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Changes in the Adriatic oceanographic properties induced by the Eastern Mediterranean Transient

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Abstract

Long-term time series of physical and chemical parameters collected between 1960 and 2010 along the Palagruža Sill transect, middle Adriatic Sea, have been investigated in terms of average water properties and their variability. Nutrients, especially orthophosphates, reached rather higher levels of concentration below the euphotic zone between 1991 and 1998, the highest in the investigated period. Simultaneously, the N:P ratio, which is normally larger than 25 : 1, decreased to values less than 16 : 1 in the euphotic zone, indicating a switch from typical phosphorus-limited to nitrogen-limited preconditioning of the primary production. Higher-than-usual nutrient levels, coupled with lower-than-usual temperature, salinity and dissolved oxygen, have been attributed to the intermediate inflow of the nutrient richer Western Mediterranean waters to the Adriatic, entering the Adriatic during the anticyclonic phase of the Bimodal Adriatic-Ionian Oscillation (BiOS). The BiOS and the Northern Ionian anticyclone have been uniquely strengthened by the Eastern Mediterranean Transient occurring in the early 1990s. The observed changes have a potential to impact the primary production and presumably the whole trophic chain in the Adriatic and were likely responsible for the observed fluctuation in abundances of various species and fish stock, indicating a high relevance of the observed physical processes.

1 Introduction

Starting with the 1980s through the POEM program (Physical Oceanography of the Eastern Mediterranean, Malanotte-Rizzoli et al., 1997), the knowledge about the hydrography, circulation, and basin scale, local and mesoscale processes of the Eastern Mediterranean has been improved a lot. A classical picture of the Eastern Mediterranean portrays it as a concentration basin, where an anti-estuarine circulation is largely the result of dense and deep water convection: (i) Levantine Intermediate Water (LIW) is generated largely in the Rhodes Gyre and the Levantine Basin (Lascaratos

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et al., 1993), flowing in a subsurface layer towards the northernmost basin (Adriatic) and the Western Mediterranean, while (ii) dense water generation sites are located in the Adriatic Sea; generated dense water spreads from the Adriatic and sinks to the deep Ionian Sea and the Levantine Basin. However, an abrupt change, called the Eastern Mediterranean Transient (EMT, Klein et al., 1999; Roether et al., 2007), occurred in the early 1990s. The EMT was characterized by a massive generation of dense water in the Aegean Sea driven by exceptional heat losses and winds (Josey, 2003). The EMT generated a shift of deep water characteristics (Kress et al., 2003) and impacted the circulation, particularly of the Ionian Sea, where the anticyclonic circulation was strengthened during the EMT phase, and turned over to cyclonic in 1997 during the EMT relaxation phase (Borzelli et al., 2009).

Gačić et al. (2010) suggested a generalised concept of circulation fluctuations of the central Mediterranean, hypothesizing that the Ionian upper circulation variability is driven by internal dynamics. Namely, formation of dense water in the Adriatic Sea (North Adriatic Dense Water, NAdDW, Vilibić and Supić, 2005; Adriatic Deep Water, ADW, Vilibić and Orlić, 2001) and it's spreading to the deep Ionian Sea influences vorticity balance there, causes a shrinking of the water column along the western perimeter, changes geostrophic balance between the perimeter and the inner Ionian, and induces anticyclonic circulation. The anticyclonic circulation drags a branch of the Modified Atlantic Water (MAW) towards the Adriatic. The MAW is characterised by lower salinity, temperature and density, and it preconditions generation of the NAdDW and ADW of lower density. These waters then flow towards the northwestern Ionian perimeter and, together with less dense MAW lying above them, stretch the water column and change geostrophic balance, resulting in a shift of the circulation to the cyclonic one. This important concept called Bimodal Adriatic-Ionian Oscillation (BiOS) which was introduced recently for the central Mediterranean basin, was further extended towards the Levantine Basin and the EMT preconditioning (Gačić et al., 2011), and was found to explain a number of known phenomena such as decadal salinity oscillations in the Adriatic called the Adriatic ingressions (Buljan, 1953; Civitarese et al., 2010) and the decadal variations of the MAW meandering in the Ionian Sea (Malanotte-Rizzoli et al., 1997).

These physical concepts have an important consequence to the biogeochemical properties and biodiversity of the whole Eastern Mediterranean basin. Namely, it is known that the Eastern Mediterranean is ultra-oligotrophic area, with extremely high N:P ratio in deep waters, about 28 : 1 (Krom et al., 1991, 2004, 2010). Therefore, the primary production is low and limited by phosphorus (Siokou-Frangou et al., 2010). The only exception is the northernmost Adriatic, where high river nutrient loads are responsible for the phytoplankton blooms and high levels of eutrophication (Degobbis and Gilmartin, 1990; Degobbis et al., 2000). Krom et al. (2004) propose that high N:P ratio is kept because there is no significant denitrification in either the sediments or intermediate water, maintained by anti-estuarine flow at the Straits of Sicily. Also, the unusual nutrient ratio is supposed to be due to high dissolved nitrogen and phosphorus values in all the external nutrient inputs. The Western Mediterranean differs a lot: the concentrations of orthophosphates and nitrates + nitrites are higher about 5 and 3 times than in the Eastern Mediterranean in euphotic layer, respectively, and about 2.2 and 1.6 times in intermediate and deep waters, respectively, resulting in strong nutrient horizontal gradients between the Eastern and the Western Mediterranean over Sicily Strait (Pujo-Pay et al., 2011). A number of authors attribute the gradient to the difference in the allochtonous nutrient sources in terms of quantity and quality (e.g., Ribera d'Alcala et al., 2003; Ludwig et al., 2010), and to biogeochemical processes rather than to circulation itself (Crispi et al., 2001; Thingstad et al., 2005).

