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Factors favouring large organic production 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 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 at the transect in the region, as derived from monthly oceanographic cruises, in relation to concomitant geostrophic currents distribution in the area and in the Po River discharge rates in days preceding the cruises. In winter and early spring the phyto-abundances depended on existing circulation fields, in summer and autumn they were related to 1–15 days earlier Po River discharge rates and on concomitant circulation fields, while in late spring phyto-abundances increased 1–3 days after high Po River discharge rates regardless of circulation fields. During the entire year the phyto-abundances were dependant on forcing of the previous 1–12 months of surface fluxes and/or Po River rates. Large February blooms are, as well as February circulation patterns, precondited by low evaporation rates in previous November. From 1990 to 2004 a shift towards large winter bioproduction induced by circulation changes appeared. Performed investigations represent the preliminary actions in building of an empirical ecological model of the northern Adriatic which can be used in the sustainable economy of the region, however also in validation of the numerical ecological model of the region, which is currently being developed.

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. 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 northern Adriatic (Fig. 1). Otherwise, the region is under impact of oligotrophic central Adriatic waters. Therefore, the seasonal and interannual variability in the northern Adriatic organic production is very high (e.g., Sournia, 1973). Kraus and Supić (2011) hypothesized that interannual changes in the northern Adriatic winter (February) primary production reflect on the secondary production of the entire Adriatic. This hypothesis was based on significant correlations between the intensity of phytoplankton blooms in the northern Adriatic and the total Adriatic catch of one of the most important commercial fishes of the Adriatic, 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 the 1990 and the 2004 raised, following the positive trends in winter nutrients and phytoplankton abundances in the northern Adriatic (Djakovac et al., 2010).

The circulation fields of the northern Adriatic are controlled by number of factors, among which the stratification degree plays a crucial role (e.g., Orlić et al., 1992). 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 northern Adriatic.

Based on calculations of average monthly geostrophic fields it was shown that in the stratified period, the Po River waters spread around the northern Adriatic, while in the unstratified period these waters are confined to the western coast (Krajcar, 2003). They filled an anticyclonic gyre east to 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 Po River low impact and winters with high Po impact (e.g., Grilli et al., 2005; Kraus and Supić, 2011). Namely, the geostrophic circulation of the northern Adriatic consists of several gyres, which can persist in the region for 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 materials takes place (e.g., Or-

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lić et al., 2013). It is within them where the hypoxia and anoxia events develop (e.g., Djakovac et al., 2015). Especially large amount of the Po River waters can be drawn into the northern Adriatic 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 coastal zone, the Istrian Coastal Countercurrent (ICCC; Supić, 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), organic matter (Kraus et al., 2011; Marić et al., 2012) or even large quantities of the mucilaginous material appearing sporadically in the northern Adriatic (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 northern Adriatic circulation fields is possible, to a certain extent.

The Po River discharge rate has a pronounced seasonal cycle with maximum in spring or autumn (e.g., Supić et al., 1999). The flow rate is modulated by precipitation regime and additionally, in spring and summer, is enhanced by show melting (Cushman-Roisin et al., 2001). A significant additional contribution in summer is from precipitation in Alps, which is at its yearly maximum in this period of year. Daily variations in rates are significant and within short pulses a large amount of freshened waters can be injected into the northern Adriatic. Recently, around 2000, a drastic reduction in the Po River rates was observed with consequences on the 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 it is the change in the Ionian Sea circulation (Civitarese at al., 2010)

Presence of large quantity of nutrient rich waters from the Po River is crucial for the large bioproduction in the region. We hypothesized, thus, that the degree of the bioproduction in it directly depends on the geostrophic circulation fields and intensity of the Po River discharge. Due to pronounced seasonal component in circulation fields and discharge rates we suppose that importance of the two factors, which model the interannual variations in concentrations of organic matter produced in the northern Adriatic, changes from month to month.

In previous paper, using data collected across the transect between the Po River delta and Rovinj in 1990–2004, we documented 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 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 River Po impact is here investigated more closely, on the basis of daily discharge data.

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 organic production of the northern Adriatic 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 characterizing the region from the occasional events, respectfully.

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 of the transect between the Po River delta and Rovinj (Fig. 1), (2) monthly av-

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erages of meteorological and SST 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 interval and the other two sets, additionally 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 stations SJ108, SJ101 and SJ107 and at three standard depths (0, 10 and 30 m) at SJ103, SJ105 and RV001. Used oceanographic data set is described in more detail in our previous paper (Kraus and Supić, 2011; we also give cruise dates there).

Temperature was measured by protected reversing thermometers (Richter and Wiese, Berlin, precision ±0.01 °C), while salinity was determined by using high precision laboratory salinometers (±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 a Zeiss inverted microscope, 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; W m^{-2}) and water fluxes (W; mm d^{-1}) from the atmosphere into the sea and three of their components, namely the fluxes due to insolation (Qs; W m^{-2}), evaporation (E; mm d^{-1}) and precipitation (P; mm d^{-1}). The fluxes for the 1989–2004 interval were computed from monthly means of the atmospheric data and SST, as was in more details discussed 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 two neighbouring stations at the delta Po-Rovinj section (i.e., at SJ108/SJ101, SJ101/SJ103, SJ103/SJ105, SJ105/SJ107 and

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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 northern Adriatic and the ICCC is the current at SJ107/RV001 of negative sign.

2.4 Average phytoplankton abundance of the water column

The phytoplankton analyses were performed with original and transformed (log10) phytoplankton abundances. 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 interval, using data collected at 0, 5, 10, 20 and 30 m (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 st. 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 st. SJ103, SJ105 and RV001 can be approximated by the abundances sampled at 0, 10 and 30 m, respectively. Values aSTAT were than computed according to formula: $\mathrm{aSTAT} = 1/30\sum_{l=0\,\mathrm{m}}^{l=30\,\mathrm{m}} a(\mathrm{STAT}, l)$; $l = 0, 1, \ldots, 30$ m; $a(\mathrm{STAT}, l)$ – phytoplankton abundances at station STAT at level l.

2.5 PCA analysis

Principal component analysis (PCA) was performed, for each month separately, to extract the first main component of the interannual changes of phytoplankton abundance (F1i; $i = 1,\ldots,12$) and their logarithmic (FL1i; $i = 1,\ldots,12$) values at the three standard depths (0, 10 and 30 m) at six stations between the Po River delta and Rovinj in the 1990–2004 interval. Furthermore, the first main component of the long term changes in surface geostrophic currents relative to 30 m between 6 stations (at SJ108/SJ101, at SJ101/SJ103, at SJ103/SJ105, at SJ105/SJ107 and at SJ107/RV001) for each month were extracted (C1i, $i = 1,\ldots,12$). Interannual variability in it is given by the PC1 "scores". PCA was conducted using PRIMER (Plymouth Routines In Multivariate Ecological Research) v5 software package.

2.6 Po River discharge

Daily values of Po River discharge rate were derived from data collected at station Pontelagoscuro. The data were supplied by Assessorato Programazione, Piafinicazione e Ambinete 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).

3 Results

3.1 Circulation at the section

3.1.1 General circulation patterns

Average monthly values show several typical circulation patterns across the Po Rovinj delta-Rovinj section (Fig. 2a). Currents are generally stronger in warmer (April–October) than in colder part of the year. In January, like in 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 section along with the inflow in the middle part of the profile and near the eastern coast. From February and 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 section drastically changes as very strong currents appear there. The pronounced inflow in 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

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pattern is very similar to the one in summer, only the inflow in the middle part of the section is less pronounced.

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

The PC1 explains between 40 and 70 % of the total variance in the fields of surface geostrophic currents across the Po River delta-Rovinj section (Fig. 2b). The lowest values, around 40 %, are obtained in summer (July and August) and the highest ones, around 70 %, in winter (February 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 changes near the western coast play the main role in year-to-year changes of the circulation patterns. During 1990–2004 interval trends in circulation patterns were, apparently, more pronounced only in February (positive) and August (negative; Fig. 2c).

