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Recent Trends Towards Oligotrophication of the Northern Adriatic: Evidence from Chlorophyll *a* Time Series

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Abstract The results of the updated and quality-checked data base of field observations on chlorophyll *a* (Chl *a*) collected in the period 1970–2007 in the Northern Adriatic Sea are presented. From the last decade, SeaWiFS satellite information was also considered. Results demonstrate a global tendency towards Chl *a* reduction in the period of investigation, which is more marked in the eutrophic area under the influence of the Po River. In the rest of the basin, which presents meso- or oligotrophic characteristics, long-term changes are more difficult to detect. The long-term field dataset can be divided into two periods: the last decade characterized by the strong decrease observed in the whole northern Adriatic and the earlier period with no or slight increase. The recent substantial reduction of Chl *a* concentrations is confirmed all over the basin (-0.11 mg m^{-3} $year^{-1}$) from satellite-derived information. Results are consistent with recently evidenced decrease in concentrations of phosphate and ammonia and point to the existence of oligotrophication in the Northern Adriatic. Results indicate forcefully that the still common perception of the Adriatic Sea as a very eutrophic basin is no longer appropriate, at least for its northern part and in recent years.

Keywords Northern Adriatic · Chlorophyll *a* · Time series · Phytoplankton · Trends

Introduction

Important information on the functioning of marine pelagic ecosystems can be derived from investigation of long-term planktonic studies that can encompass a period of time of up to several decades (e.g., Helgoland Reede data archive, CPR in the North Atlantic; Leterme et al. 2005; Wiltshire and Durselen 2004). Such studies with a historical perspective in time and space are primarily utilized to distinguish nonsystematic natural variability from trends or shifts in the ecosystem that have often been related to eutrophication or anthropogenic disturbances. Sensitive and rapidly changing marine areas like coastal seas and estuaries, where specific hydrology and nutrient loading determine the physical and biochemical properties of the area (e.g., D'Alcala et al. 2004; Harding et al. 1999; Johns et al. 2003; Rydberg et al. 2006; Yunev et al. 2005), are obvious targets for long-term observation.

Not all changes are, however, linked to eutrophication. In the last two decades, several studies (e.g., Goffart et al. 2002;

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Mc Quatters-Gallop et al. 2007; Raitsos et al. 2005; Reid et al. 2001) have indicated a relationship between changing climate and pelagic communities, whose responses can differ at regional scales. Moreover, there is evidence that phytoplankton biomass in either marine (Mc Quatters-Gallop et al. 2007; Smetacek and Cloern 2008) or freshwater ecosystems (Anneville et al. 2002) remains high or even continues to increase despite decreasing nutrient concentrations and inputs from land.

In the Northern Adriatic, several attempts have been made to determine the interannual and seasonal variability of different environmental and biological parameters using datasets of varying time spans, consistency of sampling, and spatial coverage. Most studies, however, were based on data referring to a specific site, such as the Gulf of Trieste (Cataletto et al. 1995; Conversi et al. 2009; Fonda Umani et al. 2004; Kamburska and Fonda Umani 2006; Mozetič et al. 1998; Solidoro et al. 2007), the coastal area in front of Venice (Bernardi Aubry et al. 2004), the central part of the basin (Degobbis et al. 2000), and the Po delta area (Tedesco et al. 2007), while a few studies attempted to address a regional basin scale (Solidoro et al. 2009; Zavatarelli et al. 1998).

Probably the longest time series that covers the whole Northern Adriatic basin is that of an 82-year period of oxygen measurements, which was analyzed with respect to increased eutrophication (Justić 1987). The area was long considered as one of the most productive of the Mediterranean Sea (Sournia 1973), receiving in the 1970s and 1980s around 12×10^9 and 0.5×10^9 mol year^{-1} of total nitrogen and total phosphorus, respectively, from the major freshwater source, the Po River (Degobbis and Gilmartin 1990). This oversimplification was later replaced by the well-recognised division of the Northern Adriatic Sea into eutrophic, mesotrophic, and oligotrophic regions, with only western coastal waters considered as eutrophic (Hopkins et al. 1999). Despite the high variability of the Northern Adriatic both in space and time (seasonal and interannual fluctuations), some authors (Harding et al. 1999; Rinaldi et al. 1998) have, in the late 1990s, documented hints of an inverse trend towards oligotrophication of the basin during certain periods of the year, following the reduction of the phosphorus load in Po River water in the late 1980s (de Wit and Bendoricchio 2001; Pagnotta et al. 1995) and the subsequent increase in N/P ratio (Degobbis et al. 2000) of the notoriously phosphorus-limited Northern Adriatic waters (Chiaudani and Vighi 1982; Maestrini et al. 1997; Pojed and Kveder 1977). This hypothesis was confirmed by recent analysis of a database obtained by compiling and integrating biogeochemical data collected over the last 20 years, which evidences a reduction in the values of ammonia and phosphate (Solidoro et al. 2009). Authors suggest that these observations could be a result of both climatic factors and anthropogenic pressures (i.e., cultural oligotrophication) since the main features emerging from this analysis are the increment in salinity. This might be interpreted as a consequence of both reduced outflows from rivers (higher salinity in coastal areas) and a more sustained ingression of Levantine water (higher salinity in open waters) and a clear reduction in the concentration of phosphate and ammonia in coastal areas. This study, however, derived no conclusive results on the multiannual time course of chlorophyll *a* (Chl *a*) concentrations.

The data set compiled in the present study covers a larger area and a longer period than the ones used in previous studies. The aim is to identify trends of chlorophyll *a*, used as a proxy for phytoplankton biomass in different subareas of the northern Adriatic and on the basin level. Changes in chlorophyll *a* concentrations and seasonal patterns will be discussed in relation to major environmental perturbations during the last decades.

