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Factors favouring phytoplankton blooms in the northern Adriatic: towards the northern Adriatic empirical ecological model

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Abstract. Influenced by one of the largest Mediterranean rivers, Po, the northern Adriatic (NA) production is highly variable seasonally and interannually. The changes are especially pronounced between winters and seemingly reflect on total Adriatic bioproduction of certain species (anchovy). We analysed the long-term changes in the phytoplankton production in the region, as derived from monthly oceanographic cruises, in relation to concomitant geostrophic currents distribution in the area and to Po River discharge rates in days preceding the cruises. In winter and early spring the phytoplankton abundances depended on existing circulation fields, in summer and autumn they were related to Po River discharge rates 1–15 days earlier and on concomitant circulation fields, while in late spring phytoplankton abundances increased 1–3 days after high Po River discharge rates regardless of the circulation fields. During the entire year the phytoplankton abundances were dependent on forcing of the previous 1–12 months of surface fluxes and/or Po River rates. The role of wind was uncertain but that was partly due to unmatched sampling time frames between meteorological and sea data. Low evaporation rates in November reflected significantly on the next February circulation pattern and, although with somewhat lower significance, on large phytoplankton blooms in the same month. We showed that the role of wind in evaporative flux enhancements is not straightforward as evaporative fluxes are highly dependent on other factors, e.g. air–sea temperature difference. Wind-induced vertical mixing was only sporadically related to phytoplankton abundances. From 1990 to 2004 a shift towards large winter bioproduction induced by circulation changes appeared. The investigations performed represent the preliminary actions in the construction of an empirical ecological model of the NA which can be used in the sustainable economy of the region, as well as for validation of the numerical ecological model of the region, which is currently being developed.

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1 Introduction

The relatively shallow and restricted area of the northern Adriatic (NA) is held to be one of the most productive regions of the Mediterranean Sea (e.g. Sournia, 1973). However, its productivity is high only when influenced by the Po River, one of the largest Mediterranean rivers, with delta located in the western part of the NA (Fig. 1). Otherwise, the region is under impact of oligotrophic central Adriatic waters. Therefore, the seasonal and interannual variability in the NA organic production is very high (e.g. Sournia, 1973). Kraus and Supić (2011) hypothesised that interannual changes in the NA winter (February) primary production reflect on the secondary production of the entire Adriatic. The hypothesis was based on significant correlations between the intensity of phytoplankton blooms in the NA and the total Adriatic catch of one of its most important commercial fishes, anchovy, *Engraulis encrasicolus* (L.). Interestingly, and in spite of generally oligotrophic trends documented for the region (Mozetič et al., 2010; Djakovac et al., 2012; Marić et al., 2012), the anchovy population between 1990 and 2004 increased, following the positive trends in winter nutrients and phytoplankton abundances in the NA (Djakovac et al., 2010).

The circulation fields of the NA are controlled by a number of factors, among which the stratification degree plays a crucial role (e.g. Orlić et al., 1992). In general, the water column in the region is uniform in January–February, weakly stratified in March–April and November–December, and highly stratified from March to October (e. g., Supić and Vilibić,

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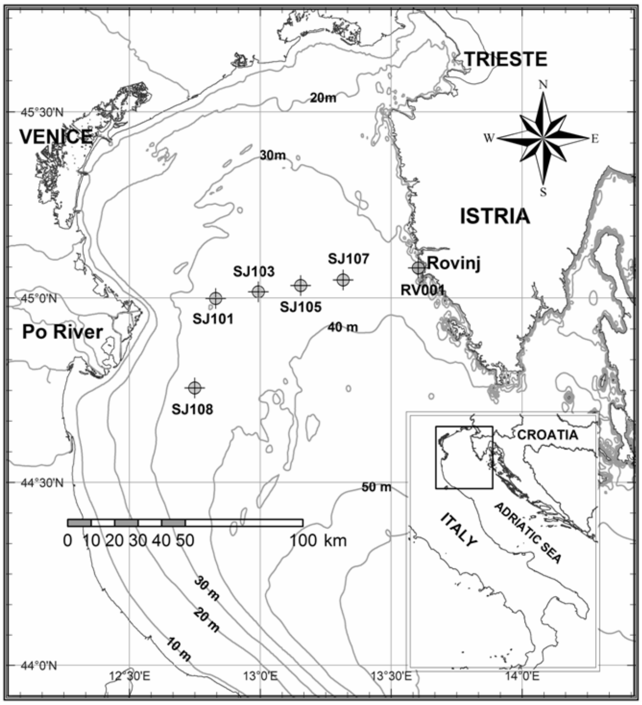

Figure 1. Map of the NA with sampling stations.

2006; Supplement 1). Although wind-induced currents of the region are pronounced (e.g. Kuzmić et al., 2007; Cosoli et al., 2012), the geostrophic component presumably plays a major role in redistributing freshened waters and organic/inorganic substances across the NA.

Based on the calculation of average monthly geostrophic fields, it was shown that in the stratified period the Po River waters spread around the NA, while in the unstratified period these waters are confined to the western coast (Franco and Michelato, 1992; Cushman-Roisin et al., 2001; Krajcar, 2003). They filled an anticyclonic gyre east of the Po River delta which gradually became larger and reached the Istrian coast in summer. However, the more detailed analyses of geostrophic fields showed that interannual variability in current fields is large and there are summers with the low Po River impact and winters with high Po River impact (e.g. Grilli et al., 2005; Kraus and Supić, 2011). Namely, the geostrophic circulation of the NA consists of several gyres, which can persist in the region for a longer time period (e.g. Supić et al., 2012). Their position and extent is changeable and differs from year to year. They can be filled with freshened waters of the Po River so that within them the accumulation of nutrients and organic matter takes place (e.g. Orlić et al., 2013). It is within them where the hypoxia and anoxia events develop (e.g. Djakovac et al., 2015). Especially, a large amount of the Po River waters can be drawn into the NA when an anticyclonic gyre appears at a large distance from the delta at the opposite side of the basin, off the eastern (Istrian) coast. Presence of the gyre is indicated by a current of southern direction in the coastal zone, the Istrian Coastal Countercurrent (ICCC; Supić et al., 2003). Long-term changes in the intensity of the ICCC were found to be related to long-term changes in nutrients (Djakovac et al., 2012), phytoplankton (Kraus and Supić, 2011; Marić et al., 2012) or even large quantities of the mucilaginous material appearing sporadically in the NA (e.g. Supić et al., 2000). Finally, it was shown that the geostrophic fields formed in autumn can remain unchanged for several months and persist even during severe wind forcing (Supić et al., 2012). Winter circulation pattern after prevailing *jugo* episodes in the autumn favoured the Po River spreading, while the one after prevailing autumnal *bora* episodes did not. This finding implied that the prognosis of the NA circulation fields is possible, to a certain extent.

The Po River discharge rate has a pronounced seasonal cycle with a maximum in spring or autumn (e.g. Supić and Orlić, 1999). The flow rate is modulated by the precipitation regime and additionally, in spring and summer, is enhanced by snow melting (Cushman-Roisin et al., 2001). A significant additional contribution in summer is from precipitation in the Alps, which is at its yearly maximum in this period of the year. Daily variations in rates are significant and within short pulses a large amount of fresh water can be injected into the NA. Recently, around 2000, a drastic reduction in the Po River rates was observed with consequences on the marine environment (e.g. Djakovac et al., 2012; Giani et al., 2012). However, the changes in the Adriatic environment can be induced by changes in other factors, as the inversion of the Ionian Sea circulation (Civitarese at al., 2010).

The presence of a large quantity of nutrient-rich waters from the Po River is crucial for the large bioproduction in the region. We hypothesised, thus, that the degree of the bioproduction directly depends on the geostrophic circulation fields and intensity of the Po River discharge. Due to pronounced seasonal component in circulation fields and Po discharge rates we suppose that the importance of the two factors, which modulate the interannual variations in concentrations of organic matter produced in the NA, changes from month to month.

In a previous paper, using data collected along the transect between the Po River delta and Rovinj in 1990–2004, we documented the relation between the large phytoplankton blooms in February, March, July and October, months when the largest blooms in the region usually occur, and the intensity of the ICCC (Kraus and Supić, 2011). In this paper we perform a more complex analysis of the same data set as used in a previously mentioned paper (Kraus and Supić, 2011), for each month within a year. The principal component analysis, used now, allowed us to extract the most important modes of long-term changes in the circulation patterns and in phytoplankton abundance distribution in the region at the Po River delta–Rovinj transect. The Po River impact is here investigated more closely, on the basis of daily discharge data.

The effect of vertical motions in the water column (intense in conditions of low stratification and weak when the water column is highly stratified) on phytoplankton abundances was investigated via analysis of stratification degree for each month separately.

Wind, inducing changes in air–sea fluxes (of heat, moist and impulse), indirectly affects horizontal and vertical motions in water column. In that way, winds reflect on phytoplankton abundances, dependent on sea dynamics. In order to find out whether it is possible to relate winds of certain strength and direction to the increase in phytoplankton abundances we performed a descriptive analysis of winds preceding measurements of large or low phytoplankton abundances.

In addition, we tried to relate the appearance of the large blooms to the surface fluxes and Po River rates of the previous periods, up to a year before sampling, to investigate whether phytoplankton production of the NA is, at least to a certain point, predictable.

In our analysis we used log-transformed phytoplankton data in addition to original values, which enabled us to discern the major processes characterising the region from the occasional events, respectively.

2 Materials and methods

2.1 Data sets

We analyse three sets of data: (1) oceanographic data including temperature, salinity and phytoplankton (in the size range 20–200 µm) collected monthly or seasonally at six stations in the transect between the Po River delta and Rovinj (Fig. 1); (2) monthly averages of meteorological and SST (sea surface temperature) data collected at three locations in the NA (Trieste, Rovinj and Mali Lošinj; Fig. 1); and (3) daily values of the Po River rates. The oceanographic data set covers the 1990–2004 period and the other two sets also cover the year 1989. At each station of the profile, temperature and salinity data were obtained at five standard depths (0, 5, 10, 20 and 30 m). The phytoplankton samples were taken at five standard depths at the Po River delta–Rovinj transect, at stations SJ108, SJ101 and SJ107, and at three standard depths (0, 10 and 30 m) at SJ103, SJ105 and RV001. The oceanographic data set used is described in more detail in our previous paper (Kraus and Supić, 2011).

Temperature was measured by protected reversing thermometers (Richter and Wiese, Berlin, precision ±0.01 °C), while salinity was determined by using a high-precision laboratory salinometer (RBR Precision Instruments Microsalinometer-310, precision ±0.01). Phytoplankton abundance and composition were determined at 200× magnification in 100 random fields of vision (if necessary, 50, 200 or 400 depending on the sample density) after 40 h sedimentation of a 50 ml subsample by an inverted microscope, Zeiss Axiovert 200, using the Utermöhl settling technique (1958).

2.2 Surface fluxes

Monthly values of the NA surface heat flux discussed here include total downward heat (Q; $\mathrm{W m^{-2}}$) and water fluxes (W; $\mathrm{mm\,d^{-1}}$) from the atmosphere into the sea and three of their components, namely the fluxes due to insolation (Qs; $\mathrm{W m^{-2}}$), evaporation (E; $\mathrm{mm\,d^{-1}}$) and precipitation (P; $\mathrm{mm\,d^{-1}}$). The fluxes for the 1989–2004 period were computed from monthly means of the atmospheric data and SST, supplied by the Hydrometeorological Institute in Zagreb, as discussed in more details by Kraus and Supić (2011) and Supić et al. (2012).