3.1.2 The ICCC

In the 1990–2004 interval geostrophic currents at RV001/SJ107 were up to around $10\,\mathrm{cm\,s^{-1}}$ (Fig. 4). In winter period negative trends, indicating more often appearance of the ICCC, prevailed. On the contrary, in spring and summer, trends were positive, indicating less often appearance of the ICCC.

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3.2 Po River rates

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 Phytoplankton at the section

Phytoplankton seasonal cycle of the section is based on the monthly averages from the original 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 February–October period, with the vertical gradient more pronounced from the horizontal one. At the eastern part, upper layer is highly stratified only during several months (February–March and October), while the stratification is usual in the west (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 at the seasonal cycle which is based on the transformed data (Fig. 7). High abundances are from February to September restricted to the western part of the section, spreading in some months in a rather thin surface layer over to the mid of the section and only occasionally more closely to the eastern parts. Only in October and November a uniform vertical gradient over the entire section is present. In the remaining winter months (December–January), phytoplankton is completely uniform over the entire section.

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

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

Yearly changes obtained by calculating PCA from original data (not shown) show a distinctive trend of increase in yearly 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 on both original and transformed data showed increase in trend and a distinct decrease in December. Other months showed slight or no trends at all.

3.5 Phytoplankton forcing pressures

Circulation impact at the phytoplankton is observed during winter (January–February), early spring (March–April) and again in autumn (September; Table 1). In January, impact is restricted to the western (SJ101) and eastern parts (SJ107 and RV001), how-

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ever during February it spreads over the almost entire profile (SJ101–SJ107). The high correlations between the scores of transformed phytoplankton data and currents indicate this relations are limited to the typical January–February phytoplankton situation. On the contrary, the correlations obtained for March indicate that the currents impact at the phytoplankton at SJ101 is limited to the exceptional conditions (the scores of original phytoplankton with currents). During April, the negative impact of currents is noticed at SJ107 (slight) and SJ108 (strong). Interestingly, September phytoplankton is strongly impacted by the currents. More specifically, the impact of Istrian Coastal Countercurrent (ICCC; Table 1) at the phytoplankton was acknowledged in January, February, April and September, as a part of the complete circulation pattern (Table 1). Only in July and October, we acknowledged the sole impact of the ICCC.

The Po River impact at the phytoplankton is quite complementary to already described circulation forcing (Table 1). Slightly positive fortnightly postponed Po River impact which is restricted in March over the mid of the profile is followed by an immediate impact at the east in April and a negative one at the west in May. June and July are characterized by both, immediate and postponed, relatively high impact of the Po River over the profile. This impact diminishes and reverses into a negative one during August. Impact again increases, turns positive and spreads profile-wide during September and October, both of immediate and postponed nature. While the impact during November is scarce, during December is spread profile-wide, however with a postponed fortnight effect.

The correlations between the phytoplankton or currents 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 one to 12 months ahead).

High January phytoplankton is induced by a relatively steady water column and an increased Po River outflow sporadically over the previous winter, spring and summer, with the additional intense summer precipitation and water column mixing and finishing up with a low autumn Po River outflow. On the contrary, high February phytoplankton is preceded by a steady water column with slight precipitation and riverine outflow

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throughout the previous spring and summer, which are substituted by an intense autumn evaporation and riverine outflow. High phytoplankton in March is preceded also by a relatively calm year with occasional high precipitation restricted to the eastern part in preceding May and high impact of riverine outflow in January with the intense November water column mixing. Generally, high phytoplankton in winter months is preconditded by a relatively steady period and an intense water mixing episode four months earlier with an additional necessity of a water ingression a few months earlier.

High phytoplankton in spring months is precondited by a steady year. For all spring months increased precipitation is noticed to occur sporadically over the year, however only for June with the additional riverine episodes. Similarly as for the winter period, intense water mixing episodes are observed, a year ahead for April and May and in previous October for high phytoplankton in following June.

High phytoplankton in summer months is preconditioned by alternating periods of high and low precipitation and riverine outflow. However, for July intense Po River outflow is characteristic during entire year and high precipitation for September. These months are rather dynamic. Intense period of water column mixing is noticed to occur from late winter to midsummer for July, in winter–spring period for August and from summer to mid winter for September.

High phytoplankton in autumn months are caused by rather diverse preconditions. For October they are caused by exceptionally low precipitation and riverine outflow during the entire previous year, especially in the winter months, and calm water column throughout the entire year. For November, low precipitation and riverine outflow and calm water column are substituted with the impact of precipitation, riverine inflows and water column mixing episodes in spring, summer and autumn ahead. Finally, high phytoplankton in December is preceded by the intense water column mixing episodes several times during the year, sporadic precipitation episodes from autumn to spring and high riverine outflows in previous winter–spring period and again in August, ultimately ending by calm autumn conditions.

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4 Discussion

4.1 Characteristics of phytoplankton distribution

A rather stable horizontal and vertical phytoplankton abundance gradients are characteristic for almost the entire year. Only in coldest of months (December–January) water column habitually uniforms (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, 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 the smaller scope 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 is dependent on the circulation pattern. The blooms respond to 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.

The February circulation is according to the PC1 of the two types – the cyclonic one (Fig. 9), transporting freshwater from the Po River towards south in western part of the Adriatic with the mid Adriatic oligotrophic waters inflow in the NA along the eastern coast, and the anticyclonic one, allowing the Po River water spreading towards

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the eastern Adriatic coast. Our analyses of PC1 scores (long-term changes; Fig. 2) show that both circulation modes are equally probable. The correlation of scores of transformed phytoplankton data with February C1 (Table 1) indicates that cyclonic circulation pattern favours low February phytoplankton in the NA (Figs. 2c and 8c). On the contrary, the anticyclonic February circulation mode, as given by PC1 results in high phytoplankton in the entire NA as the freshwater influence is felt at the eastern part as well.

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 appearance of the large blooms by following another approach, i.e. by relating phytoplankton abundance of 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 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 northern Adriatic 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 reflects 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

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high, as the one between the blooms and PC1 or ICCC, meaning that waters from Po River recirculate within the region.

Interestingly, we obtained sporadic or none 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.

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 cycle. What we found is as follows:

- for winter, alternation of low and intense evaporation and vertical mixing, as well as periods of low and high freshwater pressure
- for spring, completely calm conditions with low freshwater pressure
- for summer, intense evaporation and vertical mixing events, as well as periods of low and high freshwater pressure and
- for autumn, relatively intense evaporation and vertical mixing events, with periods of very high freshwater pressure.

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 longer period of steady conditions (lower

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evaporation and vertical mixing). On the contrary, mixing is more intense in more dynamic years.

High correlation between the circulation pattern and phytoplankton blooms in February, as well as correlations between both parameters and evaporation, 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 anchovy catch in the subsequent year, 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. According to our results, an intense Po River impulse two months earlier seem to be a requirement for the February blooms. February F1 and C1, show very similar pattern of correlation coefficients with 1–12 time lag in evaporation (Fig. 10). Detailed comparison of PC scores of evaporation in these months against February phytoplankton and geostrophic currents at the profile during 1990–2004 period is presented at Fig. 10. It shows that the abundant February phytoplankton production, represented by negative PC scores of log values is preceded by intense evaporation in preceding February and October, each followed by light evaporation in June and November. In contrast, intense February anticyclonic circulation (as shown in Fig. 9), which corresponds to positive PC scores of profile geostrophic currents, favouring spreading of phytoplankton eastwards from the eutrophic western parts, are also preceded by intense evaporation in preceding February and October and light 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 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 total pycnocline destruction. Different meteorological conditions in the autumn 1999 and 2000 were invoked in explanation of different circulation in subsequent

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winters. Our results, showing that large evaporation events favour cyclonic circulation (as shown in Fig. 9) is in line with this previous assumption. The high correlation with other months (October, June and February) are interesting but cannot be commented without further future 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 western part of the northern Adriatic, and for the 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 winter 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 often winter anticyclonic circulation type (Fig. 9) existed and were possibly induced by complex air–sea interactions of 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 month in advance, we indeed are able to give prognosis of the winter phytoplankton abundance and circulation conditions. However, more field work as well as applied theoretical models are to be used to verify and give more support our findings. And what about the summer? In this period, especially in July, blooms are directly related to the previous Po River discharge and current existence of the ICCC. Thus, by monitoring conditions which induce large discharges in summer (that is better understanding of the Po River regime, related to e.g. ice and snow melting in Alps, etc.) we could possibly be a step closer to predicting summer bloom conditions as well.