However, the circulation may be quite important on interannual and decadal scales over the specific Mediterranean basins like the Adriatic, as horizontal or vertical advection and displacement of nutrients may cause shifts in primary production at specific locations, such as the deep-convection locations, e.g. the South Adriatic Pit where phytoplankton blooms follow the deep convection events (Gačić et al., 2002; Vilibić and Šantić, 2008). Aside for that, the Adriatic Sea upper layer circulation is driven by the freshwater input, particularly of the Northern Adriatic rivers, that result in an estuarine

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surface circulation, with the outflowing West Adriatic Current (WAC) and the inflowing LIW and the surface Ionian waters. Although the nutrient load by the Northern Adriatic rivers is significant, this impact is mainly restricted to the Northern Adriatic and the WAC (Grilli et al., 2005; Polimene et al., 2006; Solidoro et al., 2009) as the nutrients are normally consumed very fast during their transport towards the southeast and the open Adriatic (Campanelli et al., 2011). The same, i.e. fast consumption of nutrients and restriction of primary production to the coast, has been found around the eastern Adriatic freshwater inputs (Marini et al., 2010; Ninčević Gladan et al., 2010; Viličić et al., 2011). By contrast, the open Adriatic waters nutrient load is mostly controlled by the inflowing waters coming from the Ionian Sea (Šolić et al., 2008).

Therefore, the inflow of the intermediate waters from the Ionian Sea, mainly of the LIW, is a major supplier of the open Adriatic nutrients, and is found to influence the Adriatic long-term productivity (Marasović et al., 1995, 2005; Grbec et al., 2009). A maximum in different different bacterial and plankton populations, from plankton through fish eggs towards bacterial production (Šolić et al., 2008), has been found to coincide with the inflow of the LIW. Civitarese et al. (2010) applied the BiOS concept to the observed biological changes in the Adriatic, and found a correlation between high salinity periods and allochtonous organisms coming from the Eastern Mediterranean. Furthermore, they found correlation between allochtonous organisms coming from the Western Mediterranean and low salinity periods; however, their data has been largely restricted to the last 20 years. The discovery of the Western Mediterranean organisms in the mid 1990s in the Adriatic favours the hypothesis that the Western Mediterranean waters entered the Adriatic during these years: This hypothesis is further supported by salinity and nutrient load being out of phase in the mid 1990s in the Southern Adriatic Pit and the Ionian Sea (Civitarese et al., 2010).

Following the studies by Gačić et al. (2010) and Civitarese et al. (2010), our study attempts to test the relevance of the BiOS mechanism and its impact to the Adriatic Sea through an introduction of long-term physical and nutrient data collected between 1960 and 2010 at the Palagruža Sill transect (Fig. 1). The data has been collected through

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permanent monitoring programme, covering the open and the eastern coastal Adriatic waters. In addition, our data allow for an assessment of the uniqueness of the EMT in terms of its impact to the biogeochemical properties of the Adriatic Sea. In Sect. 2 data and their availability are presented, in Sect. 3 the series and average values of all parameters at the profile compared to the 1991–1998 period are displayed, in Sect. 4 our findings are discussed in the light of existing hypotheses, and summary and major conclusions are given in Sect. 5.

2 Material and methods

The investigated area, the Palagruža Sill (Fig. 1), is one of the Adriatic transects which are monitored regularly since the mid last century. An importance of its position in tracing the Adriatic circulation and water masses has been recognized by a number of authors (e.g., Buljan and Zore-Armanda, 1976; Vilibić et al., 2004). The Palagruža Sill separates circular 1200-m deep South Adriatic Pit from the 280-m deep Jabuka Pit multidepression system and the shallow Northern Adriatic. We examined long term temperature, salinity, dissolved oxygen (DO), orthophosphate, total inorganic nitrogen (TIN) and orthosilicate concentration data measured at 5 permanent stations at standard oceanographic depths (0, 10, 20, 30, 50, 75, 100, 150, bottom) from 1960 to 2010. The data were normally collected monthly (stations P1 and P2) or seasonally (stations P3 to P5) in time intervals indicated in Fig. 2. Altogether 478, 542, 186, 177 and 173 surveys were carried out at stations P1 to P5, respectively, with some parameters collected over the full time interval and others over a fraction of the full time interval. Temperature and salinity have been collected at all stations during all cruises, dissolved oxygen and orthophosphates have not been determined in the first decades at stations P3 and P4, TIN data do not cover the first 10–20 years at P1, P2, and P5, while orthosilicates data cover only the last 25 years of the interval or less.

Sampling methodology for some variables was changed during the study period, and the consistency of the data (shifts, drifts) between periods was checked through statistical procedures and through calibration experiments that were carried out during a number of research cruises when transitions in methodology occurred. The temperature and salinity were measured with Nansen-bottles until 1998. Reversing thermometers with an accuracy of ±0.02 °C were used for temperature measurements. Salinity measurements were obtained by titration with $AgNO_3$ (with an accuracy for chlorinity of ±0.01) until the 1980s, when the use of a portable induction salinometer RS-10, Beckman Industrial, was introduced (with an accuracy of ±0.003). After 1998, IDRONAUT 316 CTD and Seabird-25 CTD probes have been used to measure temperature and salinity, with accuracy values of 0.003 °C and 0.002 °C for temperature, 0.0003 S m^{-1} and 0.0003 S m^{-1} for conductivity, and 0.05 % and 0.1 % of the full-scale range for pressure. Dissolved oxygen was determined using classical Winkler titration (Grasshof, 1976) throughout the study period with an accuracy of ±2 µmol l^{-1}. Concentrations of dissolved inorganic nutrients, including orthophosphate (HPO_4^{2-}) and the sum of nitrates, nitrites and ammonia (total inorganic nitrogen, TIN), were determined spectrophotometrically according to Strickland and Parsons (1968) until the 1970s. AutoAnalyzer II and III colorimeters (Bran & Luebbe, Seal Analytical) have been used subsequently, following modified methods based on those proposed by Grasshof (1976).

