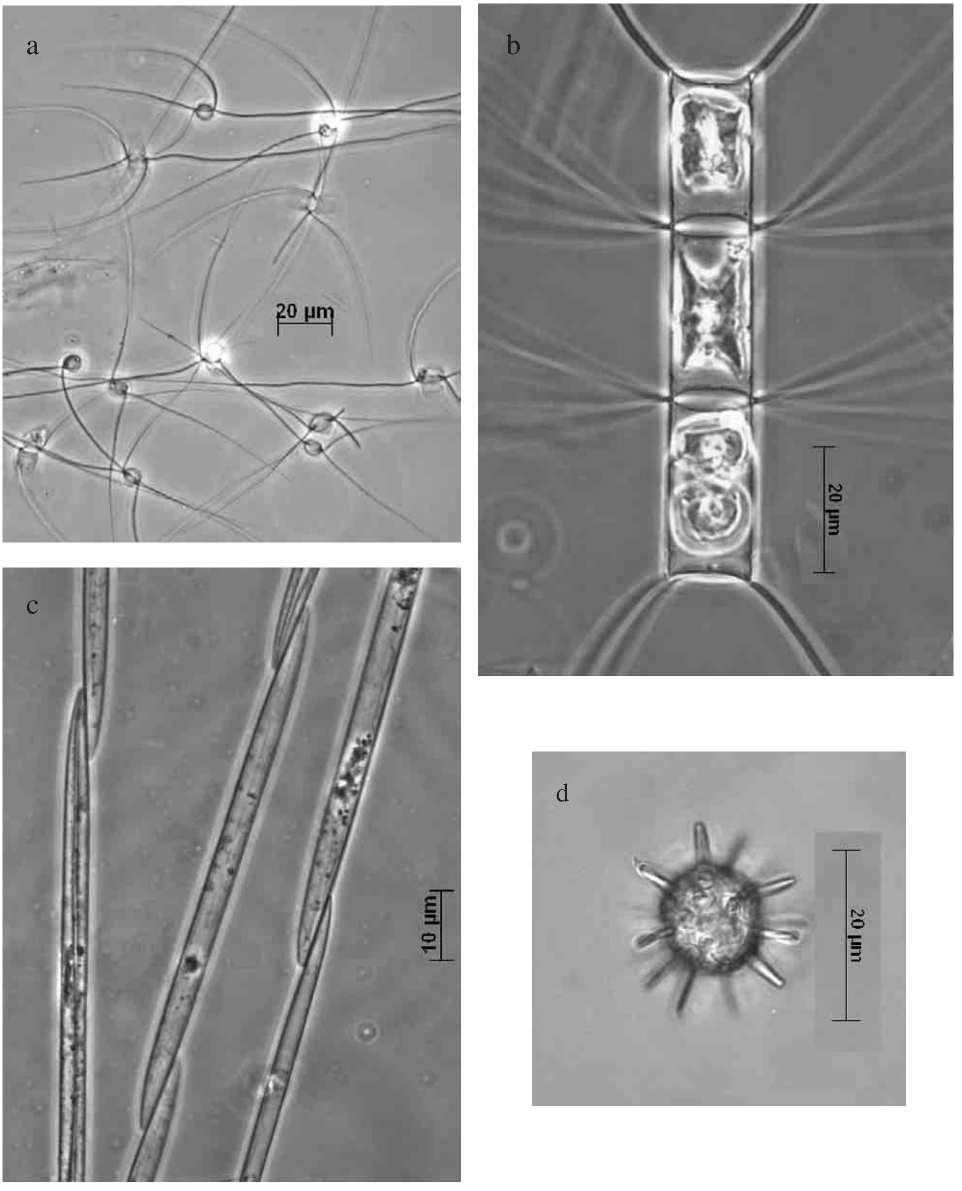

Fig. 7. The most abundant phytoplankton in the NE Adriatic Sea in 2006. Diatoms (a–c), and coccolithophorids (d); a – *Chaetoceros socialis*, b – *Chaetoceros affinis*, c – *Pseudo-nitzschia* sp., d – *Rhabdosphaera tignifer.*

Development of the potentially toxic diatom *Pseudo-nitzschia* was low, however, this species should be monitored in the future due to the potential of cells to synthesize domoic acid during global environmental changes and thus changes in physiological activity.

Tab. 1. Seasonal distribution of dominant phytoplankton taxa (with maximum monthly abundance >10000 cells L^{-1} and frequency of appearance >10%) along the Istrian profile in 2006. Total number of samples 217. Maximum monthly abundances for the whole profile are presented. MAX – maximum abundance (cells L^{-1}), Fr (%) in the drought period (January to June 2006). Fr(%) – relative frequency. Differential species from those in 2001 (presented in Tab. 3) are underlined.