Site Description

The separation line of the semi-enclosed northern basin from the rest of the Adriatic Sea is conventionally defined at the 100 m isobath, at about 43°20′ N (Cushman-Roisin et al. 2001), from where the bottom depth moderately decreases up to the northern coast reaching the smallest average depth in the northernmost protrusion of the basin, the Gulf of Trieste (Fig. 1). Besides the topographic features, the main processes that define the physical properties and dynamics of the Northern Adriatic are atmospheric forcing, as wind stress and heat flux, and the freshwater inputs of the major rivers along the Italian coast. Due to intense evaporation during winter, caused by cold and dry winds blowing over the Northern Adriatic, dense water is formed (Artegiani et al. 1989; Gačić et al. 1999). As for atmospheric forcing, dominant winds are the Sirocco (from the southeast) and the Bora (from the northeast). Wind-induced circulation in the case of the Bora, more frequent in autumn and winter, might generate a “double gyre” configuration (Kuzmić and Orlić 2006), with a cyclonic gyre in the northern part of the basin, able to push the Po freshwater flux up to the Istrian coast and the Gulf of Trieste on the eastern part of the basin, and an anticyclonic gyre in front of the Southern Istrian coast, thus decoupling the Northern and Central Adriatic basins. Sirocco events tend to pile up water along the Italian coast and the circulation results more uniform. In the Gulf of Trieste, the Isonzo River plays a role similar to that of the Po River in the Northern Adriatic, either as the physical forcing that, together with the local meteorology (winds), regulates

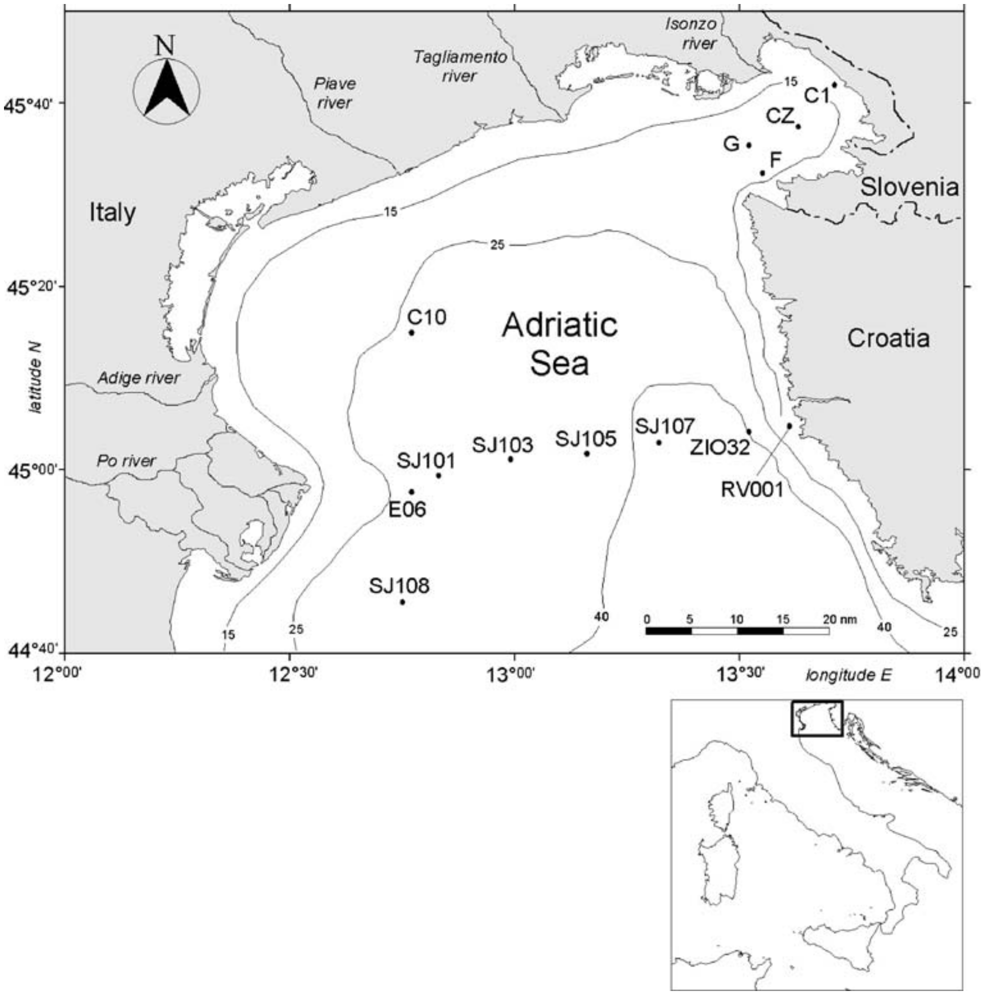


Fig. 1 Study area and location of the 13 sampling stations

the circulation of the water masses (Malačič and Petelin 2001; Querin et al. 2006) or as the main external nutrient source (Olivotti et al. 1986).

These physical features, together with large freshwater discharges (mainly from the Po River) along the western coast, generate a marked west–east gradient of nutrient and chlorophyll concentrations (Socal et al. 2008; Solidoro et al. 2009). Nutrient concentrations are high during the cold season, when heterotrophic processes prevail (Solidoro et al. 2007). Substantial late winter–early spring river water discharges then trigger and sustain the first, often diatom dominated, phytoplankton bloom, followed in turn by the blooming of highly efficient smaller autotrophic plankton. In the absence of an external supply of nutrient, this might cause depletion in pools of dissolved inorganic nutrients in the surface layer, an increment in excretion of dissolved organic matter and a decoupling between primary production and bacterial carbon demand (Fonda Umani et al. 2007; Pugnetti et al. 2005). In late summer–early autumn, new inputs of river water possibly trigger a second diatom bloom, in turn, followed by microbial food web activities as described above. Remineralization prevails again in late autumn and winter (Solidoro et al. 2007).