2.3 Geostrophic currents

Temperature and salinity data were used to compute surface geostrophic currents relative to 30 m depth between each pair of neighbouring stations at the Po River delta–Rovinj transect (i.e. at SJ108/SJ101, SJ101/SJ103, SJ103/SJ105, SJ105/SJ107 and SJ107/RV001) by means of a standard dynamical method (e.g. Supić et al., 2000). The currents are positive when they mark an inflow in the NA and the ICCC is the current at SJ107/RV001, with a negative sign.

2.4 Phytoplankton abundance

The phytoplankton analyses were performed with original and transformed (log10) phytoplankton abundances. The seasonal cycle of the phytoplankton was additionally presented by geometrical means. The average phytoplankton abundance of the water column of each station at the transect aSTAT (STAT = SJ108, SJ101, SJ105, SJ103, SJ107 or RV001) was computed for each cruise in the 1990–2004 period, using data collected at 0, 5, 10, 20 and 30m (SJ108, SJ101 and SJ107) or at 0, 5 and 3 m (SJ103, SJ105 and RV001). It was assumed (1) that the bottom depth is equal to 30 m; that (2) the abundances within layers 0–2.5, 2.5–7.5, 7.5–15, 15–25 and 25–30 m at SJ108, SJ101 and SJ107 can be approximated by the abundances sampled at 0, 5, 10, 20 and around 30 m, respectively; and that (3) the abundances within layers 0–5, 5–20, and 20–30 m at SJ103, SJ105 and RV001 can be approximated by the abundances sampled at 0, 10 and 30 m, respectively. Values for aSTAT were then computed according to the formula $\mathrm{aSTAT} = 1/30\sum_{l=0\,\mathrm{m}}^{l=30\,\mathrm{m}}\mathrm{a}(\mathrm{STAT},l)$; $l = 0, 1, ..., 30\,\mathrm{m}$; $\mathrm{a}(\mathrm{STAT},l)$ – phytoplankton abundances at station STAT at level l.

2.5 Principal component analysis (PCA)

PCA was performed, for each month, to extract the first main component of the interannual changes of phytoplankton abundance (pPC1) and their logarithmic values (lpPC1) at the three standard depths (0, 10 and 30 m) at six stations between the Po River delta and Rovinj in the 1990–2004 period. Furthermore, the first main component of the long-term changes in surface geostrophic currents relative to 30 m between six stations (at SJ108/SJ101, SJ101/SJ103, SJ103/SJ105, SJ105/SJ107 and SJ107/RV001) for each month was extracted (cPC1). Interannual variability in it is given by the PC1 "scores". PCA was performed using the PRIMER (Plymouth Routines In Multivariate Ecological Research) v.5 software package.

2.6 Po River discharge

Daily values of the Po River discharge rate were derived from data collected at station Pontelagoscuro. The data were supplied by the Assessorato Programmazione, Piafinicazione e Ambiente of the Emilia Romagna region (Italy). Monthly means were computed and used in further computations. For purposes of preconditioning analyses, we used Po River discharge rates with various time lags (1, 3 and 15 days).

2.7 Wind data

Daily values of wind data for November in 1993, 1998, 1999, 2001, 2003 and 2004; for February in 2003 and 2004; and for July in 1997, 2000 and 2001 were supplied by the Hydrometeorological Institute in Zagreb. Assessments of wind values (in Beaufort scale numbers) were obtained three times a day at the Pula (44°51′56″ N, 13°50′46″ E, 43 m above the sea level) station.

2.8 Stratification degree

The stratification degree for the stations (SJ107 and SJ108) and each cruise ($\Delta\sigma_t$) was defined as the difference between bottom and surface density.

3 Results

3.1 Circulation at the transect

3.1.1 General circulation patterns

Average monthly values show several typical circulation patterns across the Po River delta–Rovinj transect (Fig. 2a). Currents are generally stronger in warmer (April–October) parts of the year. In January, as in the previous November and December, there are several circulation cells across the profile: there is an outflow near the western coast and in the open waters of the eastern part of the transect along with the inflow in the middle part of the profile and near the eastern coast. From February to May the outflow prevails over the inflow across the profile. Weak inflow appears near the eastern coast in April and is present throughout spring, until June. But in June, circulation in the middle part of the transect drastically changes as very strong currents appear there. The pronounced inflow in the middle part of the profile is typical for the summer July–September pattern, along with the pronounced outflow near the western coast and moderate outflow near the eastern coast. In October, the circulation pattern is very similar to the one in summer, only with the less-pronounced inflow in the middle part of the transect.

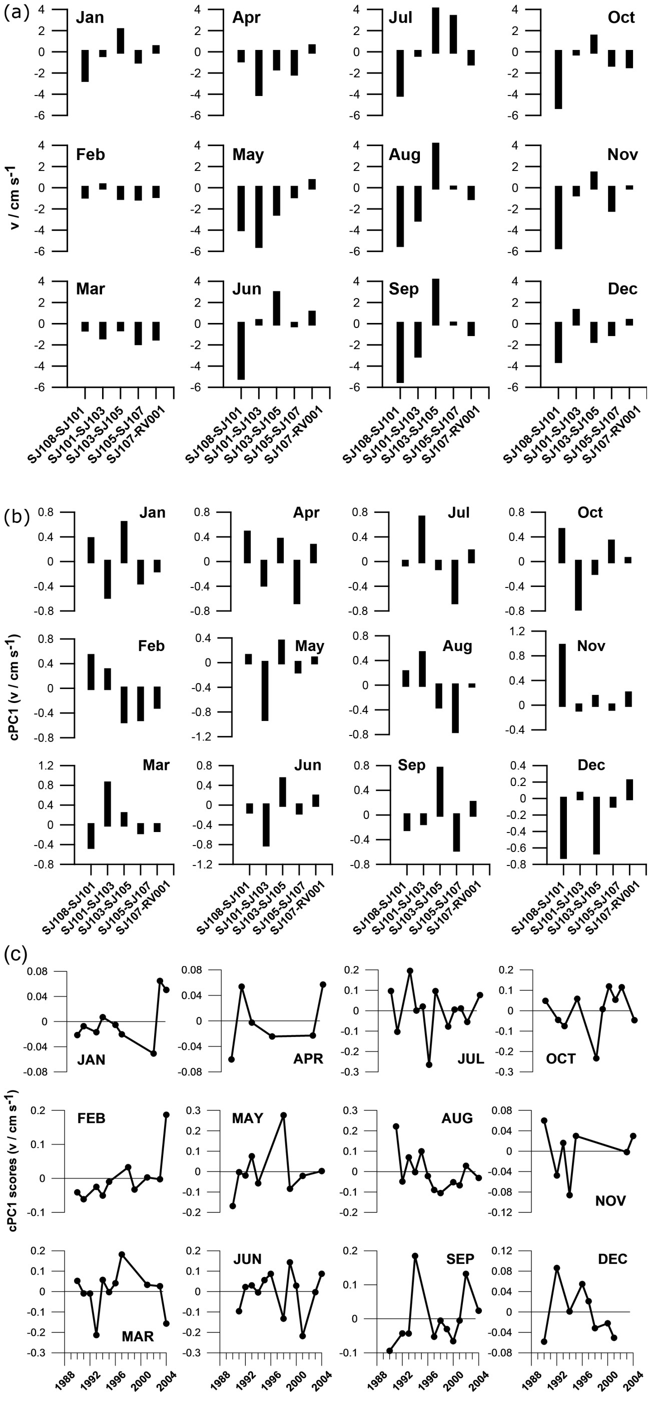

Figure 2. Monthly averages **(a)**, cPC1 loadings **(b)** and cPC1 scores **(c)** of geostrophic currents relative to 30 dbar between stations of the Po River delta–Rovinj profile for the 1990–2004 period.

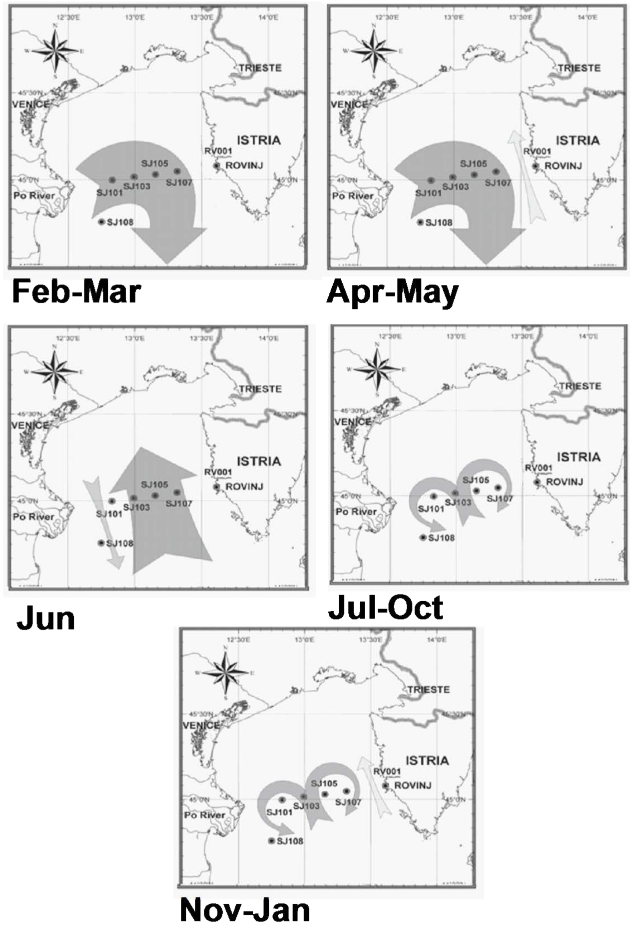

Figure 3. NA circulation patterns as hypothesised from average surface geostrophic currents relative to 30 dbar in 1990–2004 between neighbouring stations at the Po River delta–Rovinj profile. Istrian Coastal Countercurrent (ICCC) at SJ107/RV001 directed towards SE.

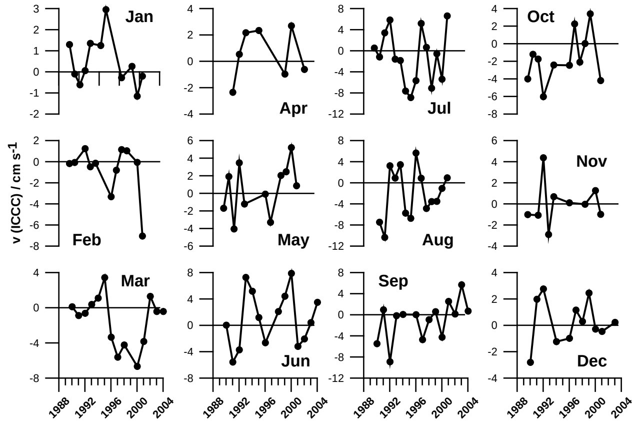

Figure 4. Geostrophic currents relative to 30 dbar between stations SJ107 and RV001 in the 1990–2004 period for each month in a year. The ICCC is current of negative sign.

According to the average circulation patterns, mainly three typical current distributions exist (Fig. 3): the first one indicates the presence of two large gyres, a cyclonic and an anticyclonic one, with an inflow in the middle part of the transect (Fig. 3). This one is typical during most of the year, namely from July to January. From November to January this pattern is modified by an inflow along the Istrian coast. From February to May, which is from winter to early spring, the circulation is a large anticyclonic gyre with waters from the Po River spreading across the NA. In April–May a weak inflow appears near the Istrian coast. And only in one month (June) do the typical circulation patterns reveal the presence of a cyclonic gyre across the transect.