The data quality was checked by using min-max conditions for each parameter, and by imposing a threshold to the spikes and rapid changes along the vertical for each parameter. A significant seasonality in all parameters, which is normally occurring in the upper and euphotic layers, has been removed from the series by a year-day least squares fitting of a combination of 12- and 6-month sinusoidal functions applied to each series. The procedure was separately applied on each station, depth and parameter.

Differences between overall averages of parameters (the data collected between 1960 and 2010) and averages of the data collected between 1991 and 1998 (the EMT period) have been analyzed. The initial year (1991) for the period of the EMT influence to the Adriatic properties was selected from the available literature, which documents the triggering of the EMT in winters of the early 1990s (Klein et al., 1999). The last year,

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1998, has been chosen following the 1997 change from the anticyclonic to cyclonic circulation in the Ionian Sea (Borzelli et al., 2009).

3 Results

Time series of all de-seasoned parameters show a noteworthy variability, but also a clear interannual and multidecadal variability over some intervals. Deep temperatures at all parts of the transect (Figs. 3 to 5) show an interchange of several maxima and minima, with the most prominent minimum and maximum occurring in the last two decades – especially over the eastern part of the transect (Fig. 3). Temperature minimum in the early 1990s was stretching over the transect in deep layers (Figs. 4 and 5), and was followed by a strong temperature increase towards the early 2000s. This temperature shift was already documented for the South Adriatic (Vilibić et al., 2011) and was recognized as a result of the Bimodal Adriatic-Ionian Oscillation (BiOS, Gačić et al., 2010). The minimum in temperature is accompanied with the minimum in salinity in the early 1990. This minimum is a part of the known salinity fluctuations in the Adriatic (so-called Adriatic ingressions, Buljan, 1953; Civitarese et al., 2010): salinity oscillates between 38.4 and 38.9, aside from the isolated minimum present at the beginning of the series, in the early 1960s.

Although dissolved oxygen has negative trends over the whole interval, it follows the same oscillatory pattern as temperature and salinity. The most prominent DO minimum can be found in the early 1990s, when the values in deep waters decreased to less than 220 $\mu mol\,l^{-1}$, and even less than 200 $\mu mol\,l^{-1}$ at the deepest station P3 (Fig. 4). After the early 1990s, the deep DO values rose a bit, becoming stable at values around 220–230 $\mu mol\,l^{-1}$.

The largest anomaly in the 1990s can be found in nutrient data. An increase of deep orthophosphates, TIN and orthosilicates concentrations took place in 1991 and generally reached a maximum in 1994 and 1995. Orthophosphates increased 2–3 times in the mid 1990s, especially at the deepest parts of the transect (Fig. 4). TIN

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and orthosilicates follow the same rates and patterns of increase. Some differences in the anomaly rates can be found between the stations due to differences in processes they capture, but it is apparent from the data that a basin scale process is driving all of these changes, from thermohaline properties, through oxygen and nutrient changes. We will ascribe the changes to the changes in the Ionian circulation and to the EMT driven changes of the inflowing Adriatic currents.

We've estimated averages of all parameters during the whole studied interval (1960–2010) and during the 1991 to 1998 time interval, when the EMT and BiOS driven changes in the Mediterranean were found to influence the South Adriatic Sea (Gačić et al., 2010; Civitarese et al., 2010). Figure 6 portray a classical hydrographic picture known to occur over the Palagruža Sill transect (e.g., Buljan and Zore-Armanda, 1976; Artegiani et al., 1997): (i) salinity maximum over the deepest part of the transect, ascribed to the LIW inflow; (ii) deep temperature gradient, where the colder waters close to the western shore are a result of the NAdDW outflow, while warmer waters along the eastern shore are a result of the LIW inflow, driving the deep anti-estuarine Adriatic circulation, and (iii) freshened surface waters which are a result of the outflow of the Northern (western part) and Eastern (eastern part) Adriatic rivers which drive the Adriatic estuarine surface circulation. DO values portray the maximum values between 20 and 50 m, where the primary production maximum is normally occurring (Marasović et al., 2005), decreasing towards the deep layers. The minimum in all nutrients may be found in the first 50 m, increasing the values towards the bottom. The strongest vertical gradient in nutrients, i.e., nutricline, is positioned around 100 m, already documented by Civitarese et al. (2010) for the southern parts of the Adriatic.

Comparison of the 1991–1998 and the all-data averages exhibits a significantly different picture of hydrographic and chemical properties along the transect (Fig. 7). Except for the first 10 m, the temperature was significantly lower during the 1991–1998 interval, up to −0.7 °C along the western part of the transect. The salinity decreased everywhere, except in the very surface of the station P1. The decrease is as large as −0.1, larger in the intermediate eastern (station P1) than western (station P4)

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waters. The DO changes are particularly interesting, mostly characterized by an increase (up to 5 µmol l^{-1}) in the first 50 m and by strong decrease in the deep waters (up to 15 µmol l^{-1}).

Orthophosphates exhibited a significant increase during the 1991–1998 period, from 30 % along the eastern up to 100 % along the western section of the transect. The orthophosphates average values at the bottom of stations P3 to P5 were larger than 0.12 µmol l^{-1}, much larger than the documented values characteristic for the open middle Adriatic (Šolić et al., 2008) and even for the open Northern Adriatic (Zavatarelli et al., 1998), where a significant input of phosphates comes through rivers (Lipizer et al., 2011). TIN values decreased in the surface layer (up to 25 %) between 1991 and 1998, and increased towards the bottom (up to 40 %), with a no-change-line stretching along the 50 m depth. Orthosilicates concentrations did not change significantly in the upper 50 m, but they increased towards the bottom, especially at station P5.