Material and Methods

Field Data: Sampling and Laboratory Procedures

Field sampling was carried out at 13 stations located in coastal and open waters of the Northern Adriatic in an area that extends north of the line Po River mouth – Rovinj (western Istrian coast; Fig. 1). Since the acquisition of samples was performed by five institutes within different scientific projects and monitoring programs, datasets have different characteristics, which include period and length of sampling and of intermediate gaps, frequency, and sampling depths (Table 1). The lengths of datasets vary from 9 (station C1) to 38 years (stations SJ105 and SJ107). Samples were collected weekly to monthly at four to seven standard depths throughout the water column using 5-l

Table 1 Zones of the satellite time series and field sampling stations appertaining to each zone

Zone				Field station						
	Label	Long.	Lat.	Label	Long.	Lat.	Max depth (m)	Sampling layers (m)	Period	Frequency
Northern Adriatic (NA)		12–13.9	44.4–45.8							
Gulf of Trieste_east	a	13.6–13.8	45.6–45.8	C1	13.71	45.70	17	0, 5, 10 ,15	1999–2007	Monthly/ weekly/ biweekly (gaps)
Gulf of Trieste_south	b	13.5–13.7	45.5–45.7	F	13.55	45.54	21	0, 5, 10, 15, 21	1988–2007	Monthly (gaps)
				CZ	13.63	45.62	24	0, 5, 10, 24	1990–2007	Monthly (gaps)
				G	13.52	45.59	22	0, 5, 10, 22	1990–2003	Monthly (gaps)
Gulf of Venice	c	12.7–12.9	45.2–45.4	C10	12.77	45.25	29	0, 5, 10 [15], 20, [25], [25–29]	1988–2006	Monthly (gaps)
Po River plume area_east	d	12.7–12.9	44.9–45.1	E6	12.77	44.96	32	0, 5, 10, [15], 20, [29–32]	1979–2007	Monthly (gaps)
				SJ101	12.83	44.99	30	0, 5, 10, 20, 30	1973–2007	Monthly (gaps until 1989)
Western central NA	f	12.9–13.1	44.9–45.1	SJ103	12.99	45.02	32	0, 5, 10, [15], 20, [25–27], [30–32]	1973–2007	Monthly (gaps until 1989)
Eastern central NA	g	13.1–13.4	44.9–45.2	SJ105	13.16	45.03	35	0, 5, 10, [15], 20, 30, 35	1970–2007	Monthly (gaps until 1989)
				SJ107	13.32	45.05	37	0, 5, 10, [15], 20, 30, 35	1970–2007	Monthly (gaps until 1989)
Istrian coastal area	h	13.4–13.7	45–45.2	ZI032	13.52	45.07	33	0, 5, 10, 20, [30–33]	1988–2007	Monthly (gaps until 1989)
				RV001	13.61	45.08	29	0, 5, 10, 20, [27–29]	1978–2007	Monthly (gaps until 1989)
Po River plume area_south	e	12.7–12.9	44.7–44.9	SJ108	12.75	44.76	30	0, 5, 10, [15], 20, [25], 30	1978–2007	Monthly (gaps until 1989)

For each sampling station, information is reported on geographic coordinates, water column depth, levels of samplings (in square brackets levels not always sampled), period, and frequency of sampling (with gaps marked)

Niskin bottles and, when sampled near shore, were kept in a dark and cold place prior to analysis in the laboratory. During cruises, samples were filtered on board and filters kept at −20°C until analyzed in the laboratory (within 2 weeks). Due to the disharmony of sampling and differences in maximal depth of stations, only surface concentrations were considered in data analyses except for the general seasonal distribution.

Chl *a* concentrations, corrected for phaeopigments, were determined fluorometrically (Holm-Hansen et al. 1965) in 90% acetone extracts.

Satellite Data

Satellite data of Chl *a* were acquired using the NASA Giovanni website. These data consist of monthly mean values of level 3 SeaWiFS data with a spatial resolution of 9×9 km^2, from January 1998 to December 2007. Time series of monthly mean values were calculated for the entire Northern Adriatic and, for eight zones selected on the basis of the overall-averaged satellite-determined Chl *a* concentrations in the proximity of field stations. The eight zones and their geographical position are reported in Table 1 and Fig. 2.

Data Analysis

The general seasonal distribution of Chl *a* was constructed for six representative stations by computing the overall monthly medians of field data. These data, measured at different water column depths (see Table 1), were aggregated in layers of thickness of 5 m. Visual inspection of periods of Chl *a* peaks and lows enabled time windows, i.e., seasons of particular interest, to be identified. It was then possible to aggregate surface Chl *a* values within these periods and construct time series for each period. The analysis of yearly aggregated data would otherwise be biased by the uneven seasonal distribution of data (spring and summer more represented than autumn and winter).

Trends were detected by the nonparametric Kendall–Tau–Sen test (Burkey 2006; Sen 1968) applied to seasonally aggregated field time series and to satellite time series. The Kendall–Tau–Sen test computes the yearly averaged variation associated with all possible couples of data, and then tests if the median of the resulting distribution is significantly different from zero. In this way, the presence of gaps is overcome, and no assumption on the distribution of data is needed. In satellite time series, the seasonal component was removed by applying the centered moving average of 13 values. The reliability of satellite Chl *a* was checked by comparing satellite and field time series for each zone in the period 1998–2007. Spearman rank correlation and the relative mean difference were computed.

Another nonparametric test, the Wilcoxon–Mann–Whitney test, is used to verify whether the medians of two independent samples are equal (Hollander and Wolfe 1973). In our analysis, this test was used three times. First, we tested the difference between the distributions of data of pairs of two consecutive 5-year periods over the whole 1973–2007 time series. Seasonally aggregated time series were divided into seven 5-year periods centered to the years 1975, 1980, 1985, 1990, 1995, 2000, and 2005. This approach, and subsequent analysis, was only applied to the six stations for which the longest time series are available (see Table 1). Secondly, we tested the difference between the 1973–1977 and 1988–1992 periods. Finally, we tested the difference between the distributions of the day-of-the-year of late winter–early

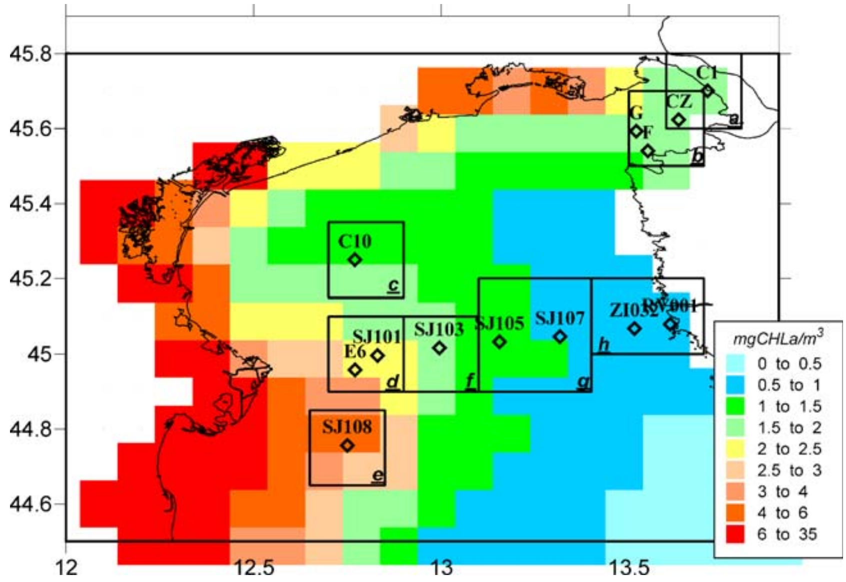


Fig. 2 Map of the satellite-derived surface chlorophyll *a* concentrations (mg m^{-3}), showing the average of monthly data for the period January 1998–December 2007. *Diamonds* denote positions of sampling stations (as in Fig. 1). *Squares* labeled from *a* to *h*, represent eight zones with typical average chlorophyll concentrations derived from satellite data and include one to three sampling stations

spring and autumn Chl *a* peaks of two periods—recent (1998–2007) vs. past (1970–1995).