The cPC1 explains between 40 and 70 % of the total variance in the fields of surface geostrophic currents across the Po River delta–Rovinj transect (Fig. 2b). The lowest values, around 40 %, are obtained in summer (July and August) and the highest ones, around 70 %, in winter (January and March) and spring (May). Changes in the circulation patterns, as given by the first PCA mode, for most months are driven by the changes in the middle part of the profile. Only in November and December do changes near the western coast play the main role in year-to-year changes of the circulation patterns. During the 1990–2004 period, trends in circulation patterns were, apparently, more pronounced only in February (positive) and August (negative; Fig. 2c).

3.1.2 The Istrian Coastal Countercurrent – ICCC

In the 1990–2004 period, geostrophic currents at RV001/SJ107 were up to around 10 cm s^{-1} (Fig. 4). In the winter period negative trends, indicating increased recurrence of the ICCC, prevailed. In contrast, in spring and summer trends were positive, indicating lower recurrence of the ICCC.

3.2 Po River rates

The seasonal cycle from 1989 to 2004 shows (Fig. 5) that Po River rates are predominantly high in spring and autumn, with marked daily oscillations. In some years (1990, 1995, 2001 and 2003) the rates were considerably lower during the entire year.

3.3 Evaporation and precipitation

Precipitation generally prevails over evaporation (Fig. 6). While precipitation oscillates throughout the entire year, the evaporation is generally higher and more variable from September to December.

3.4 Seasonal phytoplankton cycle

The seasonal phytoplankton cycle at the transect is based on the monthly averages from the original (not shown)

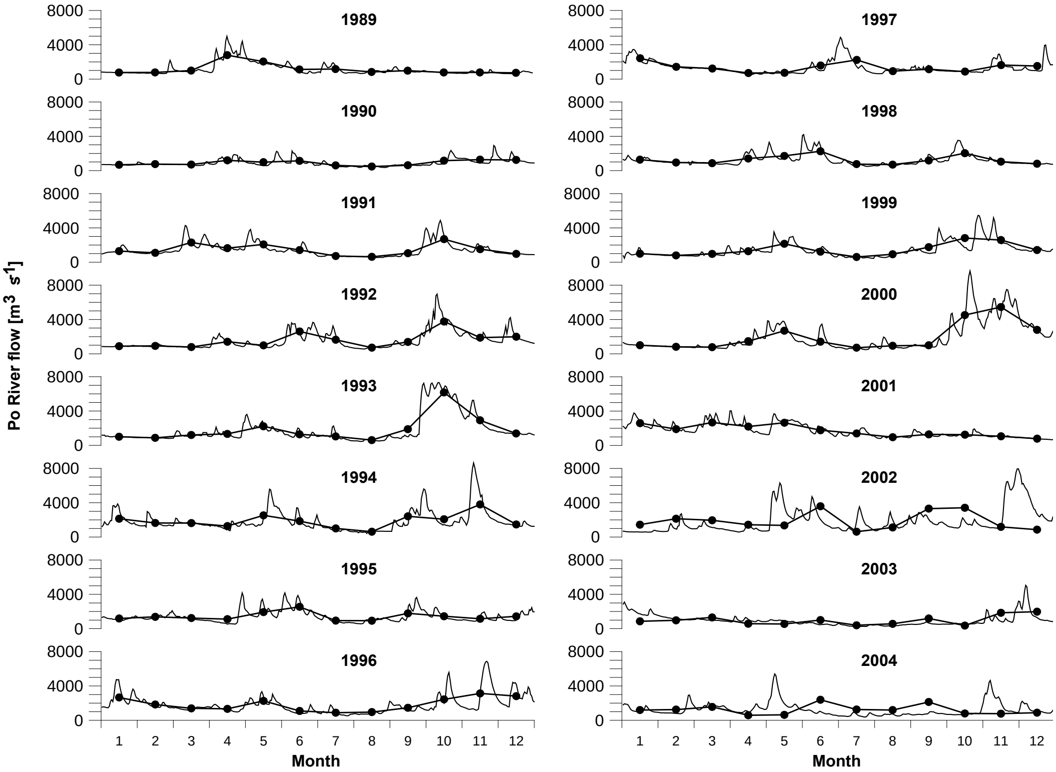

Figure 5. Daily Po River flow (thin line) with monthly averages (thick line with dots) in the analysed years (1989–2004).

and transformed data collected over the 1990–2004 period (Fig. 7). Original data (not shown) indicate west-to-east and surface-to-bottom decreasing gradients during the February–October period, with the vertical gradient more pronounced from the horizontal one. At the eastern part, the vertical gradient is pronounced only during several months (February–March and October), whereas in the west it is common (during entire period February–October). Abundances in the water column are mostly uniform during the rest of the year (November–January). Both horizontal and vertical gradients are more emphasized when the seasonal cycle is based on the transformed data (Fig. 7). High abundances from February to September are restricted to the western part of the transect, spreading in some months in a rather thin surface layer to the middle of the transect and only occasionally more closely to the eastern parts. Only in October and November does a uniform vertical gradient over the entire transect present. In the remaining winter months (December–January) phytoplankton is completely uniform over the entire transect.

The PC1 explains between 40 and 90 % of total variance of original phytoplankton data (Fig. 8a) and between 40 and 70 % of the total variance of transformed phytoplankton data (Fig. 8b). The lowest values, around 40 %, are obtained in spring (June) and autumn (September) for original data and in spring–summer (from June to August) for transformed data, while the highest values, around 90 %, are obtained in May, July and October for original data, and around 70 %, in March and December for transformed data.

Changes in the seasonal phytoplankton cycle, as given by the first pPC1 mode which was based on the original data, are from January to August driven by changes in the western or west–middle part of the profile, in September in the western and east–middle part, in October only in east–middle part, while from November to December changes were rather spread over the entire profile (Fig. 8a). All mentioned changes, except November and December, were driven in the surface to upper layer. First, the lpPC1 mode, which was based on the transformed data, indicated that the changes in the seasonal phytoplankton cycle were driven throughout the entire year in widespread west–middle, middle and east–middle parts of the profile (Fig. 8b). Additionally, over the year changes occur in February in the western part, in March in the eastern part, in May–June in the western part, in July in both western and eastern parts, in November in the eastern part and in December again in both western and eastern parts of the profile. The impact was mostly throughout the entire water column.

Yearly changes obtained by calculating pPC1 from original data (not shown) show a distinctive trend of increase in the January–February period, followed by a decrease in March, while the same analysis on transformed data (Fig. 8c) showed opposite trends. In further months, April and May, as well as later in the year, in October and November, analyses

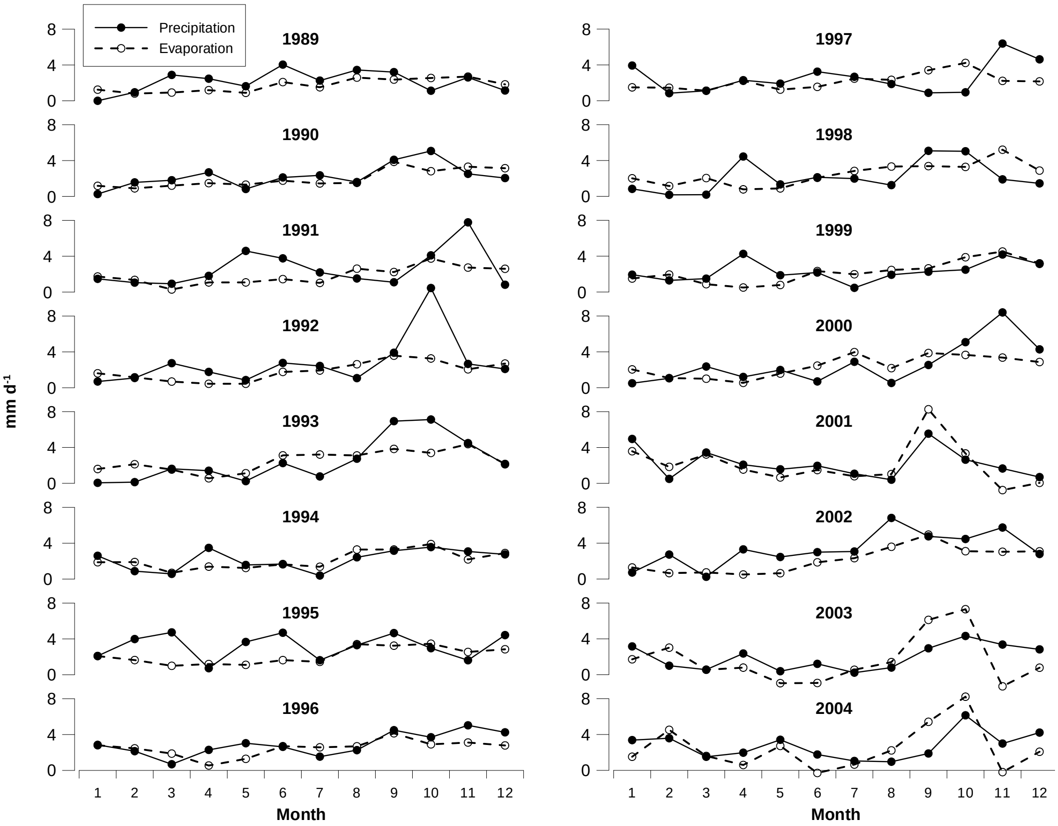

Figure 6. Monthly averages of precipitation (full line with black dots) and evaporation (dashed line with white dots) at the Po River delta–Rovinj profile in the analysed years (1989–2004).

on both original and transformed data showed an increase in the trend and a distinct decrease in December. Other months showed slight or no trends at all.

3.5 Pressures forcing phytoplankton

The influence of geostrophic currents, ICCC and Po River flow in the original and transformed phytoplankton data at the complete Po River delta–Rovinj transect, as well as at each of the stations along the transect, was analysed. The highest impact of circulation on the phytoplankton occurs during winter (January–February), early spring (March) and in autumn (September; Table 1). In January, the impact is restricted to the western (SJ101) and eastern parts (SJ107 and RV001); however, in February it spread to the middle of the transect (SJ103). Correlations based on non-transformed pPC1 data show that the circulation during January and February affect the phytoplankton through the entire transect, and the one based on lcPC1 is limited to specific stations (SJ101 and SJ107). Correlation observed for March indicates the impact of currents on the phytoplankton at SJ101 and also in the entire transect (lpPC1). During April, May and June, the impact of currents is noticed sporadically over the transect, while in August the circulation impact is practically non-existent. Interestingly, September phytoplankton is strongly impacted by the currents, from the middle to the eastern part of the transect (SJ105, SJ107 and RV001), and also in the entire transect (lpPC1). More specifically, the impact of the ICCC (Table 1) on the phytoplankton was acknowledged in January and February, as a part of the complete circulation pattern, and in July and October, where the ICCC impact does not reflect the complete circulation of the transect, while in September no impact of the ICCC over the complete circulation pattern was established.

The February circulation is, according to the cPC1 of the two types, the cyclonic (Fig. 9), transporting freshwater from the Po River towards the south in the western part of the Adriatic with the mid-Adriatic oligotrophic water inflow in the NA along the eastern coast; the anticyclonic circulation allows the Po River water to spread towards the eastern Adriatic coast. Our analyses of cPC1 scores (long-term changes; Fig. 2) show that both circulation modes are equally probable. The correlation of scores of transformed phytoplankton data with February cPC1 (Table 1) indicates that a cyclonic circulation pattern favours low February phytoplankton in the NA (Figs. 2c, 8c). In contrast, the anticyclonic February circulation mode, as given by PC1, results in high phyto-

Table 1. Positive (+) or negative (−) correlation between changes in phytoplankton abundance (pPC1 scores or average water column values at SJ108, SJ101, SJ103, SJ105, SJ107 and RV001) during 1990–2004 and changes in (i) cPC1 scores, (ii) the ICCC and (iii) Po flow discharge rates 1, 3 and 15 days before the PA sampling, for original and log data. The signs and signs in parentheses indicate significances of 80 and 95 %, respectively.