The ratio between TIN and orthophosphates (Fig. 8) over the common period of their data is characterized by lower values in the surface layer (up to 50 m), where the primary production is taking place, and higher values in the bottom waters (ratio up to 35 : 1 at the bottom of station P2). The ratio is everywhere above 16 : 1, suggesting the phosphate limited conditions for primary production. The TIN to $HPO_4{}^{2-}$ ratio decreased between 1991 and 1998, mostly in the surface waters, where the ratio was below 16 : 1 and occasionally fell to 10 : 1, indicating the transition toward the nitrogen limited conditions for primary production. The TIN to $SiO_4{}^{4-}$ ratio is spatially stable during the 1960–2010 period, between 1.3 : 1 and 1.5 : 1, following the same ratios found in the Eastern Mediterranean (e.g., Ribera d'Alcala et al., 2003). A decrease in the ratio can be found at the most of the profile between 1991 and 1998, expect at the surface of P1 and P2, and bottom of P4. The $SiO_4{}^{4-}$ to $HPO_4{}^{2-}$ ratio (not shown) is 20 : 1 in average, but ranging from 15 : 1 (surface waters) to 35 : 1 (deep waters).

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4 Discussion

4.1 Adriatic ingressions

There are two theories about the Adriatic ingressions, i.e., decadal variations in salinity of the Adriatic, which are presently discussed in the literature: (1) the salinity variations are a result of pulsation of the LIW towards the Adriatic, i.e. oscillations in the Otranto Strait along-strait transport are driving salinity fluctuations in the Adriatic, as originally raised by Buljan (1953) and further developed by a number of authors (e.g., Grbec et al., 2003); and (2) the salinity fluctuations are associated with different water masses entering the Adriatic, driven by the BiOS and circulation in the Northern Ionian Sea (Gačić et al., 2010; Civitarese et al., 2010). An affirmative argument for the first hypothesis is the increased productivity in the middle Adriatic which partially coincided with the Eastern Mediterranean Transient. Namely, Grbec et al. (2009) document increased mean productivity at station P2 between 1980 and 1996, increasing up to 1986, and thereafter decreasing towards 1996. The increase in productivity before the EMT has been associated with the nutrient rich inflow of the LIW, which was lowered by a decrease in the inflowing LIW current driven by the EMT. On the other hand, Civitarese et al. (2010) found that nitrate and salinity in the Ionian and South Adriatic Seas have been out of phase for the last 20 years (i.e., high salinities are coupled with low nutrient concentrations and vice versa) suggesting that different water masses enter the Adriatic during low and high salinity periods rather than blocking of the inflow is in progress during low salinity periods. Our findings are in favour of the second hypothesis: low salinity and temperature observed between 1991 and 1998 are accompanied with significantly larger orthophosphates (Fig. 7), which are known not to be controlled by the Adriatic sources (partially controlled just in the Northern Adriatic, Degobbis and Gillmartin, 1990; Degobbis et al., 2000) but rather by the waters inflowing from the Eastern Mediterranean (e.g., Buljan and Zore-Armanda, 1976; Krom et al., 2004; 2010). Moreover, TIN and orthosilicates have higher-than-average

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concentration below the euphotic zone, indicating the inflow of the water with increased nutrient content to the Adriatic.

A strong increase in orthophosphates between 1991 and 1998 at levels not present in the Eastern Mediterranean is directing our search for their source to the Western Mediterranean. Namely, in the upper few hundred meters the Western Mediterranean orthophosphate concentrations are 2–5 times higher and in the deep waters about 2 times higher than the Eastern Mediterranean ones (Pujo-Pay et al., 2011). Also, nitrate and nitrite concentrations are about 2 times higher in the Western than in the Eastern Mediterranean, while ammonia concentrations are similar (Pujo-Pay et al., 2011). Result is an east-west gradient of TIN and orthophosphates along the Sicily Strait. Our assumption is therefore that, the Western Mediterranean intermediate waters presumably entered the Adriatic through the northwestern branch of the anticyclonic circulation in the Northern Ionian Sea – the circulation was additionally intensified by the EMT in early 1990s (Borzelli et al., 2009) – and stopped in 1997 when the reversal of the Northern Ionian circulation happened due to the internal feedback process (Gačić et al., 2010). The Western Mediterranean intermediate waters, as old as the LIW waters but with even lower dissolved oxygen content (Fig. 7), reached the Palagruža Sill profile and increased the deep nutrient concentrations, especially of orthophosphates.

4.2 Uniqueness of the 1991–1998 period

Although time series of all nutrients do not cover the whole 61 years period (1960–2010), the data still allow us to discuss the uniqueness of the 1991–1998 period. Gačić et al. (2010) developed the theory that the BiOS is a decadal oscillations, but did not say anything about long-term variability in strength of the process. Civitarese et al. (2010) did a throughout investigation of existing literature on biodiversity changes in the Adriatic serving as a proxy for the circulation regimes, and found that the Western Mediterranean organisms were found in the Adriatic during anticyclonic circulation in the Northern Ionian Sea, while the Eastern Mediterranean organisms were observed during the LIW inflow and cyclonic circulation in the Northern Ionian Sea; however,

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only sporadical data were available before 1990s (see their Table 2), while most of the data cover the last 20 years when the EMT occurred. Also, there are some papers that consider the EMT to be a climate shift (e.g., Conversi et al., 2010), indicating uniqueness of the process; on the other hand, Gačić et al. (2011) raise a possibility that the EMT may repeat when the preconditioning and severe wintertime cooling and winds match together. High-resolution numerical modelling partially supports the latter: Beuvier et al. (2010) applied the eddy-permitting numerical model for the 1960–2000 period and found that the EMT is dominantly driven by winds and surface fluxes over the Aegean, which were uniquely extreme during winters of 1991 and 1992, but which may repeat with longer return period than the investigated time interval in the future.