Results

Long-Term Series, 1970–2007

The Northern Adriatic extends over a large spatial gradient of Chl *a* (Fig. 2) from oligotrophic mean values around 0.5 mg m^{-3} on the Istrian coast, reaching 35 mg m^{-3} south of the Po delta, which is, however, outside the investigated area.

Long-term series of field data collected at 13 stations in the Northern Adriatic Sea from 1970 onwards (Fig. 3, dots) show, first of all, not only large spatial and interannual variations but also a great discrepancy and inconsistency in the sampling strategy of stations. Although exceptionally high concentrations up to 13 mg Chl *a* m^{-3} were measured in zones b (stations G, F, CZ), g (stations SJ105, SJ107), and h (station RV001), they occurred only sporadically, whereas the majority of peak values is around 4 or even 2 mg m^{-3}. Zones e and d, with stations lying south-easterly from the Po River plume, are, on the contrary, characterized by blooms with concentrations usually in the range from 8 to 14 mg m^{-3}.

Satellite time series are superimposed on field data for the last 10 years (Fig. 3, lines) and also indicate great variability, which is likely to be greater on a temporal scale than among certain stations/zones. The lowest panel on the right of Fig. 3 shows satellite time series of the whole Northern Adriatic.

Mean Annual Pattern

The mean annual pattern of Chl *a* biomass was constructed using monthly field data from the entire investigated period (Fig. 4). Six representative stations were selected at random. Two annual maxima are identified at all stations, spring (Apr to May) and autumn (Oct to Nov). A third but smaller peak is present in winter (Jan to Feb) being more distinctive in some areas (e.g., Gulf of Trieste, Fig. 4a, b) than the spring peak. Summer (Jul to Aug) is the season of the lowest Chl *a* concentrations in the whole Northern Adriatic basin.

Color plots of field data distributed throughout the water column show that blooms develop quite regularly in the upper 5-m layer, especially at station in the Po River plume (Fig. 4d). High concentrations are, nevertheless, also measured in deeper layers in periods of a mixed water column (e.g., later winter and autumn) and close to the bottom of shallower stations during summer (e.g., station CZ). Surface peaks support the choice of considering only surface values in further analysis. This choice was, however, imposed by the fact that this layer was the one most consistently sampled at all stations.

Long-Term Seasonal Trends

The Kendall–Tau–Sen test was run on seasonally aggregated field data in order to detect long-term trends in periods of up to 35 years. The coefficients of trends, with their respective *p* values, are reported in Table 2. The most evident feature in all seasons is the decrease of Chl *a* concentration in the most eutrophic zone e (station SJ108), but especially in the winter (−0.05 mg m^{-3} $year^{-1}$), which is followed by autumn (−0.04 mg m^{-3} $year^{-1}$) and summer (−0.02 mg m^{-3} $year^{-1}$). Other zones of the Northern Adriatic are more steady in the Chl *a* temporal dynamic, with slight tendencies towards increase or decrease. An increase of Chl *a* concentration was observed in the central part of the basin (stations SJ105, SJ107) during winter and autumn, but a slight decrease was found in the southern part of the Gulf of Trieste (stations CZ, G) during autumn. There is a general trend of decrease in Chl *a* concentrations during summer all over the basin.