Taxa/months 2006	JAN	FEB	MAR	APR	MAY	JUN	JUL	SEP	OCT	NOV	MAX JAN–JUN x 10^3 c L^{-1}	Fr (%)
COCCOLITHOPHORIDS												
Calyptrosphaera oblonga Lohm.	1510	2840	8510	0	8510	14190	5680	2840	1420	2840	14	16.6
Rhabdosphaera tignifer Schiller	1420	0	2840	0	5680	19870	31210	28360	8510	2840	31	50.7
Syracosphaera pulchra Lohm.	1420	380	190	0	2840	5680	4260	2840	12770	8510	12	34.6
DIATOMS												
Asterionellopsis glacialis (Castr.) Round	0	0	0	0	0	0	0	10600	**39400**	11000	11	11.5
Cerataulina pelagica (Cleve) Hendey	945	1135	2650	360	760	1510	380	4550	760	12120	4	39.6
Chaetoceros affinis Laud.	0	0	120	0	0	40	0	24240	**244240**	12120	24	13.4
Chaetoceros curvisetus Cleve	360	570	0	0	0	0	0	2270	2270	30300	2	10.6
Chaetoceros decipiens Cleve	755	2270	1510	0	0	380	0	4170	7580	99090	4	16.1
Chaetoceros rostratus Laud.	0	0	0	0	0	0	0	6060	9090	15150	6	12.0
Chaetoceros sp.	0	0	760	0	28268	18990	22700	221280	47120	128600	28	19.8
Chaetoceros socialis Laud.	0	0	0	0	12770	0	5680	38300	**217030**	**683230**	38	20.7
Chaetoceros vixvisibilis Schiller	0	0	0	0	1895	6060	1140	24240	15150	0	24	12.0
Cyclotella sp.	240	0	1140	0	**56720**	**65260**	0	44260	7090	0	65	20.2
Guinardia flaccida (Castr.) Perag.	190	120	380	40	190	40	190	1140	11401	6060	1	30.9
Leptocylindrus danicus Cleve	0	0	0	0	0	12120	190	19700	10600	42560	19	23.0
Leptocylindrus mediterraneus (Perag.) Hasle	1140	0	380	0	380	755	4170	19000	2650	0	19	22.6
Proboscia alata (Brightw.) Sund.	380	0	190	0	190	3030	12120	11360	1520	3030	12	56.2
Pseudo-nitzschia spp.	1510	160	6820	2275	16720	27270	4550	71440	53960	**120080**	71	61.3
Thalassiosira sp.	1420	14190	0	0	1140	**36890**	1520	**45380**	4920	2840	45	20.3
Penatae	0	2840	1420	0	1510	11350	5680	2840	2840	2840	11	34.1
DINOFLAGELLATES												
Scrippsiella sp.	0	0	380	40	190	17030	5680	760	1140	0	17	21.2

Tab. 2. Seasonal distribution of toxic and potentially toxic phytoplankton along the Istrian profile in 2006. Maximum abundances (MAX, cells L^{-1}) in the layer 0–20 m, and annual relative frequency of appearance of species (Fr%) and average abundance (AVG) at stations Zi 012, Zi 022, Sj 107, Sj 209, Zi 052, Vv 034, Ri 019 and Cr 001. 1 denotes findings exclusively in net samples. Total number of samples 259 (217 taken by Niskin sampler, 52 by net).

Istrian profile/months 2006	**JAN**	**FEB**	**MAR**	**APR**	**MAY**	**JUN**	**JUL**	**SEP**	**OCT**	**NOV**	**2006**		
											MAX	Fr%	AVG
Pseudo-nitzschia spp.	1510	160	6820	2275	16720	27270	4550	71440	53960	120080	120080	61.3	5737.7
Dinophysis acuminata Clap. et Lachm.	0	0	0	0	0	0	1	0	0	0	1	0.0	1.5
Dinophysis caudata Seville-Kent	0	0	0	0	1	1	40	240	200	0	240	2.8	5.9
Dinophysis fortii Pav.	0	0	0	0	0	0	0	40	190	380	380	2.3	6.4
Dinophysis rotundata (Clap. et Lachm.)	0	0	0	0	0	0	0	0	190	380	380	1.4	6.7
Lingulodinium polyedricum (Stein) Dodge	0	0	0	0	40	0	0	380	0	0	380	1.4	6.0
Prorocentrum minimum (Pav.) Schiller	0	8510	2840	0	2840	1420	0	380	2840	0	8510	7.8	135.5

Tab. 3. Seasonal distribution of dominant phytoplankton taxa (with maximum monthly abundance >10^4 cells L^{-1} and frequency of appearance >10%) along the Istrian profile in 2001. Total number of samples 135. Maximum monthly abundances for the whole profile are presented. MAX – maximum abundance (cells L^{-1}) during the increased Po River influence (January to June 2001), Fr (%) = relative frequency. Differential species from those in 2001 are underlined.