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
cPC1	pPC1	(-)	(-)							(+)			
	SJ108				(-)					+			
	SJ101	(+)	+										
	SJ103		+				-			+			
	SJ105		+							(+)			
	SJ107	(+)	(+)	+	-					+			
	RV001	+											
	lpPC1			(-)						(+)			
	SJ108				(-)					+			
	SJ101	(+)	(+)	(-)									
	SJ103		(+)				(-)			+			
	SJ105	+	+							(+)			
	SJ107	(+)	(+)		-	(+)				(+)			
	RV001	(+)								(+)		+	
ICCC	pPC1	-	-		-			(-)		-			
	SJ108	(+)						+					
	SJ101	+	(+)										
	SJ103		(+)		+								
	SJ105	+			+					-	+		
	SJ107	+	(+)					(+)			+		
	RV001	+					-				(+)		
	lpPC1							-			-		
	SJ108	(+)						+					
	SJ101	+	(+)										
	SJ103		(+)		+								
	SJ105	+			+					-	+		
	SJ107	+	(+)					(+)			+		
	RV001	+					-				(+)		

	Time lag (days)	Jan			Feb			Mar			Apr			May			Jun			Jul			Aug			Sep			Oct			Nov			Dec		
		1	3	15	1	3	15	1	3	15	1	3	15	1	3	15	1	3	15	1	3	15	1	3	15	1	3	15	1	3	15	1	3	15	1	3	15
Po flow	pPC1													+	+		-	-		(-)	(-)	(-)					+	+		-	(-)						-
	SJ108													-	-			+		+	(+)	+	-	(-)		+	+		+	+							+
	SJ101															-	(+)	+													+	+		+	+		(+)
	SJ103									+							+			+	(+)	+				(+)	(+)	+									+
	SJ105									+							(+)	(+)		+	+						+	+		(+)	+						+
	SJ107																+	+		+	+			-						+	(+)						+
	RV001										+	+							(+)	+	+	+															
	lpPC1																	-		(-)	(-)	(-)			-	(+)	(+)	+	-	(-)	(-)			(-)			
	SJ108												+					(+)		(+)	(+)	(+)		-			+		+	(+)	+						+
	SJ101																													+	+		+				(+)
	SJ103									(+)			(+)				+			(+)	(+)	(+)				(+)	(+)	+									+
	SJ105									+	+	+					(+)	(+)		+	+					(+)	(+)	(+)	+	(+)	(+)						+
	SJ107																(+)			(+)	(+)	+		-		(+)	(+)		+	(+)	(+)						
	RV001											+							+	-	-					(+)	(+)	+		+							

plankton abundance in the entire NA as the freshwater influence reaches the eastern part as well.

The Po River impact on the phytoplankton is quite complementary to already described circulation forcing (Table 1). Typically, postponed (14-day delay) Po River impact which is restricted in March and April to the middle of the transect is followed by a more immediate (1- and 3-day delay) impact in June. The only month when extreme Po flow influenced phytoplankton was in June when riverine impact widens over the transect (westwards to SJ101 and eastwards to RV001). July is characterized by immediate and postponed high impact of the Po River over the transect. This impact disappears during August and is again strongly established in September and October, by immediate and postponed flow. Impact during November and December is only of postponed character; however, in November it spreads along the transect while in December it is restrained to the eastern station, SJ101.

The correlations between the phytoplankton (non-transformed pPC1 and transformed data – lpPC1) or currents (cPC1) and monthly averages of the Po River discharge (Table 2a), precipitation (Table 2b) or evaporation (Table 2c) of the previous period are presented with different time lags (with 1–12 months ahead).

High January phytoplankton is abundance induced by an increased Po River outflow during the previous March in the eastern part of the transect and stable water column in the western part, which is induced by low evaporation during the previous spring, stable conditions in August induced by high precipitation over the transect, and high evaporation in September at the eastern station SJ107. Contrastingly, high February phytoplankton abundance is preceded by a steady water column with slight precipitation throughout the previous summer, intense autumn evaporation and early winter riverine outflow spreading over the middle transect. High phytoplankton abundance in March is preceded by scarce precipitation over the middle to eastern part of the transect in the preceding April. High phytoplankton abundance in April and May is generally preconditioned by low Po flow in the long period of several preceding months, from August to December, resulting in increased salinity in the upper layers,

Table 2. Positive (+) or negative (−) correlation between changes in geostrophic currents (cPC1 scores)/phytoplankton original values (pPC1 scores)/transformed values (lpPC1 scores)/transformed average water column phytoplankton values at SJ108, SJ101, SJ103, SJ105, SJ107 and RV001 during 1990–2004 and changes in surface fluxes, evaporation (E) and precipitation (P) and Po River rates (Po) in preceding month. The time lags are between 1 and 12. The signs and signs in parentheses indicate significances of 80 and 95 %, respectively.

E																									
	Dec	Nov	Oct	Sep	Aug	Jul	Jun	May	Apr	Mar	Feb	Jan		Dec	Nov	Oct	Sep	Aug	Jul	Jun	May	Apr	Mar	Feb	Jan
Jan	- 1	- 2	- 3	- 4	- 5	- 6	- 7	- 8	- 9	- 10	- 11	- 12	Jul	- 7	- 8	- 9	- 10	- 11	- 12	- 1	- 2	- 3	- 4	- 5	- 6
cPC1				(+)	+	+							cPC1		-										-
pPC1					(+)	+		-	(-)				pPC1									(-)			
lpPC1				-							+		lpPC1									-			
logaSJ108			+				-	(-)	(-)	(-)			logaSJ108					+					+		
logaSJ101				+							-		logaSJ101	-				+			(+)				
logaSJ103	+					-			(+)		-	-	logaSJ103							(+)			+		
logaSJ105	+			+							-	-	logaSJ105							(+)	+		+		
logaSJ107				(+)									logaSJ107										+		+
logaRV001					+						-		logaRV001		+	(+)		(+)							
Feb	- 2	- 3	- 4	- 5	- 6	- 7	- 8	- 9	- 10	- 11	- 12	- 1	Aug	- 8	- 9	- 10	- 11	- 12	- 1	- 2	- 3	- 4	- 5	- 6	- 7
cPC1		-	(+)				(-)				(+)		cPC1						-						
pPC1					(+)	+							pPC1				+		(-)		(-)				
lpPC1		+	(-)				+				-		lpPC1								+				
logaSJ108					-		(-)						logaSJ108	(-)							(+)			(+)	
logaSJ101		-	(+)				(-)				+		logaSJ101								(+)				+
logaSJ103			+			+					+		logaSJ103					-			+			+	
logaSJ105		-	+								+		logaSJ105												(+)
logaSJ107		-	(+)				(-)				+		logaSJ107		-		+								
logaRV001	+				-		-		+				logaRV001			-					+			(+)	
Mar	- 3	- 4	- 5	- 6	- 7	- 8	- 9	- 10	- 11	- 12	- 1	- 2	Sep	- 9	- 10	- 11	- 12	- 1	- 2	- 3	- 4	- 5	- 6	- 7	- 8
cPC1		(+)	-				(+)	(+)		+			cPC1				+	(+)							
pPC1								-					pPC1				+	(+)							
lpPC1		-											lpPC1				(+)	(+)						+	
logaSJ108													logaSJ108					+				(-)			
logaSJ101													logaSJ101									(-)			
logaSJ103		+			-					+			logaSJ103		(+)		+								
logaSJ105		(+)						+		+			logaSJ105				(+)	(+)							
logaSJ107		+						+		+			logaSJ107				+	(+)	-					(+)	
logaRV001				(-)		-							logaRV001	-			+		-					(+)	
Apr	- 4	- 5	- 6	- 7	- 8	- 9	- 10	- 11	- 12	- 1	- 2	- 3	Oct	- 10	- 11	- 12	- 1	- 2	- 3	- 4	- 5	- 6	- 7	- 8	- 9
cPC1			+	(-)									cPC1	(+)	+	-							(-)		
pPC1		+				(+)							pPC1							(-)				-	
lpPC1							+	(-)	(-)				lpPC1												+
logaSJ108			-	+			-		+				logaSJ108												-
logaSJ101							-		+				logaSJ101			-									-
logaSJ103								(+)	(+)	-	-		logaSJ103				-					-			
logaSJ105								+	+	-			logaSJ105												-
logaSJ107								(+)	(+)				logaSJ107												-
logaRV001				-						-			logaRV001		-										
May	- 5	- 6	- 7	- 8	- 9	- 10	- 11	- 12	- 1	- 2	- 3	- 4	Nov	- 11	- 12	- 1	- 2	- 3	- 4	- 5	- 6	- 7	- 8	- 9	- 10
cPC1		-	(+)							(+)			cPC1		(-)	(-)							(+)		
pPC1	+		(+)	+		+					(+)	(+)	pPC1	(+)		+		(+)						(+)	+
lpPC1						+					(+)	+	lpPC1	+		(+)				-				(+)	+
logaSJ108		-				(-)	(-)	-			(-)	-	logaSJ108	(-)										-	(-)
logaSJ101			-		(-)	-					(-)		logaSJ101	-						+	(+)				-
logaSJ103			-			-					(-)	(-)	logaSJ103	-			-		-	+				(-)	-
logaSJ105					(-)			(+)	(+)		-		logaSJ105	-		-			-					(-)	-
logaSJ107					-			+			-		logaSJ107			-				+				(-)	
logaRV001							-		-				logaRV001	-		-				+	+		+	-	
Jun	- 6	- 7	- 8	- 9	- 10	- 11	- 12	- 1	- 2	- 3	- 4	- 5	Dec	- 12	- 1	- 2	- 3	- 4	- 5	- 6	- 7	- 8	- 9	- 10	- 11
cPC1					(+)				(-)				cPC1		-										
pPC1				(+)		(+)				+	(+)		pPC1	-		+	-			(-)				(-)	(-)
lpPC1			(-)	(+)							(+)		lpPC1	(-)			-			-				-	(-)
logaSJ108				(-)	-				-	-	-	-	logaSJ108	(+)			+		+	(+)				(+)	(+)
logaSJ101			(+)	(-)	-						(-)	-	logaSJ101	+			+		+	+		-			(+)
logaSJ103		-	(+)	-	-						(-)		logaSJ103	(+)					(+)	(+)				+	(+)
logaSJ105			(+)	(-)							(-)		logaSJ105	(+)			+		+	(+)				+	(+)
logaSJ107			+	-							(-)		logaSJ107	(+)		-			+	(+)					+
logaRV001			+								-		logaRV001	+		-	+			(+)				(+)	+

Table 2. Continued.