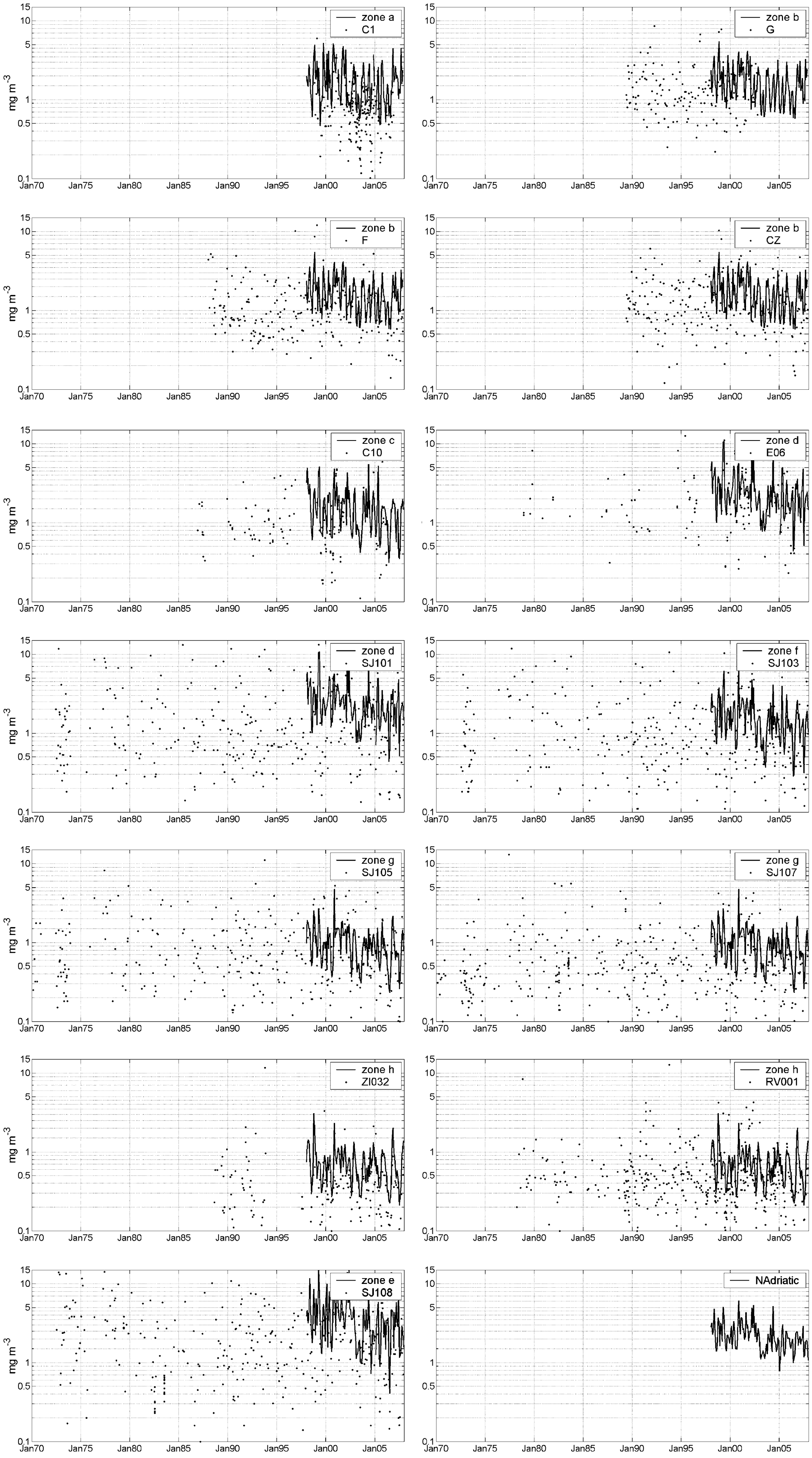
The next step in this analysis comprised splitting the 35-year time series (where they existed) into shorter periods of 5 years and comparing pairs of two consecutive quinquennia in order to detect moments of change. The strongest signal of the Wilcoxon–Mann–Whitney test (Table 3) is the abrupt change in Chl *a* concentration from the year 2000 (center of the period 1998–2002) onwards, which affects the whole area concerned but especially the western stations of the transect Po River delta—Rovinj. Conversely, earlier period is characterized by oscillations of Chl *a* concentration, the positive (from 1975–1985 in spring, summer, and autumn and again from 1995–2000 in spring) predominating over the negative (from 1990–1995 in spring), since they were more frequent and affected a larger area.

Comparison of the periods representative of the early 1970s (centered to 1975) and early 1990s (centered to 1990; Table 3, last column) evidenced nonsignificant differences or positive variations between the two distant periods. Verification of a possible trend in the period 1973–1992 (Kendall–Tau–Sen test) was not possible because of the short length of the time series and of some outliers, which would weaken the outcome of the test.

Recent Trends

Findings on recent changes in phytoplankton biomass were also verified using a "robust" dataset of satellite Chl *a* concentrations from the last decade, which is not biased by uneven sampling (see Fig. 3). Prior to checking

Fig. 3 Time series of surface Chl *a* concentrations. *Dots* field data of 13 stations in the period 1970–2007; *solid lines* satellite monthly data of eight zones in the period 1998–2007. The *lowest panel on the right* is the satellite time series of the whole Northern Adriatic



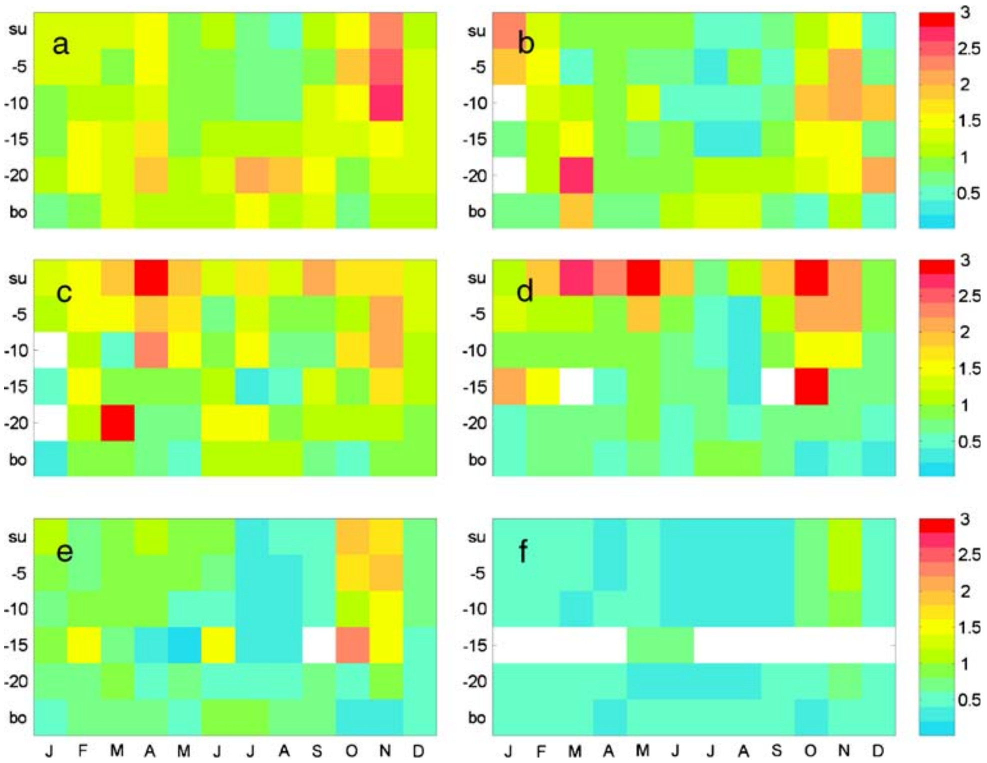


Fig. 4 Mean annual pattern of Chl *a* concentrations at selected stations: vertical profiles of monthly medians of field data for six stations. For the respective periods, see Table 1. Legend **a** station CZ, **b** station C10, **c** station E6, **d** station SJ108, **e** station SJ103, **f** station RV001, *su* surface layer, *bo* bottom layer

for trends, correlation between satellite and field time series was computed to justify the use of satellite data. It was shown that satellite-derived time series reproduce recent time courses of field data well, the correlation coefficient being larger than 0.50 (Table 4). From a quantitative point of view, satellite data, on average, overestimate field data for about 16%, and in some zones, the relative difference is less than 10% of the values.