Our data show that the orthophosphates, which were measured during the whole period at some stations, reached the highest levels between 1991 and 1998 (Figs. 3 and 5). There are some high values of HPO_4^{2-} at stations P1 and P2 in 2000 (Fig. 3), accompanied with higher-than-average DO values than in the mid 1990s, indicating more closer source of these nutrients potentially coming through the eastern Adriatic input (Marasović et al., 2005). Also, the maxima in other nutrients at almost all stations and depths are evident in the mid 1990s. Apart from the EMT- and BiOS-induced maximum of nutrient concentrations, a decadal variability may be found during the whole interval, partially following the changes of thermohaline properties and dissolved oxygen content. Namely, a weak minimum in temperature, salinity and DO values may be found in 1973–74, accompanied with a maximum in TIN and orthophosphates (Fig. 3). On the other hand, an increase in TIN and orthophosphates in 1978–79 did not merge with the salinity and temperature minimum (Figs. 3 and 4), and even coincided with the salinity maximum. Therefore, complex interactions between hydrographic and nutrient changes should be considered when assessing regular climate oscillations in the middle Adriatic ecosystem, which are driven not only by the BiOS but by the Adriatic biogeochemistry, by advection of inorganic and organic material from the Northern Adriatic and coastal regions, by vertical mixing and nutrient redistribution, and by uptakes from the atmosphere. However, we may conclude that the EMT-induced changes

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in nutrient budget and advection of the Western Mediterranean intermediate waters towards the middle Adriatic, detected by the physical and chemical data between 1991 and 1998, are unique in the whole investigated period (1960–2010).

4.3 Primary production and the EMT

One would expect that the increase in available nutrients between 1991 and 1998, especially orthophosphates which are known to limit the primary production in the Adriatic and eastern Mediterranean (Krom et al., 1991), would result in higher production rates. Indeed Grbec et al. (2009) document higher-than-average yearly and spring-summer primary production in this period at station P2 (precisely between 1991 and 1996) but preceded by similarly high production rates, which started in 1980. Even more, the 1980–1996 period is recognized by Grbec et al. (2009) as a climate shift in primary production; however, the analysis were based on the data collected at station P2 and another coastal station. Our chemical data support the documented higher production rates potentially being a consequence of the EMT, as the TIN concentrations are lower-than-average and therefore nitrogen consumption is higher-than-average in the euphotic zone between 1991 and 1998 (Fig. 7) over the whole Palagruža Sill profile. The increase in nitrogen consumption is a result of much higher availability of phosphorus, which shifted normal phosphorus-limited primary production conditions towards the nitrogen-limited conditions. In addition, the 1991–1998 DO concentrations generally increased at the level of maximum (20–30 m), especially along the western part of the section, indicating higher primary production rates driven by a significant nutrient load.

Larger orthophosphate concentrations and the documented higher primary production rates (Grbec et al., 2009) presumably shift the Adriatic to the less oligotrophic conditions, resulting in N:P ratio close to the Redfield ratio of 16 : 1 or less. Namely, the 1991–1998 N:P ratio in the most of the euphotic zone is below 16 : 1, even coming close to 10 : 1 in the western section, where an increase in primary production can be detected through the rise in DO concentrations. Therefore, the primary production

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along the most of the section was controlled by nitrogen availability between 1991 and 1998. A possibility that nitrogen-limited conditions in primary production can occur in the open middle Adriatic has been already suspected by Šolić et al. (2008), who found a positive correlation between different biological parameters and nitrogen at station P2 between 1997 and 2006.

What is still unclear here is a reason for increased primary production observed between 1980 and 1990 (Grbec et al., 2009), as the nutrients at the transect did not differ much from their average values, and the production was limited by phosphorus. It is known that more efficient vertical mixing, deep convection and a transport of deep nutrients towards euphotic zone may trigger primary production (Gačić et al., 2002; Civitarese et al., 2005); a series of severe winters occurred between 1981 and 1983 with quite anomalous heat and buoyancy fluxes in the Adriatic Sea (Josey, 2003). Furthermore, a shift in water mass characteristics has been detected in the South Adriatic Pit in 1980s (Vilibić and Orlić, 2001). However, this scenario should be further investigated and confirmed.

5 Summary and conclusions

We investigated long-term series (1960–2010) of different physical and chemical parameters along the Palagruža Sill transect, which is to our knowledge the best dataset that may be used for assessing climate conditions, shifts and fluctuations of the open Adriatic Sea. Aside from documenting known and characteristic properties, an anomaly in nutrients occurring between 1991 and 1998 came into the focus. Several important conclusions may be raised:

- A large increase of deep nutrients concentrations (below euphotic zone) along the transect has been observed between 1991 and 1998, especially of orthophosphates, accompanied with lower-than-usual temperature, salinity and DO concentrations. As no possible source for such nutrient concentration is available in

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the eastern Mediterranean, we conclude that the Western Mediterranean intermediate water, rich in orthophosphates and TIN when compared to the Eastern Mediterranean waters, were dragged to the Adriatic through anticyclonic circulation in the Northern Ionian Sea. Our results conform to the hypothesis and findings documented by Civitarese et al. (2010).

- No similar conditions have been documented between 1960 and 2010 in the middle Adriatic, supporting the uniqueness of the 1991–1998 time interval in terms of nutrient dynamics. This period coincided with the EMT period, which generated massive sinking of dense waters to the deep Ionian, forcing anticyclonic circulation of the basin. Therefore, a prerequisite for the observed high nutrient transport from the Western Mediterranean to the Adriatic is presumably achieved through simultaneous acting of the EMT, which is a unique by itself, and a right phase (anticyclonic circulation in the Northern Ionian) of the BiOS.