	P											
	Dec	Nov	Oct	Sep	Aug	Jul	Jun	May	Apr	Mar	Feb	Jan
Jan	- 1	- 2	- 3	- 4	- 5	- 6	- 7	- 8	- 9	- 10	- 11	- 12
cPC1					+					-		
pPC1												
lpPC1					(-)	-						
logaSJ108									+			
logaSJ101					(+)	+					+	
logaSJ103						+						
logaSJ105					+	+			+			
logaSJ107					(+)						+	
logaRV001			-		(+)							
Feb	- 2	- 3	- 4	- 5	- 6	- 7	- 8	- 9	- 10	- 11	- 12	- 1
cPC1						-						
pPC1												
lpPC1						+	(+)					
logaSJ108							(-)					
logaSJ101			+			(-)	(-)		-			
logaSJ103	-						(-)			-		
logaSJ105							-				(-)	
logaSJ107			+			(-)	-					
logaRV001							-					
Mar	- 3	- 4	- 5	- 6	- 7	- 8	- 9	- 10	- 11	- 12	- 1	- 2
cPC1			(-)					+				+
pPC1			(+)								-	(-)
lpPC1								-	(+)			
logaSJ108					-				-			
logaSJ101			+		(-)				-			
logaSJ103					-				(-)			
logaSJ105									(-)			
logaSJ107								+	(-)			
logaRV001							+	(+)				
Apr	- 4	- 5	- 6	- 7	- 8	- 9	- 10	- 11	- 12	- 1	- 2	- 3
cPC1		(+)		(-)			+	+				-
pPC1				+								
lpPC1												-
logaSJ108				+								
logaSJ101												(+)
logaSJ103			-									+
logaSJ105	(-)											
logaSJ107											+	(+)
logaRV001	(-)	(+)		-			(+)	(+)				
May	- 5	- 6	- 7	- 8	- 9	- 10	- 11	- 12	- 1	- 2	- 3	- 4
cPC1	(+)			-								
pPC1			+		(-)		-					
lpPC1			(+)		-		-			+		+
logaSJ108		-					+					(-)
logaSJ101			-									
logaSJ103		-	-		(+)		+					-
logaSJ105			-			+						
logaSJ107	+		(-)	-								
logaRV001		(-)										
Jun	- 6	- 7	- 8	- 9	- 10	- 11	- 12	- 1	- 2	- 3	- 4	- 5
cPC1	-	(-)				-					+	
pPC1	+			+								
lpPC1				(+)	(+)		+			(-)		
logaSJ108			-	-								-
logaSJ101		+		(-)	(-)							(-)
logaSJ103		(+)		(-)	(-)					+		
logaSJ105			-	(-)	(-)					(+)		
logaSJ107				-	-	-	-	+	-	(+)	+	
logaRV001					-		-		-	(+)		-

	P											
	Dec	Nov	Oct	Sep	Aug	Jul	Jun	May	Apr	Mar	Feb	Jan
Jul	- 7	- 8	- 9	- 10	- 11	- 12	- 1	- 2	- 3	- 4	- 5	- 6
cPC1								(-)				-
pPC1	-											
lpPC1	-							+			+	
logaSJ108	+							-				
logaSJ101	+						(-)	(-)				
logaSJ103	+							-			-	
logaSJ105	+							(-)			-	
logaSJ107	(+)	+										+
logaRV001						-	-					
Aug	- 8	- 9	- 10	- 11	- 12	- 1	- 2	- 3	- 4	- 5	- 6	- 7
cPC1	-	(-)					(+)	(+)	-			
pPC1					-				+			
lpPC1		-						(+)			+	+
logaSJ108			+			-	(-)					
logaSJ101		-							(-)		+	
logaSJ103								+				
logaSJ105	(+)		(-)					(+)			+	+
logaSJ107	+									-		
logaRV001				+				+				(+)
Sep	- 9	- 10	- 11	- 12	- 1	- 2	- 3	- 4	- 5	- 6	- 7	- 8
cPC1				(+)	(+)					-		
pPC1			+	(+)		-				(-)		
lpPC1			+	(+)		(-)			(+)	(-)		
logaSJ108		(-)								-		-
logaSJ101		(-)						+			(+)	
logaSJ103		-		(+)				+	+	(-)		
logaSJ105				+	+	-	+		+	(-)		
logaSJ107			+			(-)			+			
logaRV001			+	+		(-)			+			
Oct	- 10	- 11	- 12	- 1	- 2	- 3	- 4	- 5	- 6	- 7	- 8	- 9
cPC1												
pPC1			(-)	(-)				+				
lpPC1	+	(+)	-					+				(+)
logaSJ108		-						-		-		(-)
logaSJ101	-	(-)	+									-
logaSJ103		-										(-)
logaSJ105			+					(-)				(-)
logaSJ107	-	-	(+)					-				(-)
logaRV001		-							-			-
Nov	- 11	- 12	- 1	- 2	- 3	- 4	- 5	- 6	- 7	- 8	- 9	- 10
cPC1		-										
pPC1	+					(-)						(+)
lpPC1						(-)	-			-		+
logaSJ108	-		+			+						-
logaSJ101		-		+	+							-
logaSJ103	(-)			+		+						(-)
logaSJ105	-					+						-
logaSJ107					+	+	+			+		
logaRV001		-		+	+	+	+					-
Dec	- 12	- 1	- 2	- 3	- 4	- 5	- 6	- 7	- 8	- 9	- 10	- 11
cPC1							+					
pPC1	-							-				-
lpPC1	-							(-)				-
logaSJ108	+							(+)	-			+
logaSJ101		+						(+)			+	
logaSJ103	+							+				
logaSJ105	+							(+)	-			
logaSJ107					-		-		-	+		
logaRV001								+	-	+		+

Table 2. Continued.

Po

	Dec	Nov	Oct	Sep	Aug	Jul	Jun	May	Apr	Mar	Feb	Jan		Dec	Nov	Oct	Sep	Aug	Jul	Jun	May	Apr	Mar	Feb	Jan
Jan	- 1	- 2	- 3	- 4	- 5	- 6	- 7	- 8	- 9	- 10	- 11	- 12	Jul	- 7	- 8	- 9	- 10	- 11	- 12	- 1	- 2	- 3	- 4	- 5	- 6
cPC1				+				-		(+)	+		cPC1											-	-
pPC1					+								pPC1	(-)							+	+			-
lpPC1	+	+		-		+	-			(-)	-		lpPC1	(-)		-		(-)	-						(-)
logaSJ108				+			+						logaSJ108	+		+	+	+	+						+
logaSJ101	(-)	-		(+)		-	(+)			+	+		logaSJ101	+		(+)	+						-		
logaSJ103	-	-											logaSJ103	+				(+)	+						
logaSJ105	-					-							logaSJ105	+		+	+	(+)							+
logaSJ107	-	-		(+)		-	+			(+)	+		logaSJ107	(+)	(+)	+	(+)	+						+	(+)
logaRV001	(-)	(-)		+			+			(+)			logaRV001			+	(+)				(+)		-		
Feb	- 2	- 3	- 4	- 5	- 6	- 7	- 8	- 9	- 10	- 11	- 12	- 1	Aug	- 8	- 9	- 10	- 11	- 12	- 1	- 2	- 3	- 4	- 5	- 6	- 7
cPC1								-	-				cPC1					(-)	-						
pPC1					+					+			pPC1				-			+					
lpPC1	(-)			+				+	(+)				lpPC1			(-)						-			
logaSJ108				-	-			-		-			logaSJ108	+					+	(-)					
logaSJ101	+		-						-				logaSJ101				+			-		-			
logaSJ103	(+)			-				-	-				logaSJ103			-	-			-					
logaSJ105	(+)							-	-				logaSJ105			(-)									
logaSJ107	+							(-)	(-)				logaSJ107			(-)					-	-			
logaRV001			-	-	-			-	-	-			logaRV001							-			+	+	(+)
Mar	- 3	- 4	- 5	- 6	- 7	- 8	- 9	- 10	- 11	- 12	- 1	- 2	Sep	- 9	- 10	- 11	- 12	- 1	- 2	- 3	- 4	- 5	- 6	- 7	- 8
cPC1					+			(+)				+	cPC1				+			(+)			+	(+)	
pPC1						(+)		-			-		pPC1			+	(+)								
lpPC1				+								-	lpPC1												
logaSJ108				-	-								logaSJ108	-	-		(+)		-						-
logaSJ101				-	(-)								logaSJ101	-	(-)	(-)					-	(-)	-	-	(-)
logaSJ103				(-)	-		-					+	logaSJ103				(+)								
logaSJ105				-							+	(+)	logaSJ105											+	
logaSJ107											+	(+)	logaSJ107												
logaRV001													logaRV001			+									
Apr	- 4	- 5	- 6	- 7	- 8	- 9	- 10	- 11	- 12	- 1	- 2	- 3	Oct	- 10	- 11	- 12	- 1	- 2	- 3	- 4	- 5	- 6	- 7	- 8	- 9
cPC1			+		+				+	(-)		(-)	cPC1												
pPC1	-	-											pPC1												
lpPC1	+		(+)		(+)								lpPC1		+			+		+			+	+	(+)
logaSJ108					(-)					+			logaSJ108		-			-	(-)	(-)			(-)	(-)	(-)
logaSJ101					(-)								logaSJ101		-				-						-
logaSJ103	-		(-)		-	-	-					+	logaSJ103	-				-	-				(-)	(-)	(-)
logaSJ105	(-)		-	-	(-)								logaSJ105		-			(-)		-			(-)	(-)	(-)
logaSJ107			(-)		-						+		logaSJ107					-		-			-	-	(-)
logaRV001	-								(+)				logaRV001												-
May	- 5	- 6	- 7	- 8	- 9	- 10	- 11	- 12	- 1	- 2	- 3	- 4	Nov	- 11	- 12	- 1	- 2	- 3	- 4	- 5	- 6	- 7	- 8	- 9	- 10
cPC1						(+)		-					cPC1											-	-
pPC1	+	+	+									+	pPC1				+					-	(+)		
lpPC1	(+)	(+)	(+)					+	+	+	+	(+)	lpPC1									-			
logaSJ108	-	(-)	(-)					(-)	-	-	(-)	(-)	logaSJ108												
logaSJ101			-	(-)			(-)						logaSJ101								+	+			
logaSJ103	(-)	(-)	(-)	-							(-)	-	logaSJ103			+					+	(+)	-		
logaSJ105				-			-		+				logaSJ105						+			+			
logaSJ107			-	-			(-)						logaSJ107						+	+	+	+			
logaRV001		(-)	(-)	-				(-)			-	-	logaRV001									+			
Jun	- 6	- 7	- 8	- 9	- 10	- 11	- 12	- 1	- 2	- 3	- 4	- 5	Dec	- 12	- 1	- 2	- 3	- 4	- 5	- 6	- 7	- 8	- 9	- 10	- 11
cPC1	-	-							(-)	(-)			cPC1												
pPC1	+			+							+		pPC1					(-)			-	-	-	-	-
lpPC1		-		+			(+)						lpPC1					(-)			(-)	-	-	(-)	-
logaSJ108			-	(-)							-		logaSJ108					(+)			(+)	+	+	+	+
logaSJ101				(-)		+	(-)		+				logaSJ101		(+)	+		+			+				
logaSJ103	+	+		-		+	-		(+)				logaSJ103					(+)			(+)	+	+		
logaSJ105							-						logaSJ105					(+)			+	+		+	+
logaSJ107		+					(-)						logaSJ107					(+)			(+)	(+)	+		
logaRV001		+						+					logaRV001					+			+	+	(+)	+	+

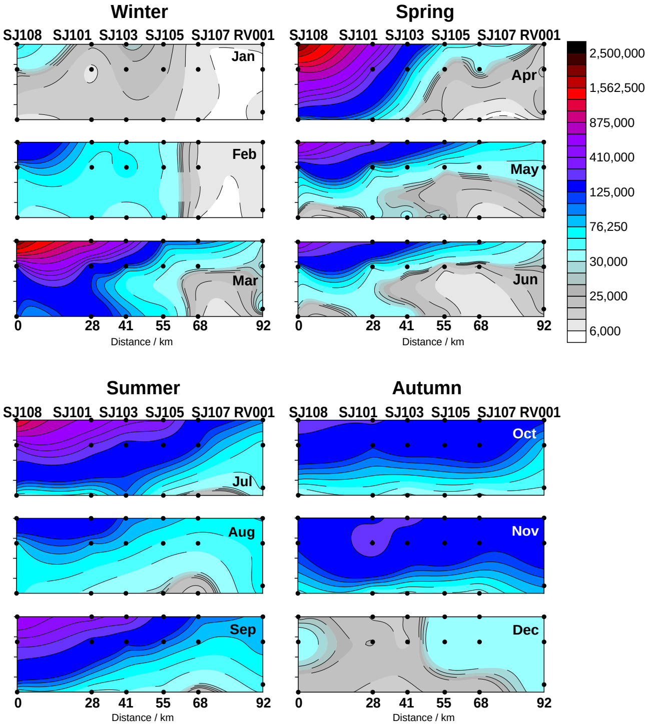

Figure 7. Geometrical means for each month of the phytoplankton abundance in the 1990–2004 period.

thus enabling more efficient autumnal water mixing and ultimately higher phytoplankton in the following spring. High phytoplankton abundance in June is favoured by stable August and September conditions characterised by low evaporation and precipitation and intense water column mixing in October, induced by high evaporation. High phytoplankton abundance in July is preconditioned by high Po River flow during long period of several preceding months, from August to December, thus enabling inflow of nutrient-enriched low saline waters over that period and also facilitating spring spreading of riverine waters due to a stratified water column. High phytoplankton abundance in August at the western part of the transect is favoured by extremely intense evaporation and thus water mixing in the previous May. High phytoplankton abundance in September is induced by low precipitation in the previous March; in October, by low evaporation during previous January in addition to low Po flow during the January–March period; and in November by low evaporation in February, favouring stable conditions. Thus, restricted water mixing in the previous January–March period favours high phytoplankton abundance in the following autumn. Interestingly, high phytoplankton abundance in December is preceded by the intense water column mixing during previous winter and spring, induced by intense evaporation.