The Kendall–Tau–Sen test performed on de-seasonalized satellite time series demonstrates a clear and statistically significant ($p<0.001$) decrease of Chl *a* concentrations in the whole Northern Adriatic and in each zone (Table 5). The time series referring to the whole basin is characterized by a mean decrement of 0.11 mg Chl *a* m^{-3} $year^{-1}$, which is more than 1 mg m^{-3} during the last decade. Negative trends (−0.12 to −0.27 mg m^{-3} $year^{-1}$) are more marked in the area directly affected by Po River discharges (zones e, d, and f) and present the highest decrements (up to 9% per year). The most oligotrophic waters on the Istrian coast (zone h) show the lowest decrement both in absolute and relative values, while the Gulf of Trieste (zones a, b), Gulf

Table 2 Coefficients of trend (mg Chl *a* m^{-3} $year^{-1}$) and corresponding *p* values calculated using the Kendall–Tau–Sen nonparametric test on seasonally aggregated field time series

Zone	Station	Winter		Spring		Summer		Autumn	
		Trend	*p* Value	Trend	*p* Value	Trend	*p* Value	Trend	*p* Value
a	C1	**−0.310**	**0.07**	0.020	0.90	−0.010	0.54	−0.070	0.54
b	F	0.005	1.00	0.016	0.35	−0.022	0.55	0.030	0.55
	CZ	0.001	0.96	−0.014	0.44	**−0.015**	**0.26**	**−0.060**	**0.27**
	G	0.016	0.56	0.025	0.38	−0.011	0.58	**−0.040**	**0.12**
c	C10	−0.028	0.37	−0.008	0.96	**−0.033**	**0.22**	0.030	0.58
d	E6	0.031	0.45	0.016	0.63	0.008	0.80	−0.010	0.78
	SJ101	0.004	0.88	0.024	0.41	−0.003	0.73	−0.020	0.61
f	SJ103	−0.003	0.89	−0.028	0.31	**−0.012**	**0.05**	−0.030	0.32
g	SJ105	**0.016**	**0.08**	−0.004	0.70	−0.003	0.40	**0.020**	**0.13**
	SJ107	**0.004**	**0.27**	0.004	0.42	**−0.003**	**0.28**	0.010	0.49
h	ZI032	0.018	0.47	**−0.008**	**0.22**	**−0.005**	**0.22**	−0.030	0.40
	RV001	0.006	0.30	0.000	0.92	−0.003	0.43	−0.010	0.48
e	SJ108	**−0.046**	**0.03**	−0.026	0.36	**−0.021**	**0.20**	**−0.040**	**0.19**

Values in bold are statistically significant at $p<0.30$. Seasons are defined as follows—*winter* Jan to Feb; *spring* Apr to May; *summer* Jul to Aug; *autumn* Oct to Nov

Table 3 Wilcoxon–Mann–Whitney test statistics showing differences in distribution between consecutive 5-year periods centered to years 1975, 1980, 1985, 1990, 1995, 2000, and 2005 for each season

	1975 → 1980	1980 → 1985	1980 → 1990	1985 → 1990	1990 → 1995	1995 → 2000	2000 → 2005	1975 → 1990
Winter								
SJ101					–	++	–	
SJ103					=	++	=	
SJ105					=	++	=	=
SJ107				–	=	=	+	+
SJ108					=	++	–	–
RV001				=	-	+	+	
Spring								
SJ101	=	++		=	-	++	–	++
SJ103	++	=		=	-	++	–	++
SJ105	=	++		=	-	++	=	++
SJ107	++	+		=	=	++	–	++
SJ108	=	=		=	–	++	=	++
RV001					+	=	-	
Summer								
SJ101	=	++		=	=	-	-	=
SJ103	=	++		–	=	-	–	=
SJ105	=	+		=	=	=	-	=
SJ107	=	++		–	=	=	+	=
SJ108	=	+		=	+	=	–	–
RV001	+	-		+	+	-	-	+
Autumn								
SJ101	++		–		++	=	–	=
SJ103	++		=		=	=	–	++
SJ105	+		++		=	=	–	++
SJ107	++		=		–	=	–	++
SJ108			–		=	++	–	
RV001			-		++	–	–	

For the definition of seasons, see Table 2. The last column lists comparison between the 1973–1977 and 1988–1992 periods. Only stations with the longest time series (1973–2007) are presented. The test was run where at least six data for each period were available otherwise the comparison was not possible (empty cells); = difference was not statistically significant at $p<0.4$; + significant positive variation from 0 to 0.2 mg m^{-3} ; ++ significant positive variation larger than 0.2 mg m^{-3} ; - significant negative variation from 0 to 0.2 mg m^{-3} ; – significant negative variation larger than 0.2 mg m^{-3}

of Venice (zone c), and central part of the Northern Adriatic (zone g) present intermediate behavior.

Changes in Seasonal Peaks

Considering only stations along the transect Po River delta—Rovinj (Fig. 5a) over the period 1970–1995, the late winter–early spring Chl *a* maxima appeared regularly between days 47 and 77 of the year. In the last decade (1998–2007), it was delayed by more than 1 month but only at the stations under the Po influence (Wilcoxon–Mann–Whitney test: p=0.02 and 0.17 for stations SJ101 and SJ108). At the eastern and central stations of the transect, the bloom timing remained the same or even developed earlier. The timing of the autumn bloom did not change significantly with time (Fig. 5b). Compared to the first-of-the-year broadened bloom (Jan–May), the autumn one remained confined to a much narrower period (Sep–Nov). Nevertheless, stations SJ101 and SJ103 showed a slight anticipation of about 2 weeks in the autumn months (p=0.12 and 0.21 for stations SJ101 and SJ103).