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All the same, what would be the purpose of being able to predict phytoplankton blooms at all? At this moment, we identified following two reasons. Firstly, we already showed at the example of anchovies (Kraus and Supić, 2011) that good understanding of the processes in the ecosystem can potentially be of great importance in maintaining sustainable fishery. Other studies following the same approach of combining knowledge about the marine species life cycles on the one hand and driving pressures of their abundances and distribution patterns on the other, could expand our capabilities of a planned exploration of the marine resources. Secondly, in extreme cases when exceptionally high amounts of organic matter are produced, ultimately huge oxygen quantities get utilised for 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) 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

Our results relieve basic relations between northern Adriatic biomass production, Po River discharge rates, circulation and surface fluxes. They are based on long-term data set which was in detail analysed 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 phyto-abundances depend on existing circulation fields and not on intensity of Po discharge. In late spring (May–June) the phyto-abundances increase 1–3 days after high Po discharge rates regardless of circulation fields. In summer and autumn (July–December) the phyto-abundances are related to 15 days earlier Po discharge rates and sometimes also on 1–3 days ago or on concomitant circulation fields. During the entire year (January–December) the phyto-abundances depend on forcing of the previous 1–12 months of surface fluxes and/or Po rates. In February, which is presumably a crucial month for the

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entire northern Adriatic production, both circulation patterns and phytoplankton production were highly dependent on evaporation rates from the preceding autumn, spring and winter. Especially interesting was the November correlations, in line with our previous research based on the case study of the 1999–2001 interval, pointing that the typical anticyclonic circulation pattern, favouring Po River spreading across the northern Adriatic and large bioproduction rates, appears after low evaporation rates in November. Vice versa, the cyclonic circulation pattern is preceded with high evaporation rate. From 1990 to 2004 a shift towards large winter bioproduction induced by circulation changes appeared.

The obtained results performs a basis of an "empirical ecological model" which can be used in assessments of the northern Adriatic productivity, useful for the environmental management of the region or in climatic studies aiming to estimate the response of northern Adriatic on climatic changes. The results obtained should be in more details investigated by means of an theoretical ecological model, which can be developed using simplification of oceanographic fields along with surface fluxes and Po rates. Our results are also 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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Table 1. Positive (+) or negative (–) correlation between changes in phytoplankton abundance (PC1 scores or average water column values at SJ108, SJ101, SJ103, SJ105, SJ107 and RV001) during 1990–2004 and changes in (i) PC1 scores of surface geostrophic currents relative to 30 dbar at stations of the Po delta-Rovinj section (Currents-PC1), (ii) the ICCC and (iii) Po flow discharge rates 1, 3 and 15 days before the PA sampling, for original (up) and log (down) data. Sign and sign in brackets indicates significances of 80 and 95 %, respectively.

	Months	Jan	Feb	Mar	Apr	May	Jun		Jul			Aug	Sep	Oct		Nov	Dec
Currents-PC1	PC1	(–)	(–)										(+)				
	SJ108				(–)								+				
	SJ101	(+)	+														
	SJ103		+				–						+				
	SJ105		+										(+)				
	SJ107	(+)	(+)	+	–								+				
	RV001	+															
ICCC	PC1	–	–		–				(–)				–				
	SJ108	(+)								+							
	SJ101	+	(+)														
	SJ103		(+)		+												
	SJ105	+			+								–	+			
	SJ107	+	(+)						(+)					+			
	RV001	+					–							(+)			
	Time lag (days)	1 3 15	1 3 15	1 3 15	1 3 15	1 3 15	13	15	1	3	15	1 3 15	1 3 15	13	15	1 3 15	1 3 15
Po flow	PC1					+ +	–	–	(–)	(–)	(–)		+ +	–	(–)		–
	SJ108					– –	+		+	(+)	+	– (–)	+ +	+ +			+
	SJ101					–	(+) +								+	+ +	+ (+)
	SJ103			+			+		+	(+)	+		(+) (+) +				+
	SJ105			+			(+) (+)		+	+			+ +	(+)	+		+
	SJ107						+ +		+	+		–		+	(+)		+
	RV001				+ +			(+)	+	+	+						

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Table 1. Continued.

	Months	Jan	Feb	Mar	Apr	May	Jun			Jul	Aug	Sep		Oct		Nov	Dec
Currents-PC1	PC1			(−)								(+)					
	SJ108				(−)							+					
	SJ101	(+)	(+)	(−)													
	SJ103		(+)				(−)					+					
	SJ105	+	+									(+)					
	SJ107	(+)	(+)		−	(+)						(+)					
	RV001	(+)										(+)				(+)	
ICCC	PC1									−				−			
	SJ108	(+)								+							
	SJ101	+	(+)														
	SJ103		(+)		+												
	SJ105	+			+							−			+		
	SJ107	+	(+)							(+)					+		
	RV001	+						−						(+)			
	Time lag (days)	1 3 15	1 3 15	1 3 15	1 3 15	1 3 15	1	3	15	1 3 15	1 3 15	13	15	1	3 15	1 3 15	1 3 15
Po flow	PC1						−			(−) (−) (−)	−	(+) (+)	+	−	(−) (−)	− (−)	
	SJ108				+			(+)		(+) (+) (+)	−	+		+	(+) +		+
	SJ101														+ +	+	(+)
	SJ103			(+)	(+)		+			(+) (+) (+)		(+) (+)	+				+
	SJ105			+	+ +		(+)	(+)		+ +		(+) (+)	(+)	+	(+) (+)		+
	SJ107						(+)			(+) (+) +	−	(+) (+)		+	(+) (+)		
	RV001				+				+	− −		(+) (+)	+		+		

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Table 2. Positive (+) or negative (–) correlation between changes in phytoplankton abundance (PC1 scores or average water column 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. Sign and sign in brackets indicates 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
scores c				(+)	+	+							scores c		–										–
scores orig					(+)	+		–	(–)				scores orig									(–)			
scores log				–							+		scores log									–			
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
scores c		–	(+)				(–)				(+)		scores c						–						
scores orig					(+)	+							scores orig				+		(–)		(–)				
scores log		+	(–)				+				–		scores log								+				
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
scores c		(+)	–				(+)	(+)		+			scores c				+	(+)							
scores orig								–					scores orig				+	(+)							
scores log		–											scores log				(+)	(+)						+	
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
scores c			+	(–)									scores c	(+)	+	–							(–)		
scores orig		+				(+)							scores orig							(–)				–	
scores log							+	(–)	(–)				scores log												+
logaSJ108			–	+			–		+				logaSJ108												–
logaSJ101							–		+				logaSJ101			–									–
logaSJ103								(+)	(+)	–	–		logaSJ103				–					–			
logaSJ105								+	+	–			logaSJ105												–
logaSJ107								(+)	(+)				logaSJ107												–
logaRV001				–						–			logaRV001		–										

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Table 2. Continued.