3.6 Wind influence

3.6.1 Wind intensity

In 2001, 2003, and 2004, years of low evaporation, the average wind speed was 4.1–4.8 $\mathrm{m\,s^{-1}}$, while in the years of high evaporation it was both higher, 5.0–6.1 $\mathrm{m\,s^{-1}}$ in 1998 and 1999, and lower, 3.4 $\mathrm{m\,s^{-1}}$ in 1993 (Table 3). High evaporation in 1993 occurred in conditions of very low air temperature and very high sea temperature (9.1 and 16.4 °C, respectively; values are monthly averages for three stations in the region, Trieste, Rovinj and Mali Lošinj and low when compared to 1966–1990 averages of 10.7 and 15.8 °C), implying that temperature conditions are, besides winds, an additional important factor regulating evaporation rates.

3.6.2 Wind direction

Winds from the NE are generally stronger than winds from other directions and, as they blow over land, are dry and consequently induce enhanced evaporation. Thus, it is to be expected that in months of enhanced evaporation rates NE winds are more pronounced and more frequent than in months of reduced evaporation rates. On the other hand, winds from the SE blow over the sea and are moist and thus are not expected to induce the evaporation rates of same intensity as do NE winds of the same strength.

In line with this expectation, in the months of November with low evaporation (in 2003 and 2004), NE winds were less frequent than in years of high evaporation (in 1993, 1998 and 1999). In addition, when evaporation was low, in 2003 and 2004, winds from the SE were pronounced and appeared with higher intensities than in other investigated years. However, in November 2001, characterised by low evaporation, winds from the NE were very strong and highly frequent, while the SE winds were weak. Presumably, low evaporation rates were in this month due to a very small difference between air and sea temperatures (monthly averages of air and sea temperature for Trieste, Rovinj and Mali Lošinj were 8.3 and 11.9 °C, respectively, implying that the air–sea temperature difference was 3.6 °C which is low when compared to the 1966–1990 average of 5.1 °C).

3.6.3 Wind several days prior to phytoplankton sampling

Bora events (mostly of (E)NE direction) were observed in days preceding winter sampling of both high and low phytoplankton abundances. On 17 February 2004, the largest winter bloom of the 1990–2004 period, extending over the entire Po River delta–Rovinj transect, in conditions of "anticyclonic" circulation, was documented. The Po River rates were, until the last days of the month, very low. Five days before the phytoplankton measurement, a moderate *bora* episode (daily average of 8.6 $\mathrm{m\,s^{-1}}$) was observed and was

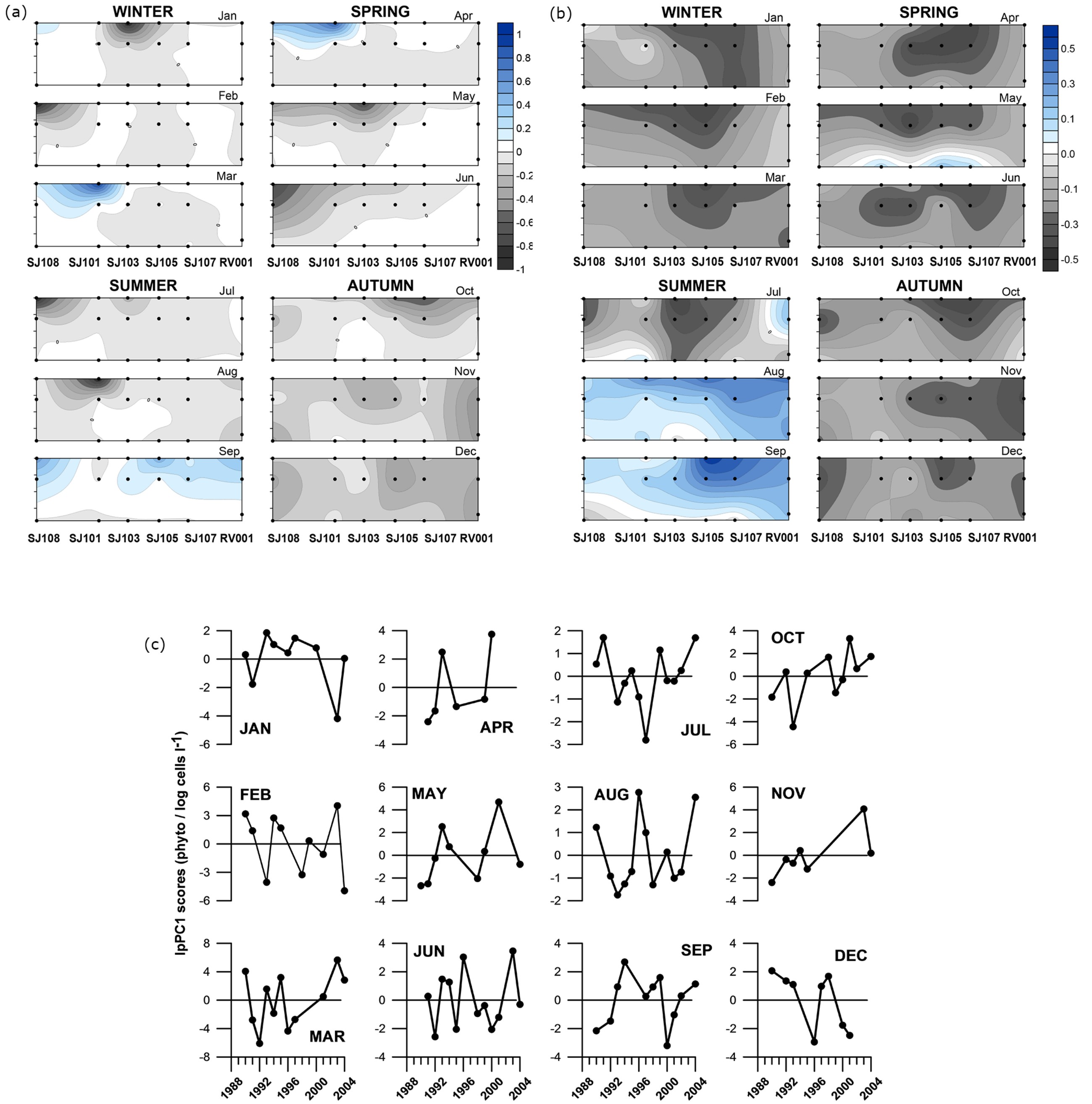

Figure 8. pPC1 loadings of original data **(a)** along with lpPC1 loadings **(b)** and lpPC1 scores **(c)** of log data for the phytoplankton abundance in the 1990–2004 period.

followed by winds with pronounced NW or NE component, up to 4 m s^{-1} in days before measurement.

Eleven days preceding the measurement of very low winter phytoplankton abundances on 20 February 2003, the wind was almost exclusively of NE direction, with speed generally over 4 m s^{-1} and occasionally reaching high values (daily average of up to 14 m s^{-1} on 16 February). Po River rates were in the first half of the month above average and in the second month below the average, while the circulation on the date of measurement was "cyclonic".

The largest summer bloom was documented on 8 July 1997 in conditions of high Po River discharge rates, a day after a strong WNW (5 B; Beaufort scale number) episode, which might have helped in spreading low salinity Po River waters from the delta area towards the east. Strong winds from the west (WSW 5 B in the morning and NNW 6 B in the evening) blew on 26 July 2001, 3 days before sampling

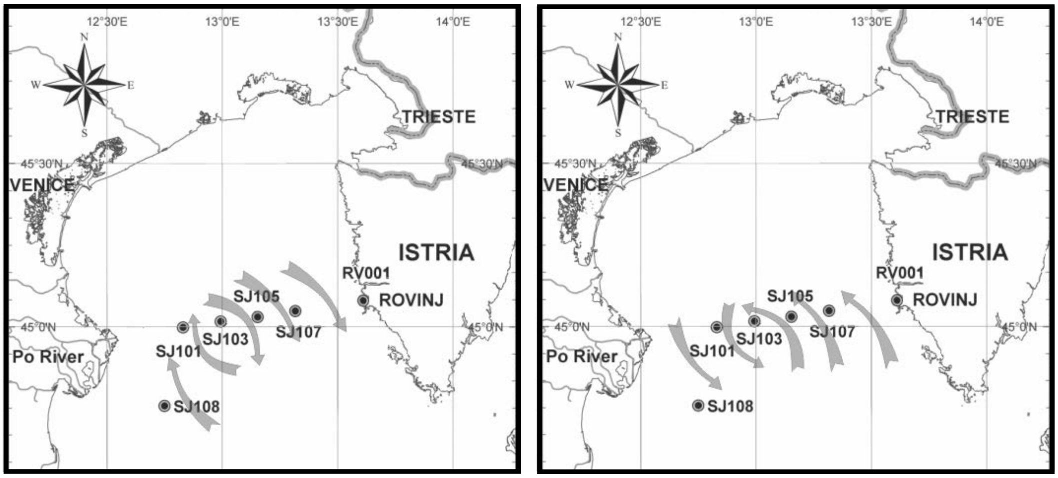

Figure 9. The two circulation patterns appearing in February: the anticyclonic (left) and the cyclonic (right).

Table 3. Frequency (FREQ) and intensity (INT) of winds from various directions (N, NE, E, SE, SW, W, NW) in November in years with high (1993, 1998 and 1999) and low (2001, 2003 and 2004) evaporation rates. The frequency is a number of occurrences of specific wind direction within a month based on three-times-per-day sampling. Total indicates the monthly wind average.

	1993		1998		1999		2001		2003		2004	
Wind direction	FREQ	INT (beaufort)	FREQ	INT (beaufort)	FREQ	INT (beaufort)	FREQ	INT (beaufort)	FREQ	INT (beaufort)	FREQ	INT (beaufort)
N	8	2.7	2	4.6	3	2.3	2	0.8	1	2.6	2	2.5
NE	43	4.2	38	8.2	38	6.5	45	6.5	29	5.1	24	8.0
E	23	3.6	16	3.6	21	4.8	15	2.9	19	5.0	23	4.6
SE	1	3.4	10	3.0	13	2.6	5	1.7	13	5.6	10	4.1
S	3	1.3	3	4.4	–	–	–	–	–	–	–	–
SW	2	1.6	8	9.4	4	5.5	12	4.8	3	2.5	9	5.0
W	3	2.2	2	4.3	4	3.4	2	1.7	5	1.9	7	1.9
NW	1	3.4	8	4.8	6	3.7	8	3.1	13	2.7	8	1.8
Total	–	3.4	–	6.1	–	5.0	–	4.8	–	4.1	–	4.7

of another large phytoplankton bloom on 23 July, which presumably favoured spreading of Po River waters whose rates were slightly above the average. Geostrophic circulation and salinity distribution on cruise dates in these 2 years show presence of two large gyres, in the eastern and western parts of the investigated area, in which low salinity water accumulated (Supić et al., 2003, for 1997 and unpublished data for 2001).