- The 1991–1998 period has been characterised by nitrogen-limited conditions for primary production over the most of the transect, opposing typical phosphorus-limited conditions found in the rest of the examined period, and normal for the Eastern Mediterranean.

- Increased nutrient concentrations may partially explain the documented maximum in primary production, i.e., the maximum between 1991 and 1996, but not between 1980 and 1990. The latter is a result of some other processes, of which the most promising is enhanced vertical mixing and transport of nutrients to the euphotic layer, but this should be further investigated in future.

A lot of implications arise from the fact that the Western Mediterranean waters may be transported to the Adriatic and significantly raise the nutrient levels there. An increase of nutrients normally boosts primary production, which may impact the abundance of higher trophic organisms, up to the fish stock. Indeed Kraus and Supić (2011) presented the anchovy catchment in the Adriatic Sea between 1990 and 2004, and found

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the minimum in 1996, and then a sharp increase (about ten times) in the next 3 years. Cingolani et al. (1996) documents much higher anchovy biomass for the period 1976–1984 than for the period 1987–1992. Santojanni et al. (2006) connects these variations with different atmospheric and hydrological variables, but we believe that a coincidence of high primary production between 1980 and 1996, anchovy collapse between 1985 and 1997 and recovery after that, and nutrient changes observed in the Adriatic are connected, which should be carefully investigated in the future.

Another important consequence is a decrease of the density of the Adriatic waters, as the salinity decrease has the stronger effect on density changes than the observed decrease of temperature. Lower density pool in the regions where deep water is generated implies the generation of less dense waters (NAdDW and ADW), which is already observed along the Palagruža Sill transect (Vilibić et al., 2012), resulting in less effective ventilation of deep layers and lowering of the intermediate and deep water DO concentrations, in addition to already lower-than-average DO concentrations that characterize the observed Western Mediterranean intermediate water. Therefore, deep pelagic and benthic organisms can suffer from these changes, especially within biodiversity niches such is Jabuka Pit (Fig. 1) (e.g., Vrgoč et al., 2004) – a multidepression complex system collecting dense water from the Northern Adriatic, horizontally mixing with intermediate waters coming from the southeast and occasionally being ventilated through severe cooling and wind-induced mixing acting from the surface (Vilibić et al., 2004), and therefore sensitive to changes in physical and chemical parameters.

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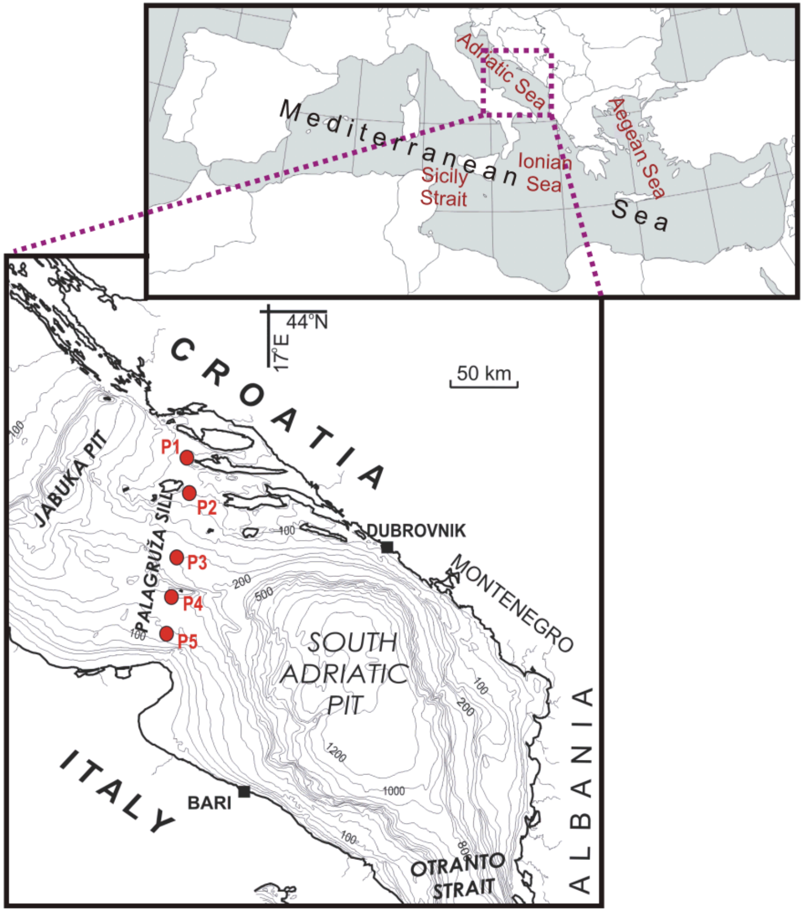

Fig. 1. The investigated area, with locations of the climatological stations (P1 to P5) along the Palagruža Sill.