E	Dec	Nov	Oct	Sep	Aug	Jul	Jun	May	Apr	Mar	Feb	Jan
May	– 5	– 6	– 7	– 8	– 9	– 10	– 11	– 12	– 1	– 2	– 3	– 4
scores c		–	(+)							(+)		
scores orig	+		(+)	+		+					(+)	(+)
scores log						+					(+)	+
logaSJ108		–				(–)	(–)	–			(–)	–
logaSJ101			–		(–)	–					(–)	
logaSJ103			–			–					(–)	(–)
logaSJ105					(–)			(+)	(+)		–	
logaSJ107					–			+			–	
logaRV001							–		–			
Jun	– 6	– 7	– 8	– 9	– 10	– 11	– 12	– 1	– 2	– 3	– 4	– 5
scores c					(+)				(–)			
scores orig				(+)		(+)				+	(+)	
scores log			(–)	(+)							(+)	
logaSJ108				(–)	–				–	–	–	–
logaSJ101			(+)	(–)	–						(–)	–
logaSJ103		–	(+)	–	–						(–)	
logaSJ105			(+)	(–)							(–)	
logaSJ107			+	–							(–)	
logaRV001			+								–	

E	Dec	Nov	Oct	Sep	Aug	Jul	Jun	May	Apr	Mar	Feb	Jan
Nov	– 11	– 12	– 1	– 2	– 3	– 4	– 5	– 6	– 7	– 8	– 9	– 10
scores c		(–)	(–)							(+)		
scores orig	(+)		+		(+)						(+)	+
scores log	+		(+)				–				(+)	+
logaSJ108	(–)										–	(–)
logaSJ101	–						+	(+)				–
logaSJ103	–			–		–	+				(–)	–
logaSJ105	–		–			–					(–)	–
logaSJ107			–				+				(–)	
logaRV001	–		–				+	+		+	–	
Dec	– 12	– 1	– 2	– 3	– 4	– 5	– 6	– 7	– 8	– 9	– 10	– 11
scores c		–										
scores orig	–		+	–			(–)				(–)	(–)
scores log	(–)			–			–				–	(–)
logaSJ108	(+)			+		+	(+)				(+)	(+)
logaSJ101	+			+		+	+		–			(+)
logaSJ103	(+)					(+)	(+)				+	(+)
logaSJ105	(+)			+		+	(+)				+	(+)
logaSJ107	(+)		–			+	(+)					+
logaRV001	+		–	+			(+)				(+)	+

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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
scores c					+					–		
scores orig												
scores log					(–)	–						
logaSJ108									+			
logaSJ101					(+)	+					+	
logaSJ103						+						
logaSJ105					+	+			+			
logaSJ107					(+)						+	
logaRV001			–		(+)							
Feb	– 2	– 3	– 4	– 5	– 6	– 7	– 8	– 9	– 10	– 11	– 12	– 1
scores c						–						
scores orig												
scores log						+	(+)					
logaSJ108							(–)					
logaSJ101			+			(–)	(–)		–			
logaSJ103	–						(–)			–		
logaSJ105							–				(–)	
logaSJ107			+			(–)	–					
logaRV001							–					
Mar	– 3	– 4	– 5	– 6	– 7	– 8	– 9	– 10	– 11	– 12	– 1	– 2
scores c			(–)					+				+
scores orig			(+)								–	(–)
scores log								–	(+)			
logaSJ108					–				–			
logaSJ101			+		(–)				–			
logaSJ103					–				(–)			
logaSJ105									(–)			
logaSJ107								+	(–)			
logaRV001							+	(+)				
Apr	– 4	– 5	– 6	– 7	– 8	– 9	– 10	– 11	– 12	– 1	– 2	– 3
scores c		(+)		(–)			+	+				–
scores orig				+								
scores log												–
logaSJ108				+								
logaSJ101												(+)
logaSJ103			–									+
logaSJ105	(–)											
logaSJ107											+	(+)
logaRV001	(–)	(+)		–			(+)	(+)				

	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
scores c								(–)				–
scores orig	–											
scores log	–							+			+	
logaSJ108	+							–				
logaSJ101	+						(–)	(–)				
logaSJ103	+							–			–	
logaSJ105	+							(–)			–	
logaSJ107	(+)	+										+
logaRV001						–	–					
Aug	– 8	– 9	– 10	– 11	– 12	– 1	– 2	– 3	– 4	– 5	– 6	– 7
scores c	–	(–)					(+)	(+)	–			
scores orig					–				+			
scores log		–						(+)			+	+
logaSJ108			+			–	(–)					
logaSJ101		–							(–)		+	
logaSJ103								+				
logaSJ105	(+)		(–)					(+)			+	+
logaSJ107	+									–		
logaRV001				+				+				(+)
Sep	– 9	– 10	– 11	– 12	– 1	– 2	– 3	– 4	– 5	– 6	– 7	– 8
scores c				(+)	(+)					–		
scores orig			+	(+)		–				(–)		
scores log			+	(+)		(–)			(+)	(–)		
logaSJ108		(–)								–		–
logaSJ101		(–)						+			(+)	
logaSJ103		–		(+)				+	+	(–)		
logaSJ105				+	+	–	+		+	(–)		
logaSJ107			+			(–)			+			
logaRV001			+	+		(–)			+			
Oct	– 10	– 11	– 12	– 1	– 2	– 3	– 4	– 5	– 6	– 7	– 8	– 9
scores c												
scores orig			(–)	(–)				+				
scores log	+	(+)	–					+				(+)
logaSJ108		–						–		–		(–)
logaSJ101	–	(–)	+									–
logaSJ103		–										(–)
logaSJ105			+					(–)				(–)
logaSJ107	–	–	(+)					–				(–)
logaRV001		–							–			–

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Table 2. Continued.

	P																								
	Dec	Nov	Oct	Sep	Aug	Jul	Jun	May	Apr	Mar	Feb	Jan		Dec	Nov	Oct	Sep	Aug	Jul	Jun	May	Apr	Mar	Feb	Jan
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
scores c	(+)			–									scores c		–										
scores orig			+		(–)		–						scores orig	+					(–)						(+)
scores log			(+)		–		–			+		+	scores log						(–)	–			–		+
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
scores c	–	(–)				–					+		scores c							+					
scores orig	+			+									scores orig	–							–				–
scores log				(+)	(+)		+			(–)			scores log	–							(–)				–
logaSJ108			–	–								–	logaSJ108	+							(+)	–			+
logaSJ101		+		(–)	(–)							(–)	logaSJ101		+						(+)			+	
logaSJ103		(+)		(–)	(–)					+			logaSJ103	+							+				
logaSJ105			–	(–)	(–)					(+)			logaSJ105	+							(+)	–			
logaSJ107				–	–	–	–	+	–	(+)	+		logaSJ107					–		–		–	+		
logaRV001					–		–		–	(+)		–	logaRV001								+	–	+		+

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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
scores c				+				–		(+)	+		scores c											–	–
scores orig					+								scores orig	(–)							+	+			–
scores log	+	+		–		+	–			(–)	–		scores log	(–)		–		(–)	–						(–)
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
scores c								–	–				scores c					(–)	–						
scores orig					+					+			scores orig				–			+					
scores log	(–)			+				+	(+)				scores log			(–)						–			
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
scores c					+			(+)				+	scores c				+			(+)			+	(+)	
scores orig						(+)		–			–		scores orig			+	(+)								
scores log				+								–	scores log												
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
scores c			+		+				+	(–)		(–)	scores c												
scores orig	–	–											scores orig												
scores log	+		(+)		(+)								scores log		+			+		+			+	+	(+)
logaSJ108					(–)					+			logaSJ108		–			–	(–)	(–)			(–)	(–)	(–)
logaSJ101					(–)								logaSJ101		–				–						–
logaSJ103	–		(–)		–	–	–					+	logaSJ103	–				–	–				(–)	(–)	(–)
logaSJ105	(–)		–	–	(–)								logaSJ105		–			(–)		–			(–)	(–)	(–)
logaSJ107			(–)		–						+		logaSJ107					–		–			–	–	(–)
logaRV001	–								(+)				logaRV001												–

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Table 2. Continued.