Discussion

This is the first attempt at a joint analysis of a 38-year long dataset of Chl *a* concentrations, measured by five different institutions in three different countries (Croatia, Italy, Slovenia) bordering the Northern Adriatic. Even though only data acquired with the same analytical method

Table 4 Comparison between satellite and field time series of Chl *a* concentrations for each zone–station pair, period 1998–2007

Zone	Station	Correlation coefficient	Mean difference (%)
a	C1	0.624	49.6
b	F	0.530	14.0
	CZ	0.547	20.4
	G	0.557	7.1
c	C10	0.637	26.7
d	E6	0.509	18.2
	SJ101	0.630	8.3
f	SJ103	0.609	6.1
g	SJ105	0.625	−13.8
	SJ107	0.731	18.8
h	ZI032	0.746	27.9
	RV001	0.668	8.9
e	SJ108	0.567	27.4

Spearman rank correlation coefficient and relative mean difference are given

(fluorometry) were considered in the analysis, the datasets, nevertheless, reflect the different characteristics (time span, frequency, consistency of sampling, etc.) resulting from the different sampling, not only between institutes but also within the same institute. The transect Po River delta—Rovinj has the best coverage with an almost continuous sampling from the early 1970s onwards, whereas the other stations present shorter and/or less continuous coverage. Consequently, it was not always possible to compare behaviors of different subareas. Nevertheless, our analyses point to some features common to the whole Northern Adriatic.

There is a tendency for Chl *a* surface concentrations to decrease, which is more marked in the eutrophic western area than in the center of the basin and the eastern coast, which have always presented mesotrophic or oligotrophic characteristics. A closer inspection of the 38-year temporal course showed that the overall decrease is determined by the substantial reduction in Chl *a* levels that occurred over the last decade, confirmed all over the basin also by satellite derived information, whereas during the first two decades there were either no significant trends or increases.

The recent trend of decrease in Chl *a* levels parallels the reductions observed in the outflows of the Po (Zanchettin et al. 2008) and Isonzo (Comici and Bussani 2007) Rivers. Reduced freshwater discharges, together with phosphorus being banned by Italian law in the mid-1980s and the general improvement in sewage treatment, could have had a strong influence on nutrient concentrations in the coastal area (de Wit and Bendoricchio 2001). In fact, both phosphorus and ammonia have decreased significantly over the last 30 years, at rates of up to −0.007 and −0.061 μmol l^{-1} $year^{-1}$, respectively (Solidoro et al. 2009).

The above-noted changes have certainly increased nutrient (especially phosphorus) limitation in the Northern Adriatic, which has been long recognized for this area (Chiaudani and Vighi 1982; Maestrini et al. 1997; Pojed and Kveder 1977). Our results constitute one of the first documented cases of cultural oligotrophication of coastal waters (Carstensen et al. 2006), a process already observed in freshwater systems (e.g., Jeppesen et al. 2005). Coupling of timing and magnitude of Chl *a* reduction with respect to recent trends of nutrient limitation are, however, difficult to demonstrate due to the resilience of the system.

To what extent environmental factors other than nutrients have influenced the decrease of Chl *a* is difficult to ascertain. It has been shown that sea surface warming, for example, influences plankton communities in the open ocean as well as in coastal environments (e.g., Falkowski

Table 5 Coefficients of trend (mg m^{-3} $year^{-1}$) with corresponding *p* values calculated using the Kendall–Tau–Sen nonparametric test on a deseasonalized time series of satellite Chl *a* data for each zone and for the whole Northern Adriatic

Zone	Median Chl *a* (mg m^{-3})	Trend (mg $m^{-3}year^{-1}$)	*p* Value	Relative coefficient (% per year)
a	1.50	−0.088	<0.001	−5.8
b	1.47	−0.090	<0.001	−6.1
c	1.47	−0.089	<0.001	−6.1
d	2.19	−0.192	<0.001	−8.8
f	1.47	−0.119	<0.001	−8.1
g	0.87	−0.056	<0.001	−6.4
h	0.67	−0.022	<0.001	−3.3
e	3.40	−0.272	<0.001	−8.0
NA	2.01	−0.108	<0.001	−5.4

NA Northern Adriatic

Relative coefficients of trend (%) are calculated as the ratio between coefficients of trend and median Chl *a* concentration of the time series (period 1998–2007).