Taxa/months 2001	**FEB**	**MAR**	**MAY**	**JUN**	**JUL**	**AUG**	**SEP**	**OCT**	**NOV**	**MAX** JAN–JUN x 10^3 c L^{-1}	**2001 Fr%**
COCCOLITHOPHORIDS											
Rhabdosphaera tignifer Schiller	3200	3200	3200	0	800	0	9600	12800	0	13	21.5
Syracosphaera pulchra Lohm.	44800	800	0	1600	0	0	12800	12800	0	45	31.9
DIATOMS											
<u>Cerataulina pelagica</u> *(Cleve) Hendey*	22400	800	4000	**141740**	0	0	3200	3200	3200	**141**	18.5
Chaetoceros decipiens Cleve	9200	0	16800	6400	0	0	2000	6400	0	17	12.6
<u>*Ch socialis*</u> Laud.	5600	166400	38400	**449970**	25600	3200	6400	99200	0	**449**	24.4
<u>*Ch. throndsenii*</u> Mar. Montr. et Zing.) Mar. Montr. et Zing.	22400	0	**40750**	0	0	3200	3200	16000	9600	41	11.1
<u>*Ch. vixvisibilis*</u> Schiller	0	0	**468650**	0	23200	0	36800	275600	0	**468**	22.2
<u>*Dactyliosolen fragilissimus*</u> (Bergon) Hasle	0	38400	13600	3200	12800	1600	1600	8000	1600	38	32.6
<u>*Hemiaulus hauckii*</u> Grun.	1200	2400	**14400**	0	800	400	800	3200	0	14	23.7
Leptocylindrus danicus Cleve	2400	4000	12800	50880	24000	800	6400	32000	3200	51	37.8
<u>*Nitzschia /Cylindrotheca*</u>	12800	1600	1600	**16000**	1600	12800	12800	19200	**32000**	16	40.7
Proboscia alata (Brightw.) Sund.	1600	1600	4000	19200	2400	51200	51200	3200	1600	19	53.3
Pseudonitzschia spp.	**413400**	23200	54400	17600	11200	251220	251220	33600	24000	54	64.4
Thalassionema nitzschioides Grun.	3200	3200	800	4000	1600	12800	12800	3200	8000	3	28.1
DINOFLAGELLATES											
Amphidinium acutissimum Schiller	0	12800	6400	0	800	0	800	12800	3200	13	18.5
Gymnodinium sp.	3200	2400	3200	1600	11200	800	1600	1600	1600	3	29.6

Discussion

The northern Adriatic has been characterized as a system where the nutrient and primary production cycles are driven by the Po river discharge, pycnocline dynamics and horizontal advection changes, and surface trophic gradients which are in qualitative agreement with the known characteristics of the surface biomass distribution of the Adriatic Sea (ZAVATARELLI et al. 2000).

Physical processes determine and maintain nutrient and phytoplankton biomass distribution in the Adriatic sea (ZAVATARELLI et al. 2000).

The seasonal cycle of the surface potential (gross) primary production rate in the northern Adriatic is characterized by three distinct peaks occurring in February, June and September (SMODLAKA 1986). Occasional increases of primary production are possible in the N. Adriatic in summer, but do not result in the biomass increase, due to zooplankton grazing that controls surface phytoplankton.

According to the model of the Adriatic Sea ecosystem dynamics (ZAVATARELLI et al. 2000), phytoplankton biomass evolves in the near surface layer during autumn-winter, and provides lower values during spring-summer. In the middle and southern Adriatic biomass begins to increase in autumn, decreases during winter, and grows again in February-March.

The N. Adriatic case studies performed in 2001 and 2006 clearly showed that the phytoplankton abundance maxima could appear at any time of the year after the enrichment of the N Adriatic with nutrients (Fig. 8). In 2001, maximum winter discharge (in January) resulted in the maximum phytoplankton abundance one month later. In 2006, the first annual pulse of the Po Riverine water discharge appeared in September, and the subsequent phytoplankton maximum abundance appeared in November. In both cases the discharge of about 4000 $m^3 s^{-1}$ resulted in the maximum phytoplankton abundance of about 5 x 10^5 cells L^{-1}, one and two months later, respectively. The more eutrophicated February to June period in 2001, was characterized by the appearance of more abundant diatoms such as *Cerataulina pelagica, Chaetoceros socialis, Chaetoceros throndsenii*, *Chaetoceros vixvisibilis, Dactyliosolen fragilissimus, Hemiaulus hauckii, Nitzschia/Cylindrotheca* complex and *Pseudonitzschia*(Tab. 3). The increased Po River discharge in autumn 2006 resulted in the development of *Asterionellopsis glacialis*, *Chaetoceros affinis*, *Ch. socialis* and *Pseudo-nitzschia* (Tab. 1). The drought January to June 2006 period was characterised by the small cell size diatoms *Cyclotella* and *Thalassiosira*, which could successfully grow during oligotrophic conditions.