Po	Dec	Nov	Oct	Sep	Aug	Jul	Jun	May	Apr	Mar	Feb	Jan
May	– 5	– 6	– 7	– 8	– 9	– 10	– 11	– 12	– 1	– 2	– 3	– 4
scores c						(+)		–				
scores orig	+	+	+									+
scores log	(+)	(+)	(+)					+	+	+	+	(+)
logaSJ108	–	(–)	(–)					(–)	–	–	(–)	(–)
logaSJ101			–	(–)			(–)					
logaSJ103	(–)	(–)	(–)	–							(–)	–
logaSJ105				–			–		+			
logaSJ107			–	–			(–)					
logaRV001		(–)	(–)	–				(–)			–	–
Jun	– 6	– 7	– 8	– 9	– 10	– 11	– 12	– 1	– 2	– 3	– 4	– 5
scores c	–	–							(–)	(–)		
scores orig	+			+							+	
scores log		–		+			(+)					
logaSJ108			–	(–)							–	
logaSJ101				(–)		+	(–)		+			
logaSJ103	+	+		–		+	–		(+)			
logaSJ105							–					
logaSJ107		+					(–)					
logaRV001		+						+				

Po	Dec	Nov	Oct	Sep	Aug	Jul	Jun	May	Apr	Mar	Feb	Jan
Nov	– 11	– 12	– 1	– 2	– 3	– 4	– 5	– 6	– 7	– 8	– 9	– 10
scores c											–	–
scores orig				+					–	(+)		
scores log									–			
logaSJ108												
logaSJ101								+	+			
logaSJ103			+					+	(+)	–		
logaSJ105						+			+			
logaSJ107						+	+	+	+			
logaRV001									+			
Dec	– 12	– 1	– 2	– 3	– 4	– 5	– 6	– 7	– 8	– 9	– 10	– 11
scores c												
scores orig					(–)			–	–	–	–	–
scores log					(–)			(–)	–	–	(–)	–
logaSJ108					(+)			(+)	+	+	+	+
logaSJ101		(+)	+		+			+				
logaSJ103					(+)			(+)	+	+		
logaSJ105					(+)			+	+		+	+
logaSJ107					(+)			(+)	(+)	+		
logaRV001					+			+	+	(+)	+	+

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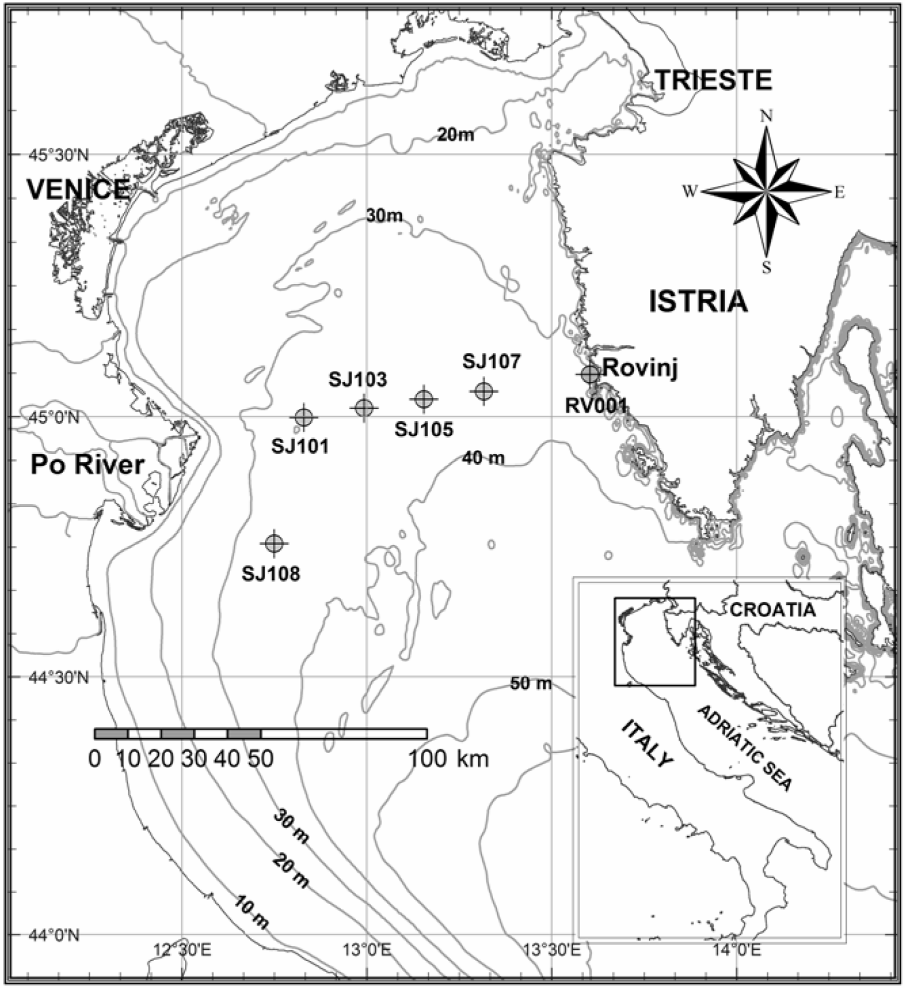

Figure 1. Map of the northern Adriatic with sampling stations.

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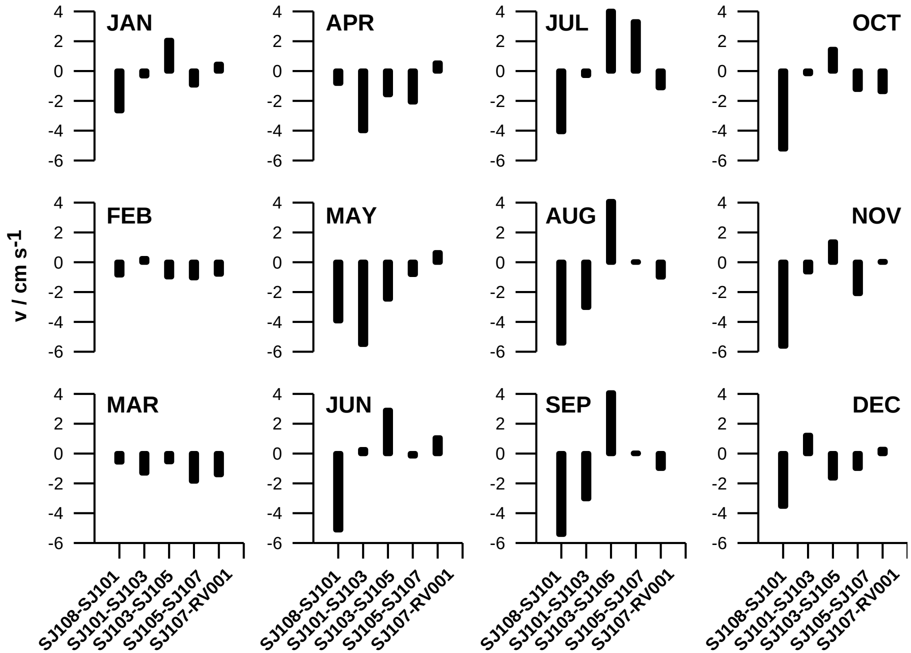

Figure 2a. Monthly averages of geostrophic currents relative to 30 dbar between stations of the Po River delta-Rovinj profile for the 1990–2004 interval.