However, in July 2000, in days preceding the 19 July cruise winds were of variable directions with only one more pronounced wind episode over 3 B (on 15 July, 4 B from ESE, midday). Po River rates were below the average, salinity between the Po River delta and Rovinj was much higher than in 1997 and 2001 and geostrophic currents were weaker than in 1997 and 2001. The large bloom which occurred might be due to more intense vertical mixing in conditions of low stratification (sigma-t was around 25–25.5 at the surface and around 28.5 at the bottom, with the difference between the two values lower than in 1997 or 2001), which enabled the rise of bottom nutrients from sea bottom (which in that part of the year accumulate near the bottom; e.g. Degobbis et al., 2000) and their use in primary production.

3.7 Stratification

Generally, there is no correlation between stratification and phytoplankton abundance (not shown). However, exceptionally intense stratification in the eastern part of the profile (SJ107) in February and October seems to be correlated with increased phytoplankton abundance.

4 Discussion

4.1 Characteristics of phytoplankton distribution

Rather stable horizontal and vertical phytoplankton abundance gradients are characteristic for almost the entire year. Only in the coldest of months (December–January) is the water column habitually uniform (Fig. 7). However, isolated shallow phytoplankton patches occasionally form in the surface layer of SJ108 and SJ103, as indicated by the monthly averages of original phytoplankton values.

Generally, a comparison between the original and transformed phytoplankton data allowed us a more comprehensive insight into the yearly phytoplankton distribution over the analysed area of the NA. The transformed data corresponds to the characteristic phytoplankton pattern in the area. In the case of the NA, this mainly means that three phytoplankton blooms develop regularly in the western part of the region during the year. On the other hand, original data are found to give us more specific information, enabling us insight into the occasional occurrences in the region. For the NA this mainly means that phytoplankton blooms of smaller intensity develop occasionally at the eastern part of the region during autumn and winter. Their occurrences are highly dependable on the regional circulation pattern, i.e. development of the ICCC (Table 1).

4.2 Simultaneous factors inducing blooms

In January and February the appearance of phytoplankton blooms depend on the circulation pattern. The blooms respond to the presence of the nutrient-enriched Po River waters which are redistributed in the NA according to the circulation pattern. The intensity of the Po River discharge plays no role in it.

Our results are in line with our previous work (Kraus and Supić, 2011) in which we came to the conclusion that February circulation patterns highly influence the appearance of the large blooms by following another approach, i.e. by relating the phytoplankton abundance of a specific station to the intensity of the ICCC. In this work we performed the PCA, which enabled a more comprehensive insight into the circulation patterns and phytoplankton of the NA, as we included a complete phytoplankton data set and circulation pattern of the entire profile (calculated by PCA). However, both analyses resulted with similar conclusions.

From March to December, the Po River outflow intensity reflects, to lower or larger degree, on phytoplankton abundances in the region. During this entire period the column is generally stratified, with highest stratification degree of 0–5 m surface layer at the stations of the profile between the Po River delta and Rovinj in June–July (Degobbis et al., 2000). Due to low turbulent mixing at the pycnocline depth, the low salinity riverine water is in highly stratified conditions retained in the surface layer and therefore spreads around the basin, regardless of the existing circulation pattern. The amount of freshened water at a certain NA location is then proportional to the discharge rate: the larger discharge, the larger amount of freshened water at the location, inducing more intensive phytoplankton blooms. Thus, in periods of high stratification degree, as are June and July, the Po River discharge rates immediately reflect on the phytoplankton blooms. However, by the end of summer the situation becomes more complex and direct Po River influence on phytoplankton turns periodical. In September and October correlations between blooms and Po River rates with 15 days time lag are high, as the one between the blooms and PC1 or ICCC, meaning that waters from the Po River recirculate within the region.

Interestingly, we obtained sporadic or no correlation between phytoplankton blooms and circulation/Po River rates in November and December. It might be that this is a period when temperature or some other factors model the interannual phytoplankton variability.

No clear relation between phytoplankton abundances and wind intensity in days preceding the measurements was observed. This is partly due to the fact that monthly sampling is too scarce to be related to highly changeable wind direction and strength. Our descriptive analysis showed that winter *bora* events preceded sampling of both high and low phytoplankton abundances. Winds with a pronounced west component along with enhanced Po River discharge favoured presumably the largest summer phytoplankton blooms. However, we also documented high phytoplankton abundance in July with low Po River discharge rates after moderate winds of highly changeable direction.

Only sporadic correlation was observed between phytoplankton abundances and stratification degree, meaning that wind-induced vertical mixing in the water column does not induce large phytoplankton abundance.

4.3 Preconditioning

Although general NA processes are not yet fully understood, the main idea for this work was to identify possible prerequisites for the phytoplankton blooms, which might occur during the preceding year's cycle. Our findings indicate the following.

- The January–March period, in conditions of low evaporation, precipitation and/or Po flow, results in a more stable vertical column which lasts for a longer period including the following spring. In spring, the regenerated nutrients remain in the lower layer resulting in low phytoplankton production; later, in the following autumn these retained nutrients are available to spread in the water column, favouring high phytoplankton abundances.

- Continuous low Po flow in the period from August to December allows for more intense vertical mixing for a longer time period including spring, thus enabling efficient use of regenerated nutrients from the bottom later in spring (April and May); in contrast, high Po flow in the same period stabilises the water column, which makes easier for the Po River waters to spread over the surface layer and accumulate in closed circulation cells until summer, inducing high blooms in July.

- Vertical distribution range of the phytoplankton blooms seems to be predetermined by vertical mixing intensity over the previous months. Namely, starting from July until November, phytoplankton blooms at the eastern part spread into lower depths, after being limited to the upper layer from April to June. We suppose that a high stratification favours accumulation of phytoplankton in the upper layer in April–June, while intense vertical mixing and deepening of the pycnocline favours accumulation of phytoplankton also in the deeper layers as in July–November. Presumably, extremely high stratification conditions are more likely to appear after a longer period of steady conditions (lower evaporation and vertical mixing). However, mixing is more intense when winds are more frequent and stronger.

The high correlation between the circulation pattern and phytoplankton blooms in February (above 95 %; Table 1), as well as correlations between circulation pattern and evaporation (above 90 %; note that correlation between phytoplankton blooms and evaporation also exists, although with significance below 90 %; Fig. 10), is an important result of our work. Namely, it is in February when exceptionally large blooms can occur with possible consequences on the anchovy catch, one of the main marine species used as food (Kraus and Supić, 2011). Large blooms at the stations SJ101 and SJ107 were highly correlated with the total anchovy catch in the subsequent year (98 and 92 %); however, the correlation at SJ101 is more reliable than the one at SJ107, the latter being based on a single year when both parameters had extremely high values (2004). Thus, long-term changes in this month can be especially important for the secondary production in the NA and deserve to be investigated more closely. Detailed comparison of evaporation in these months against PCA scores of transformed February phytoplankton abundances and geostrophic currents at the profile during the 1990–2004 period is presented at Fig. 10. It shows that the abundant February phytoplankton production, represented by negative lpPCA scores is preceded by intense evaporation in the preceding February and October, each followed by low evaporation in June and November. In contrast, intense February anticyclonic circulation (as shown in Fig. 9), which corresponds to positive cPCA scores, favouring spreading of phytoplankton eastwards from the eutrophic western parts, are also preceded by intense evaporation in preceding February and October and low evaporation in June and November. November is a month in which drastic changes in geostrophic circulation fields can occur, as was documented for 1999 (Supić et al., 2012). On the basis of the case study in 1999–2002 it was hypothesised that surface geostrophic fields are reflections of the bottom density fields which are formed in the period of pycnocline destabilisation. Different meteorological conditions in the autumns of 1999 and 2000 were invoked in explanation of different circulation in subsequent winters. Our results show that large evaporation events favour cyclonic circulation (as shown in Fig. 9), which is in line with this previous assumption, based on analysis of the 1999–2001 period, indicating that *bora* (NE) winds in autumn favour the appearance of "cyclonic" winter circulation and *scirocco* (SE) of "anticyclonic" winter circulation (Supić et al., 2012). Namely, the dry *bora* is expected to induce larger evaporation and surface heat losses than the moist *scirocco*. However, our analysis showed that evaporative fluxes in November do not depend only on wind and that the air–sea difference in temperature plays an important role in intensification/weakening of evaporative fluxes. The indication of our findings that winter and autumnal conditions were related were previously presented in Supić and Vilibić (2006) and Supić et al. (2012), where the relation between autumn and the next winter circulation were discussed. Furthermore, in an independent research by Santojanni et al. (2006), high correlations were observed between autumn conditions and the next year's anchovy stock estimate. Correlations with other months (October, June and February) are interesting but cannot be commented on without further research, based on theoretical modelling or specific case studies.

4.4 Trends

Contrary to Tedesco et al. (2007), who analysed concentrations of chlorophyll *a* in the western part of the NA and for almost the same period (1986–2005) as we did, our analysis was based on monthly interannual changes and indicated that in some periods of the year trends in bioproduction and circulation patterns are distinctive. We believe that January and February trends, which are especially pronounced in both parameters, are especially important. They show that from 1990 to 2004 a shift towards large winter bioproduction induced by more frequent winter anticyclonic circulation (Fig. 9), existed and was possibly also induced by complex air–sea interactions in the previous autumn.

4.5 Prediction of phytoplankton abundance and circulation conditions

Finally, we asked ourselves: can we actually predict blooms? According to our results, to a certain extent and several months in advance, we indeed are able to give a prognosis of the winter phytoplankton abundance and circulation conditions. However, more field work as well as applied theoretical models is needed to verify and further support our findings. And what about summer? In that period, especially in July, blooms are directly related to the previous Po River

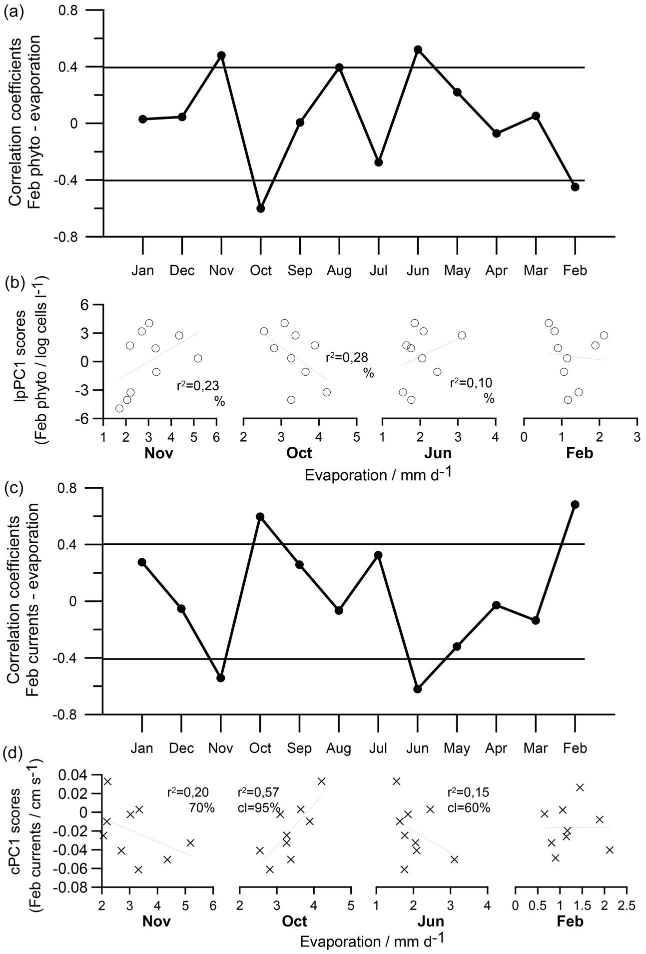

Figure 10. Correlation coefficients and lpPC1 scores of February (log values of phytoplankton; **a**, **b**) and cPC1 (geostrophic currents; **c**, **d**) against monthly averages of evaporation of the previous year during the analysed period (1989–2004) at the Po River delta–Rovinj profile **(a, c)**. Correlations in November, October, June and February are given graphically **(b, d)**.

discharge and presence of the ICCC. Thus, by monitoring conditions which induce large discharges in summer (a better understanding of the Po River regime, related to e.g. ice and snow melting in the Alps, etc.), we could possibly be a step closer to predicting summer bloom conditions as well.