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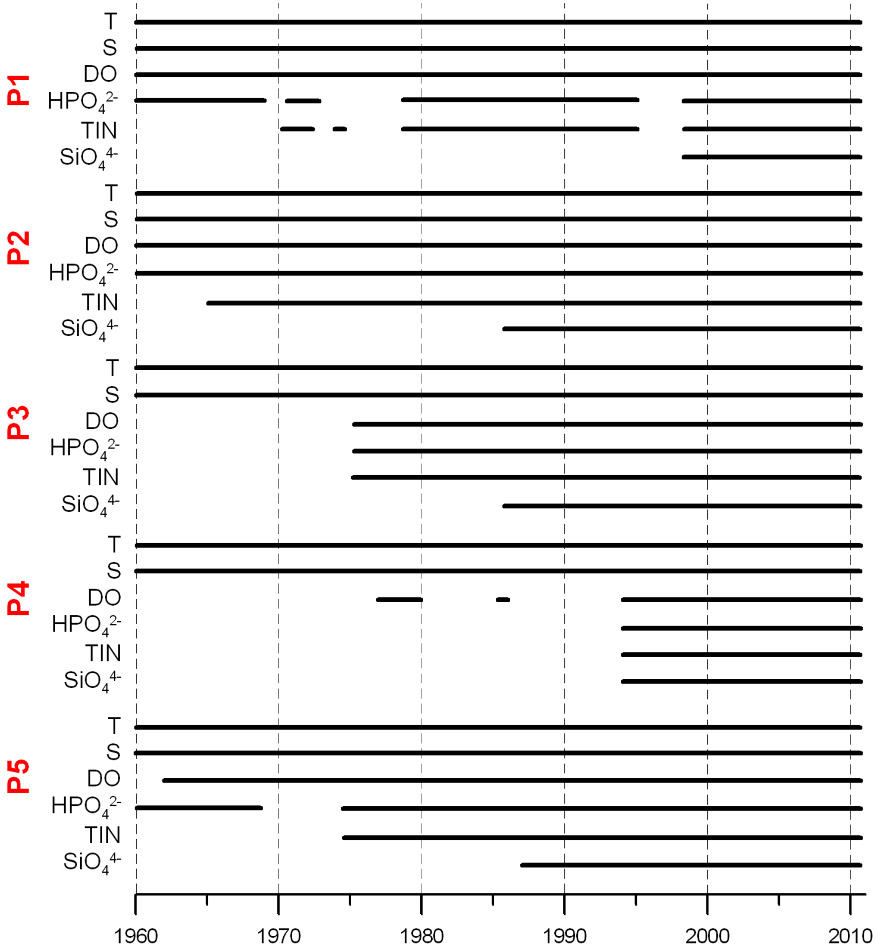

Fig. 2. Availability of the data collected at the Palagruža Sill transect.

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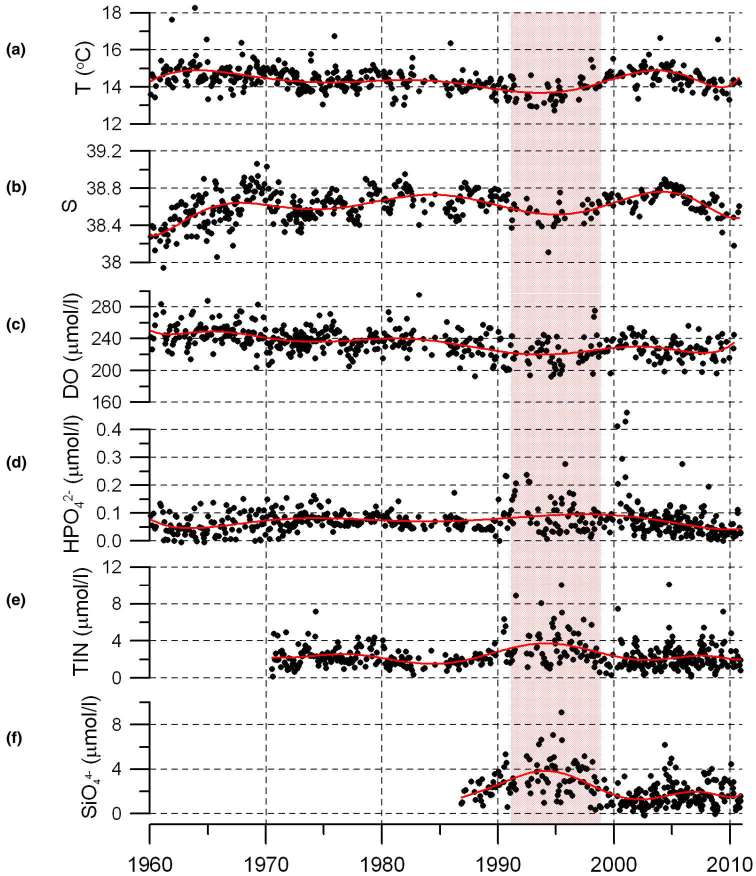

Fig. 3. Time series of **(a)** temperature, **(b)** salinity, **(c)** dissolved oxygen, **(d)** TIN, **(e)** orthophosphates, and **(f)** orthosilicates at the bottom of the station P2 (100 m). Seasonal signal is removed from the series. Full line stands for the polynomial fitting of seventh order, while the 1991–1998 period is marked by shadow.

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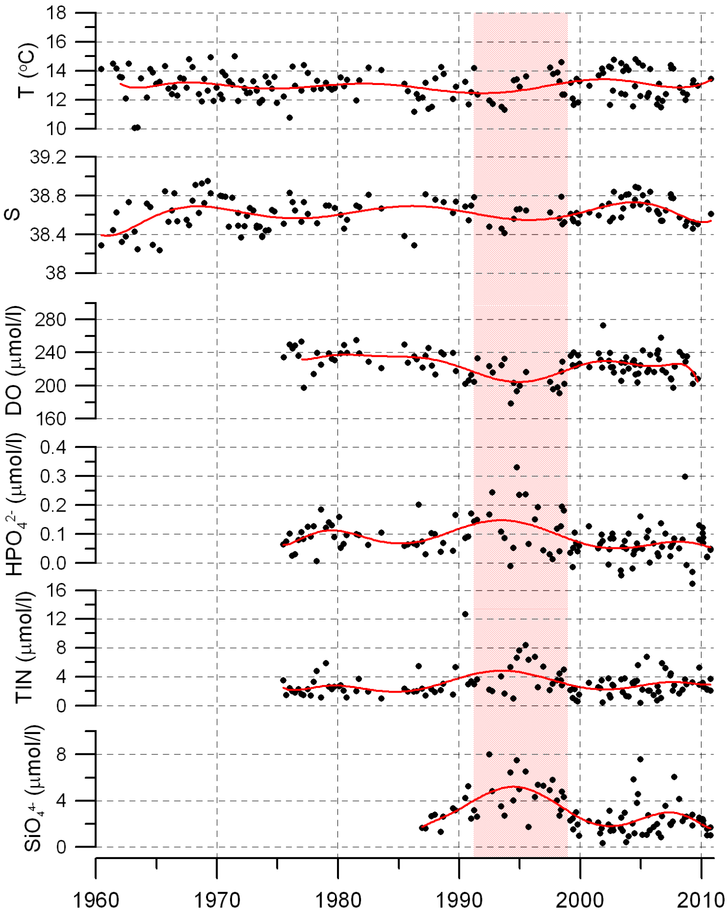