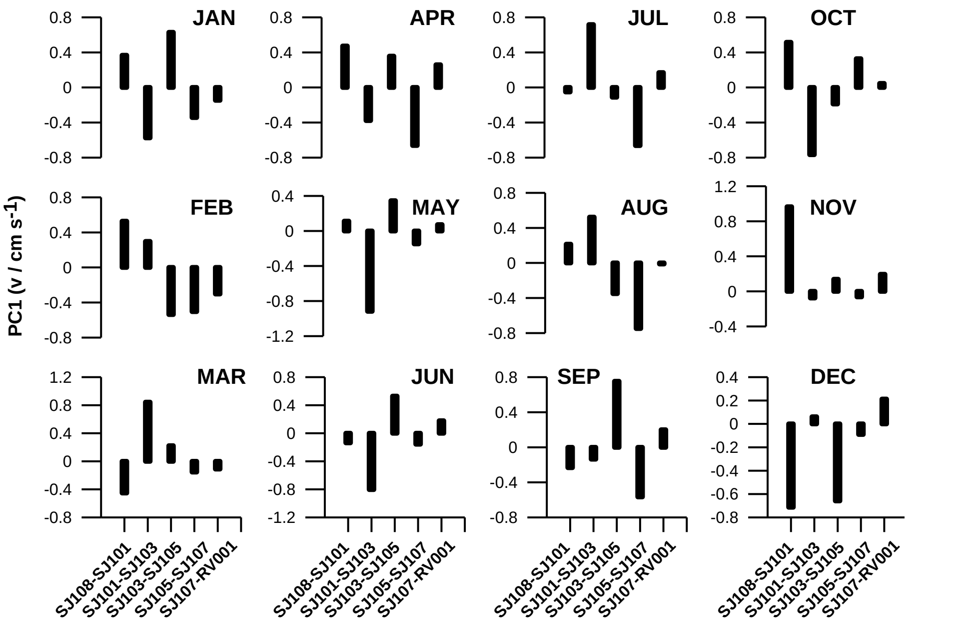

Figure 2b. PC1 loadings of geostrophic currents relative to 30 dbar between stations of the Po River delta-Rovinj profile for the 1990–2004 interval.

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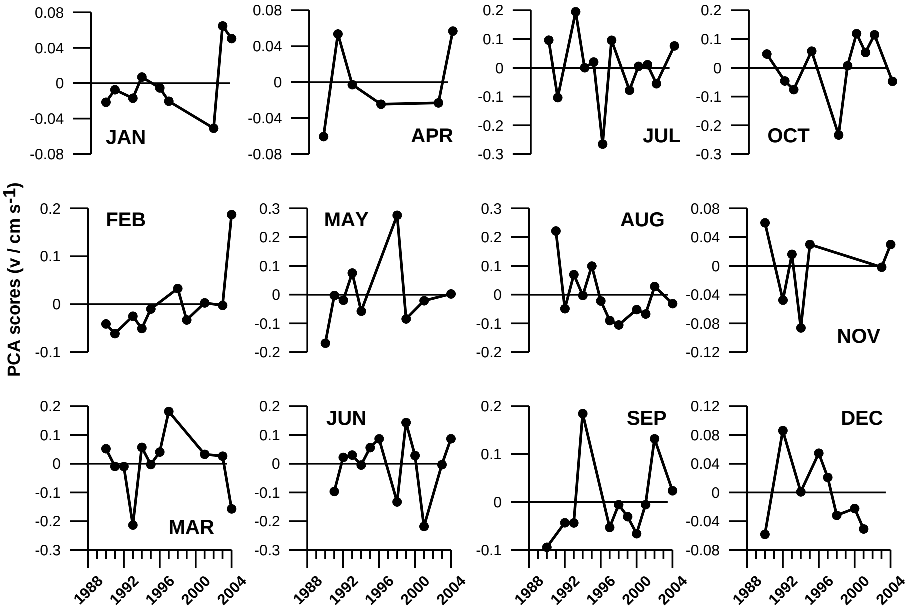

Figure 2c. PC1 scores of geostrophic currents relative to 30 dbar between stations of the Po River delta-Rovinj profile for the 1990–2004 interval.

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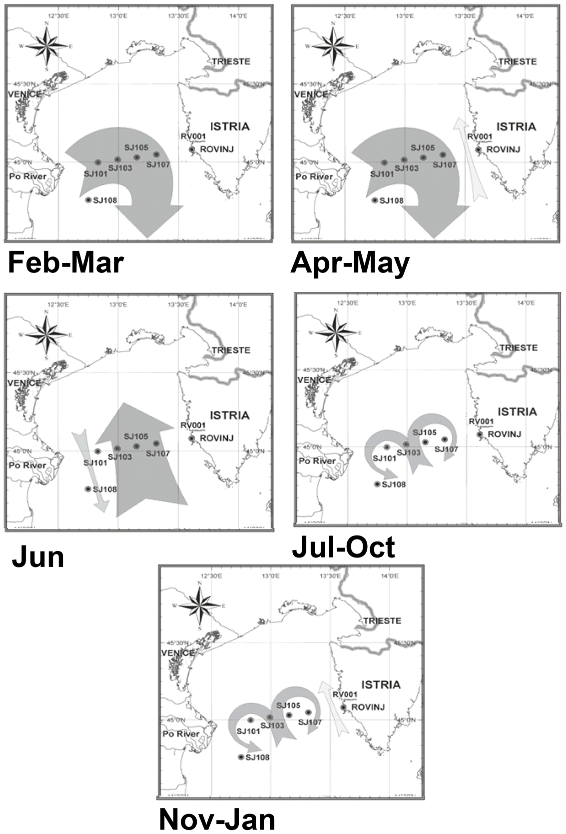

Figure 3. Northern Adriatic circulation patterns as hypothesized from average surface geostrophic currents relative to 30 dbar in 1990–2004 between neighbouring stations at the Po delta-Rovinj profile. Istrian Coastal Countercurrent (ICCC) is current at SJ107/RV001 directed towards SE.

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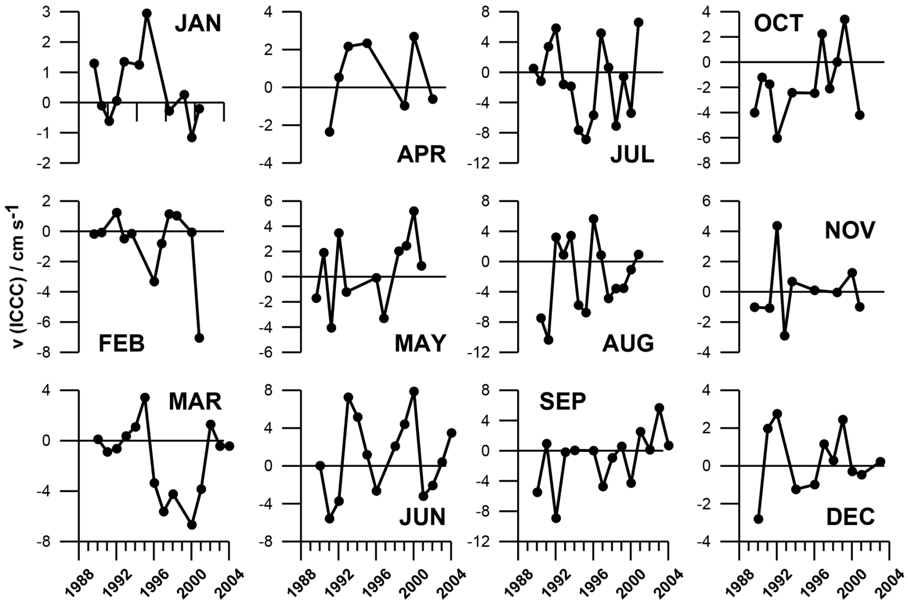

Figure 4. Geostrophic currents relative to 30 dbar between stations SJ107 and RV001 in the 1990–2004 interval for each month in a year. The ICCC is current of negative sign.