All the same, what would be the purpose of being able to predict phytoplankton blooms at all? We identified the following two reasons. Firstly, we showed the example of anchovies (Kraus and Supić, 2011; Kraus et al., 2015) and that understanding the driving forces of phytoplankton production in the ecosystem is important in other fields of marine research, such as fisheries. Other studies following the same approach of combining knowledge about the marine species life cycles on the one hand and the driving pressures of their abundances and distribution patterns on the other could expand our capabilities of a planned exploration of marine resources. Secondly, in extreme cases, when exceptionally high amounts of phytoplankton are produced, ultimately huge oxygen quantities get utilised in the degradation processes. This can easily lead to hypoxia or, in more severe cases, event to anoxia. Our thoughts are that if these events increased fishing pressure (monetary stimulated), it could have a considerable role in prevention of severe oxygen depletion. Naturally, far more work should be done in order to achieve this particular goal.

5 Conclusions

We investigated numerous correlations between various environmental parameters and time lags in order to find the ones which best explains the ecosystem functioning. Although statistical significance of 95 % is commonly used, we believe that even correlations of lower significance can be important milestones in detecting relations between meteorological, dynamical and biological factors. For the purpose of future theoretical ecological models of NA, which we plan, it is useful that all possible important relations are mentioned in our work. However, in discussion of our results, we generally limit our discussions to correlations of higher significance and make a clear distinction between the ones obtained from correlations of lower (80–90 %) and higher (over 90 %) significance.

Our results show basic relations between NA phytoplankton production, Po River discharge rates, circulation and surface fluxes. They are based on a long-term data set which was analysed in detail with PCA, for detecting typical patterns and long-term changes in phytoplankton distribution and current fields of the region.

We showed that in winter and early spring (January–April) the phytoplankton abundances depend on existing circulation fields and not on intensity of Po River discharge. In late spring (May–June) the phytoplankton abundances increase 1–3 days after high Po discharge rates regardless of the circulation fields. In summer and autumn (July–December) the phytoplankton abundances are related to 15-day prior Po River discharge rates and sometimes also the 1–3-day prior rates or on concomitant circulation fields. During the entire year (January–December) the phytoplankton abundances depend on forcing of the previous 1–12 months of surface fluxes and/or Po River flows. The role of wind was uncertain but that was partly due to unmatched sampling time frames between meteorological and sea data. In February, which is presumably a crucial month for the entire NA production, both circulation patterns and phytoplankton production were dependent on evaporation rates from the preceding autumn, spring and winter. Especially interesting were the November correlations, in line with our previous research based on the case study of the 1999–2001 period, indicating that the typical anticyclonic circulation pattern, favouring Po River spreading across the NA and large bioproduction rates, appears after low evaporation rates in November. Vice versa, the cyclonic circulation pattern is preceded by a high evaporation rate. From 1990 to 2004 a shift towards large winter bioproduction induced by circulation changes appeared. We showed that the role of wind in evaporative flux enhancements is not straightforward as evaporative fluxes are highly dependent on other factors, e.g. air–sea difference in temperature. In addition, it seems that wind-induced vertical mixing in the water column does not necessary reflect on large phytoplankton abundance as the stratification degree, when analysing data separately for each month, was only sporadically related to phytoplankton abundances.

The obtained results create the basis of an "empirical ecological model" which can be used in assessments of the NA productivity, useful for the environmental management of the region or in climatic studies aiming to estimate the response of NA to climatic changes. The results obtained should be investigated in more detail by means of a theoretical ecological model, which can be developed using the simplification of oceanographic fields along with surface fluxes and Po River flow rates. Our results are also a valuable contribution in checking the numerical ecological model of the region which is currently being developed (e.g. Lončar et al., 2013).

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References

Civitarese, G., Gačić, M., Lipizer, M., and Eusebi Borzelli, G. L.: On the impact of the Bimodal Oscillating System (BiOS) on the biogeochemistry and biology of the Adriatic and Ionian Seas (Eastern Mediterranean), Biogeosciences, 7, 3987–3997, doi:10.5194/bg-7-3987-2010, 2010.

Cosoli, S., Gačić, M., and Mazzoldi, A.: Surface current variability and wind influence in the northeastern Adriatic Sea as observed from high-frequency (HF) radar measurements, Cont. Shelf Res., 33, 1–13, 2012.

Cushman-Roisin, B., Gačić, M., Poulain, P.-M., and Artegiani, A. (Eds.): Physical Oceanography of the Adriatic Sea, Kluwer Academic Publishers, Dordrecht, The Netherlands, 304 pp., 2001.

Degobbis, D., Precali, R., Ivancic, I., Smodlaka, N., Fuks, D., and Kveder, S.: Long-term changes in the northern Adriatic ecosystem related to anthropogenic eutrophication, Int. J. Environ. Pollut., 13, 495–533, 2000.

Djakovac, T., Kraus, R., Precali, R., and Supić, N.: Winter trends in the northern Adriatic, Rapp. Comm. int. Mer Médit., 39, 739, 2010.

Djakovac, T., Degobbis, D., Supić, N., and Precali, R.: Marked reduction of eutrophication pressure in the northeastern Adriatic in the period 2000–2009, Estuar. Coast. Shelf Sci., 115, 25–32, 2012.

Djakovac, T., Supić, N., Bernardi Aubry, F., Degobbis, D., and Giani, M.: Mechanisms of hypoxia frequency changes in the northern Adriatic Sea during the period 1972–2012, J. Marine Syst., 141, 179–189, 2015.

Franco, P. and Michelato, A.: Northern Adriatic Sea: oceanography of the basin proper and of the western coastal zone, Sci. Total Environ., 1992, 35–62, 1992.

Giani, M., Djakovac, T., Degobbis, D., Cozzi, S., Solidoro, C., and Fonda Umani, S.: Recent changes in the marine ecosystems of the northern Adriatic Sea, Estuar. Coast. Shelf Sci., 115, 1–13, 2012.

Grilli, F., Paschini, E., Precali, R., Russo, A., and Supić, N.: Circulation and horizontal fluxes in the northern Adriatic in the period June 1999–July 2002, Part 1: Geostrophic circulation and current measurement, Sci. Total Environ., 353, 57–67, 2005.

Krajcar, V.: The climatology of geostrophic currents in the northern Adriatic, Geofizika, 20, 105–114, 2003.

Kraus, R. and Supić, N.: Impact of circulation on high phytoplankton blooms in northern Adriatic (1990–2004) and possibilities of bloom and fish stock long-term prediction, Estuar. Coast. Shelf Sci., 91, 198–210, 2011.

Kraus, R., Supić, N., Lučić, D., and Njire, J.: Impact of winter oceanographic conditions on zooplankton abundance in northern Adriatic with implications on Adriatic Anchovy Stock prognosis, Estuar. Coast. Shelf Sci., 167, 56–66, 2015.

Kuzmić, M., Janeković, I., Book, J. W., Martin, P. J., and Doyle, J. D.: Modeling the northern Adriatic double-gyre response to intense bora wind: A revisit, J. Geophys. Res., 111, C03S12, doi:10.1029/2005JC003377, 2007.

Lončar, G., Paladin, M., and Matošević, J.: Numerical Analysis of wind impact on the intensity of algal bloom in the North Adriatic, Hrvatske vode, 84, 109–118, 2013 (in Croatian).

Marić, D., Kraus, R., Godrijan, J., Supić, N., and Dakovac, T., Precali, R.: Phytoplankton response to climatic and anthropogenic influences in the north-eastern Adriatic during the last four decades, Estuar. Coast. Shelf Sci., 115, 98–112, 2012.

Mozetič, P., Solidoro, C., Cossarini, G., Socal, G., Precali, R., Francé, J., Bianchi, F., De Vittor, C., Smodlaka, N., and Fonda Umani, S.: 2010. Recent trends towards oligotrophication of the Northern Adriatic: Evidence from chlorophyll a time series, Estuar. Coast., 33, 362–375, doi:10.1007/s12237-009-9191-7, 2010.

Orlić, M., Gačić, M., and La Violette, P.E.: The currents and circulation of the Adriatic Sea, Oceanol. Acta, 15, 109–124, 1992.

Orlić, S., Najdek, M., Supić, N., Ivančić, I., Fuks, D., Blažina, M., Šilović, T., Paliaga, P., Godrijan, J., and Marić, D.: Structure and variability of microbial community at transect crossing a double gyre structure (north-eastern Adriatic Sea), Aquat. Microb. Ecol., 69, 193–203, 2013.

Santojanni, A., Arneri, E., Bernardini, V., Cingolani, N., Di Marco, M., and Russo, A.: Effects of environmental variables on recruitment of anchovy in the Adriatic Sea, Clim. Res., 31, 181–193, 2006.

Sournia, A.: La production primaire planctonique en Mediterranée, Essai de mise a jour, Bull. Etude Comm. Méditerr. Num. Spéc., 5, 1–128, 1973.

Supić, N. and Orlić, M.: Seasonal and interannual variability of the northern Adriatic surface fluxes, J. Marine Syst., 20, 205–229, 1999.

Supić, N. and Vilibić, I.: Dense water characteristics in the northern Adriatic in the 1967–2000 interval with respect to surface fluxes and Po river discharge rates, Estuar. Coast. Shelf Sci., 66, 580–593, 2006.

Supić N., Orlić, M., and Degobbis, D.: Istrian Coastal Countercurrent and its Year-to-Year Variability, Estuar. Coast. Shelf Sci., 50, 385–397, 2000.

Supić N., Orlić, M., and Degobbis, D.: Istrian Coastal Countercurrent in the year 1997, Nuovo Cimento, 26, 117–131, 2003.

Supić, N., Kraus, R., Kuzmić, M., Paschini, E., Precali, R., Russo, A., and Vilibić, I.: Predictability of northern Adriatic winter conditions, J. Marine Syst., 90, 42–57, 2012.

Tedesco, L., Socal, G., Bianchi, F., Acri, F., Veneri, D., and Vichi, M.: NW Adriatic Sea biogeochemical variability in the last 20 years (1986–2005), Biogeosciences, 4, 673–687, doi:10.5194/bg-4-673-2007, 2007.

Utermöhl, H.: Zur Verfollkommnung der quantitativen Phytoplankton-Methodik, Mitteilung Internationale Vereinigung fuer Theoretische und Angewandte Limnologie, 17, 47–71, 1958.