Phytoplankton seasonality (chlorophyll biomass) in the NE Adriatic in seventies to nineties (1972–1992) was characterized by bimodal distribution of maxima, with a more pronounced spring maximum, and a less pronounced autumn maximum (SUPIĆ et al. 2006), and corresponding dissolved organic matter seasonality (GAŠPAROVIĆ and ĆOSOVIĆ 2001). Some summers were characterized by blooms of diatoms and production of organic macroaggregates, i.e. mucilage phenomena (HERNDL and PEDUZZI 1988, KALTENBOCK and HERNDL 1992, DEGOBBIS et al. 1999, NAJDEK et al. 2002). Occasionally summer blooms may be induced by dinoflagellates (CATALETTO et al. 1996). In the last decade (during 1993 to 2000), a shift in the distribution of annual chlorophyll *a* biomass maxima was observed, with predominant annual maxima appearing in autumn in the NE Adriatic (SUPIĆ et al. 2006). Such a shift in the phytoplankton seasonality in the NE Adriatic was the result of a change in the Po River hydrology, i.e. the shift of annual discharge maxima from spring to autumn. In such circumstances annual phytoplankton seasonality remains bimodal, but increasing annual abundance maxima appear in autumn but not in spring. Such an atypical seasonality was found in 2006, with enhanced autumn phytoplankton abundance.

The diatoms along the Istrian profile, are most abundant at the westernmost station Sj 107, due to the greatest influence of the Po River. As in 2005, the absence of the spring development and appearance of the autumn development of phytoplankton clearly continued in 2006, due to the remarkable reduction of the Po River discharge (nutrient enrichment) in winter-spring, and the appearance of a discharge peak in the autumn.

The minimum phytoplankton abundance was most frequently found around the tip of the Istrian peninsula, at Stations Zi052 and Vv 034, due to the greatest influence of oligotrophic water masses coming by the north-westerly ingoing Eastern Adriatic current.

Coccolithophorids, cryptophytes and green nanoflagellates contributed most to the total nanoplankton abundance, as in 2005. The absence of diatoms in spring was compensated for by a greater contribution of nanoplankton (coccolithophorids, cryptophytes and green flagellates) in May 2006.

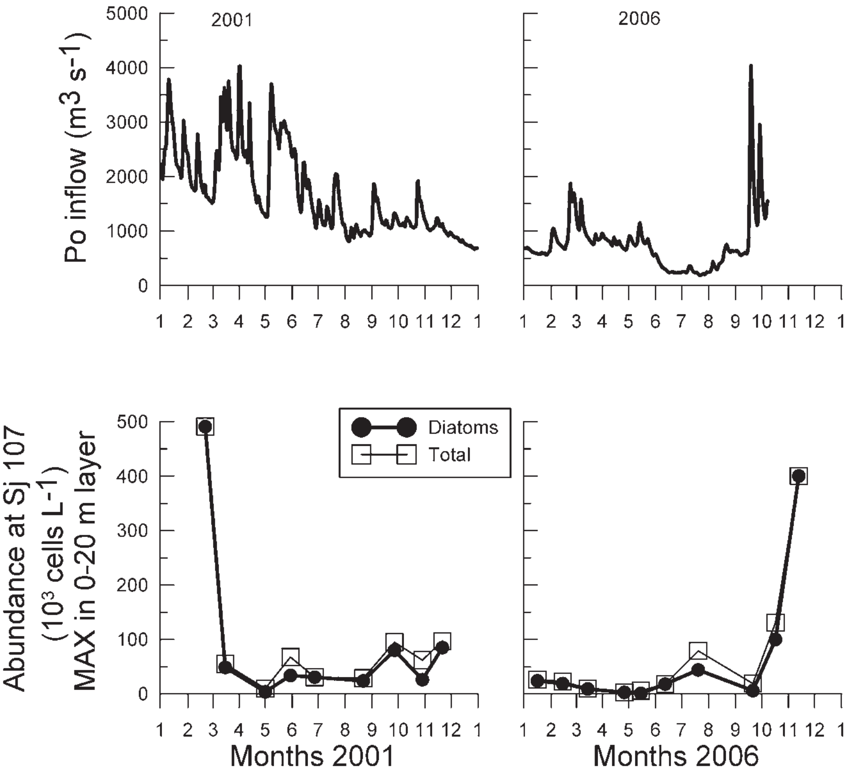

Fig. 8. Comparison between Po River discharge and diatom abundance during 2001 and 2006.

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