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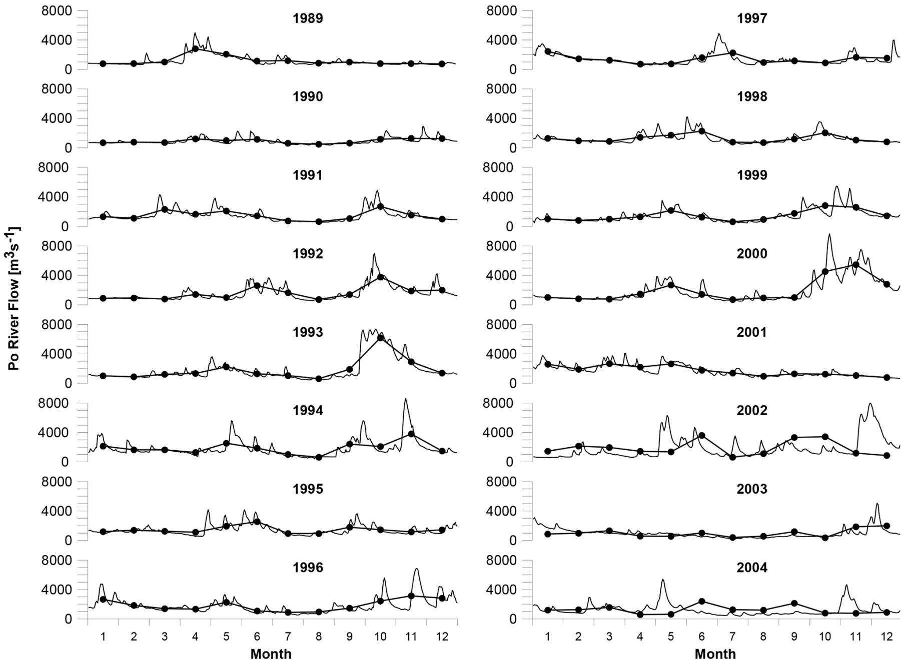

Figure 5. Daily Po River flow (thin line) with monthly averages (thick line with dots) in the analysed years (1989–2014).

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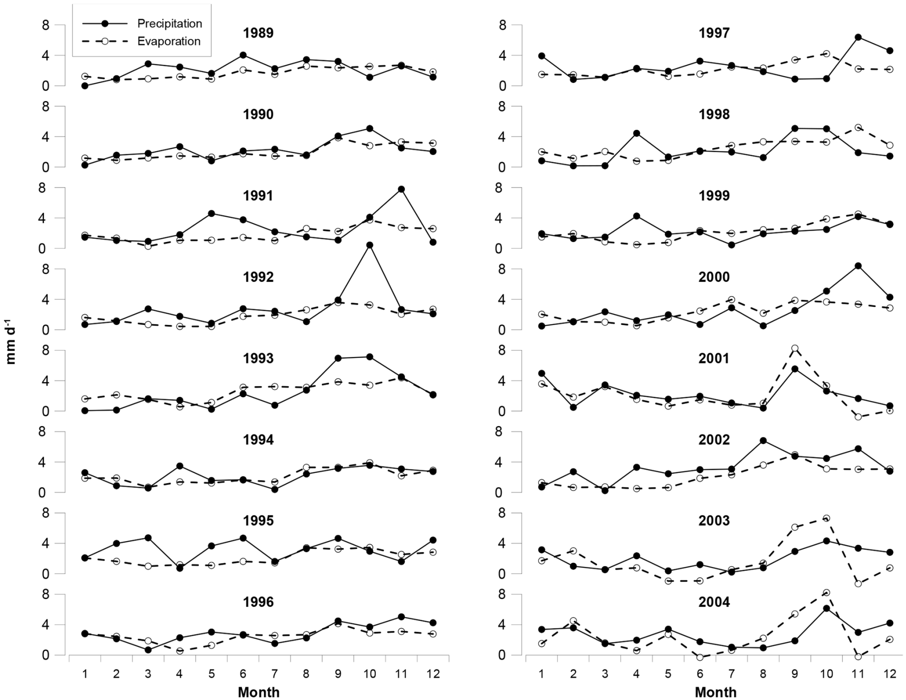

Figure 6. Monthly averages of precipitation (full line with black dots) and evaporation (dashed line with white dots) at the Po River delta-Rovinj profile in the analysed years (1989–2014).

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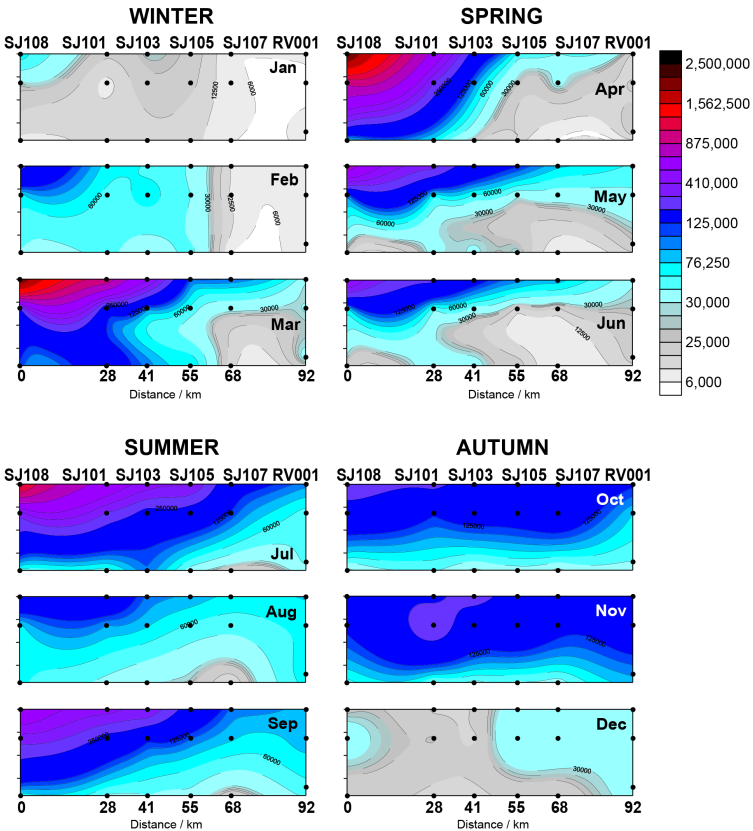

Figure 7. Geometrical means for each month of the phytoplankton abundance in the 1990–2004 interval.

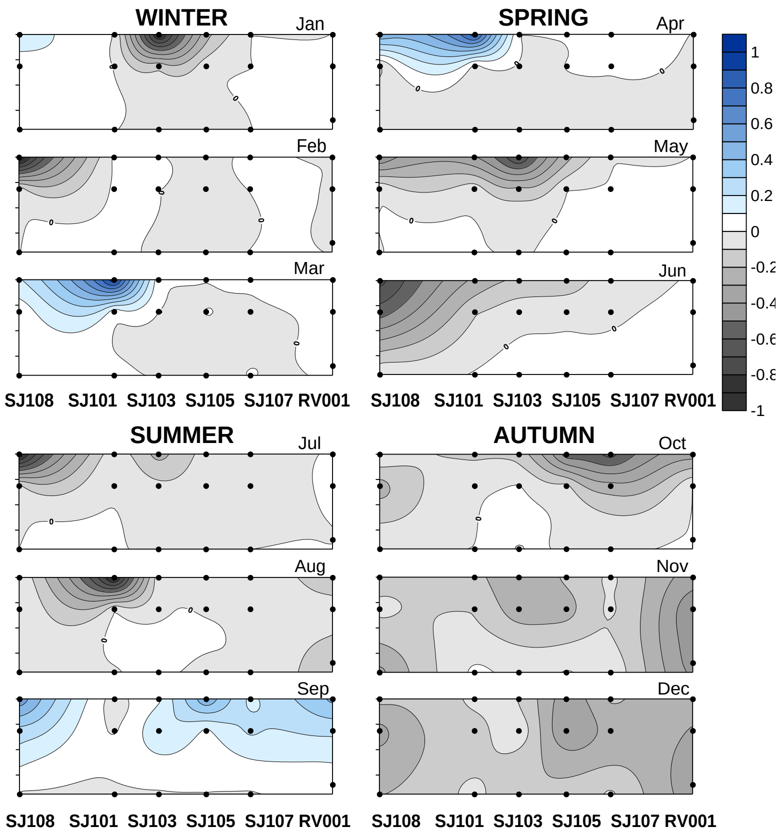

Figure 8a. PC1 loadings of original data for the phytoplankton abundance in the 1990–2004 interval.