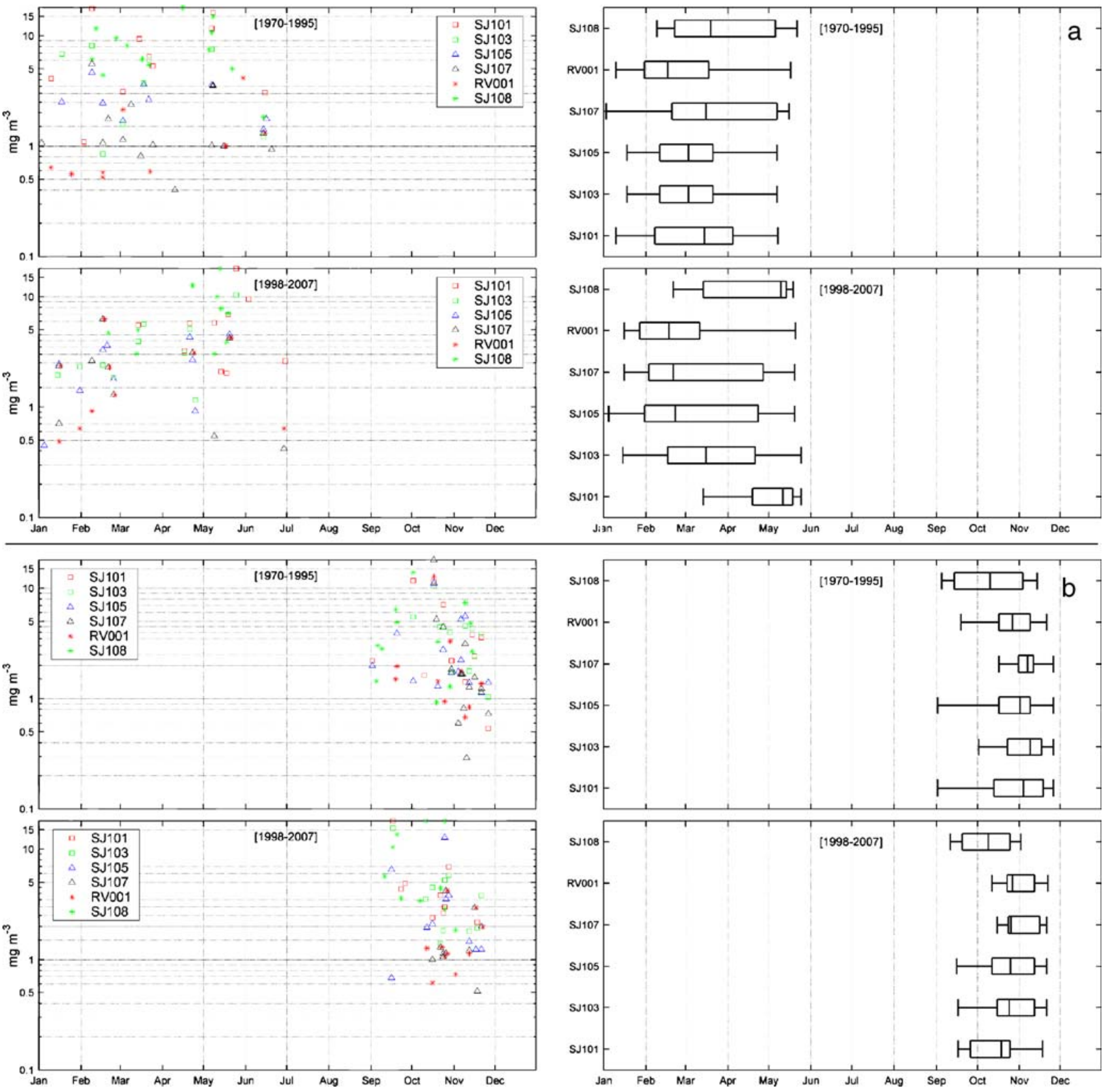


Fig. 5 Timing of the surface Chl *a* maxima of six selected stations for the **a** late winter–early spring and **b** autumn period. *Left panels*: day-of-the-year of Chl *a* peaks with respective values for the earlier (1970–1995) and recent (1998–2007) periods. *Right panels*: day-of-the-year distribution box plots for the earlier (1970–1995) and recent (1998–2007) periods. Ticks of *x* axes signal the first day of the month

and Oliver 2007; Goffart et al. 2002; Hays et al. 2005). This linkage is observed mainly through the enhanced stratification and subsequently reduced nutrient supply to photic layer from below the pycnocline, possibly resulting in a decrease of phytoplankton abundance, at least, of large cells (Richardson and Schoeman 2004) and a shift towards a microbial-dominated community (Cushing 1989). However, in a shallow, semi-enclosed basin into the surface layer of which many rivers discharge a substantial amount of nutrients and where strong wind perturbation easily disrupts stratification and efficiently mixes the whole water column, the importance of this factor may be much less relevant.

There is still no conclusive evidence of a temperature increase in the Northern Adriatic over the last 20 years (Solidoro et al. 2009), during which the decrease of Chl *a* took place. Russo et al. (2002) reported the existence of a significant warming of surface Adriatic waters between the periods 1911–1987 and 1987–1999 but did not focus on the total period of interest in this study, while Tedesco et al. (2007) considered the last 20 years, but only at two sites, and detected a significant increase for only one of them. Solidoro et al. (2009) analyzed the whole Northern Adriatic basin but advanced very little evidence supporting the hypothesis of a significant warming of Northern Adriatic waters during the last 30 years. Any speculation on possible correlations between the observed decrease in Chl *a* concentrations and temperature increase and, more generally, on a possible correlation between different variables, is, therefore, difficult to assess from a statistical point of view because of the problems in obtaining time series similar in length, frequency, and space coverage.

Separate observations on increased abundance of small nanoflagellates and reduced diatom peak abundance during blooms in last 5 years in the southern part of the Gulf of Trieste (unpubl. data) can be seen as a response of phytoplankton community to changes in nutrient concentrations and in nutrient ratios. The lack of a strong warming signal at this stage gives more support for the effect of cultural oligotrophication on the phytoplankton community.

Variations in nutrient conditions have probably also influenced phytoplankton community succession. In fact, Fig. 5 shows that Chl *a* maxima in the late winter–early spring period have shifted from Jan to Feb to Apr to May over the last decade, especially at stations most affected by reduced Po River discharges. In the former period, the majority of high Chl *a* values were associated with Jan to Feb blooms that are dominated by small diatoms like *Skeletonema marinoi* (Bernardi Aubry et al. 2006; Harding et al. 1999). In the last decade, the first seasonal bloom has generally been due to an April to May community dominated by autotrophic nanoflagellates and, occasionally, by a diatom *Cerataulina pelagica* (Socal et al. 2008) and small dinoflagellates (e.g., *Prorocentrum minimum* in 2000; Bernardi Aubry et al. 2006). Since the Jan to Feb bloom is sustained by regenerated nutrients from the late autumn, brought by mixing to the surface (Harding et al. 1999), we suggest that decrease of the magnitude of this bloom could be a signal of recent oligotrophication of the system. This could be in line with the much more frequent appearance of various diatom species of the genus *Chaetoceros* during the late winter–early spring bloom in the Gulf of Trieste in recent years, compared to the early 1990s period (unpubl. data; Virgilio 2007). Small-sized and chain-forming *Chaetoceros* spp., with a favorable surface to volume ratio, is able to grow at low nutrient concentrations and high N/P ratios (Lagus et al. 2004).

More evidence of the lowering of the trophic level is the absence of red-tide events from the late 1980s onwards. Massive and frequent dinoflagellate blooms that contributed significantly to overall Chl *a* concentrations were often recorded during summer–early autumn in the 1970s and 1980s in the Gulf of Trieste (Fanuko 1990; Fonda Umani 1985; Fonda Umani and Honsell 1984) and other coastal areas of the Northern Adriatic (Emilia-Romagna coast; in Sellner and Fonda Umani 1999), occasionally covering the entire Northern Adriatic basin (e.g., *Gymnodinium* sp. bloom in Oct 1984; Artegiani et al. 1985).

The delay and reduction of the early spring diatom bloom, which appears to be replaced by a heterogenic Apr to May bloom (mostly nanoflagellates), will probably affect the timing and composition of the second trophic level in the medium–long run. Since a change in the zooplankton community towards smaller copepod species, which prefer to graze on small-sized phytoplankton, is reported from the Gulf of Trieste (Conversi et al. 2009; Kamburska and Fonda Umani 2006), it could well be expected in the whole northern Adriatic. Nevertheless, the question remains: will the trend to oligotrophication continue, or are we approaching a period of different chlorophyll *a* fluctuation along the multiannual/decadal variations? Misjudged forecast can only be avoided by continuing long-term observations.

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