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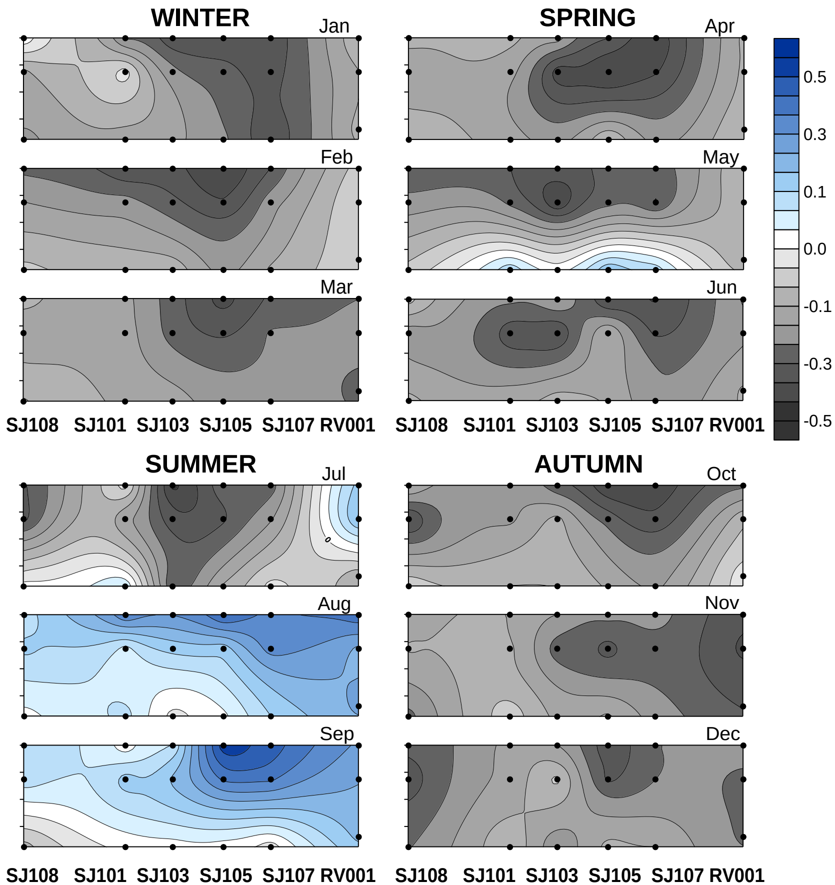

Figure 8b. PC1 loadings of log data for the phytoplankton abundance in the 1990–2004 interval.

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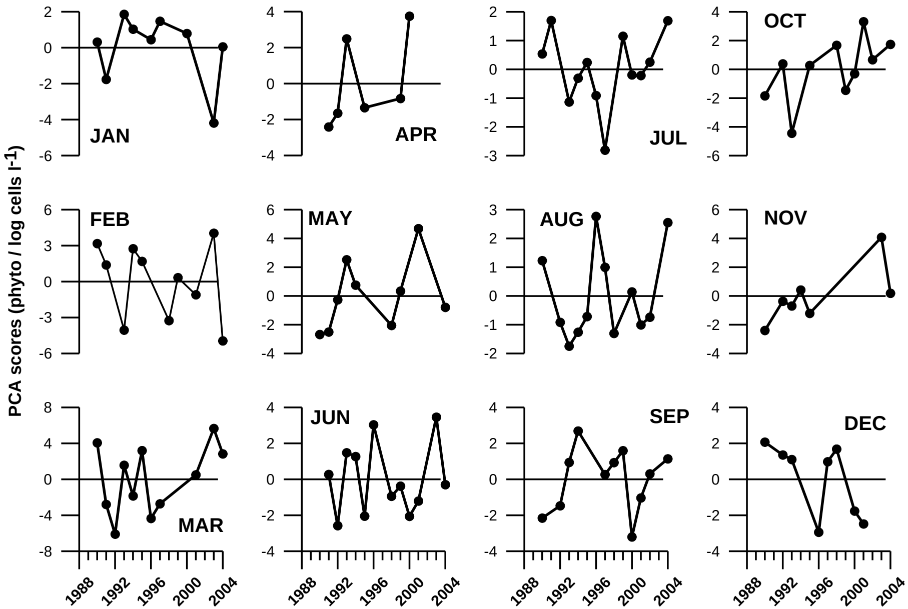

Figure 8c. PC1 scores of log data for the phytoplankton abundance in the 1990–2004 interval.

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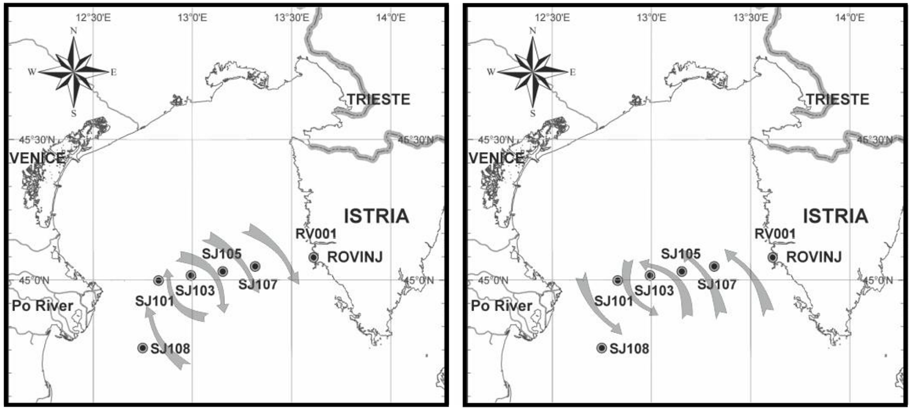

Figure 9. The two circulation patterns appearing in February, the anticyclonic (left) and the cyclonic (right) one.

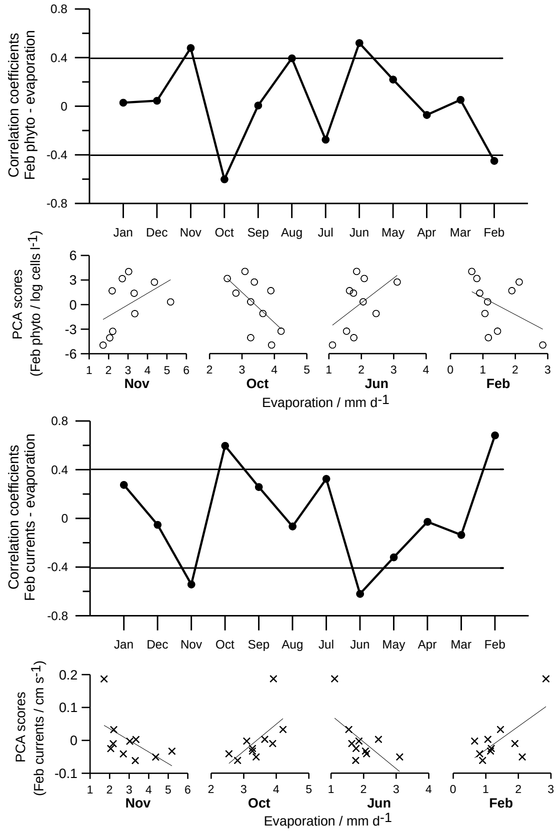

Figure 10. Correlation coefficients between PC1 Scores of February (F1) log values of phytoplankton and (C1) geostrophic currents against monthly averages of evaporation of the previous year during the analysed period (1989–2004) at the Po River delta-Rovinj profile. Correlations in November, October, June and February are given graphically.

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