Fig. 4. As in Fig. 3, but for station P3 (170 m).

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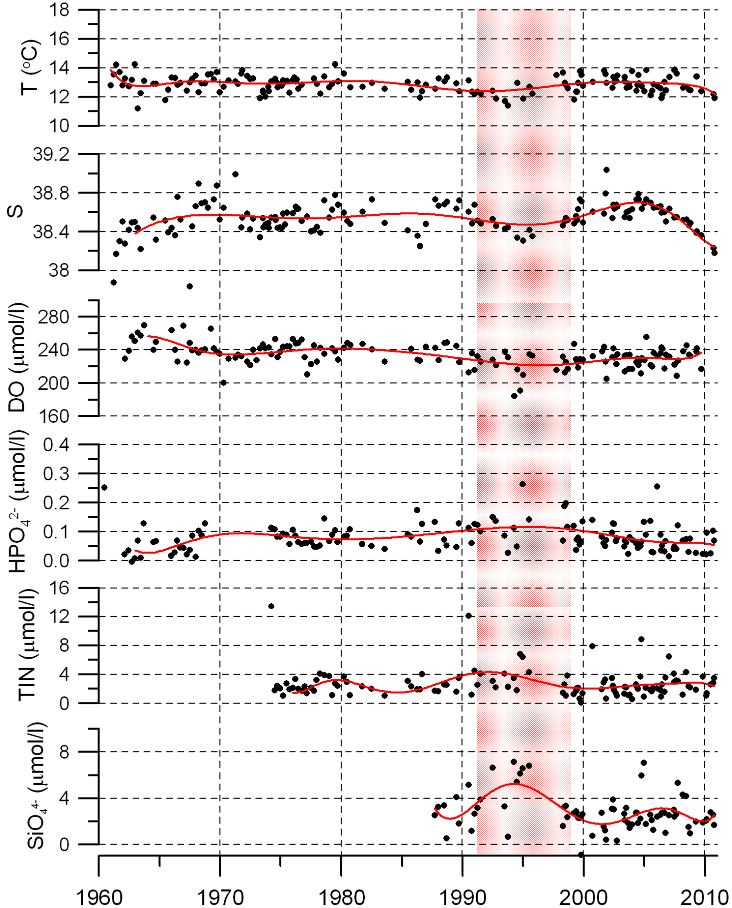

Fig. 5. As in Fig. 3, but for station P5 (110 m).

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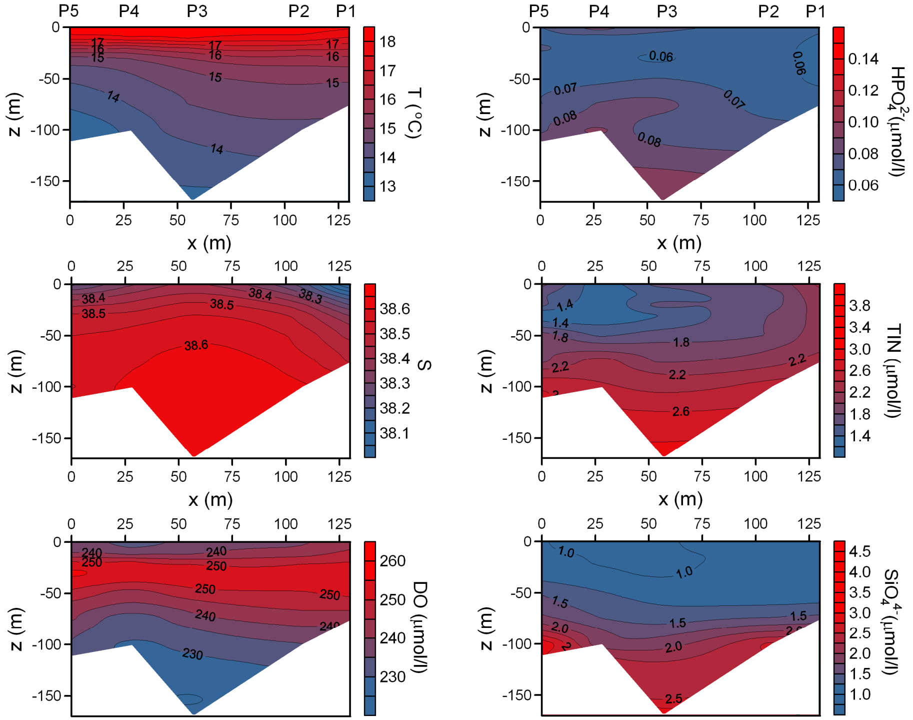

Fig. 6. Palagruža Sill profiles of temperature, salinity, dissolved oxygen, TIN, orthophosphates, and orthosilicates, averaged between 1960 and 2010.

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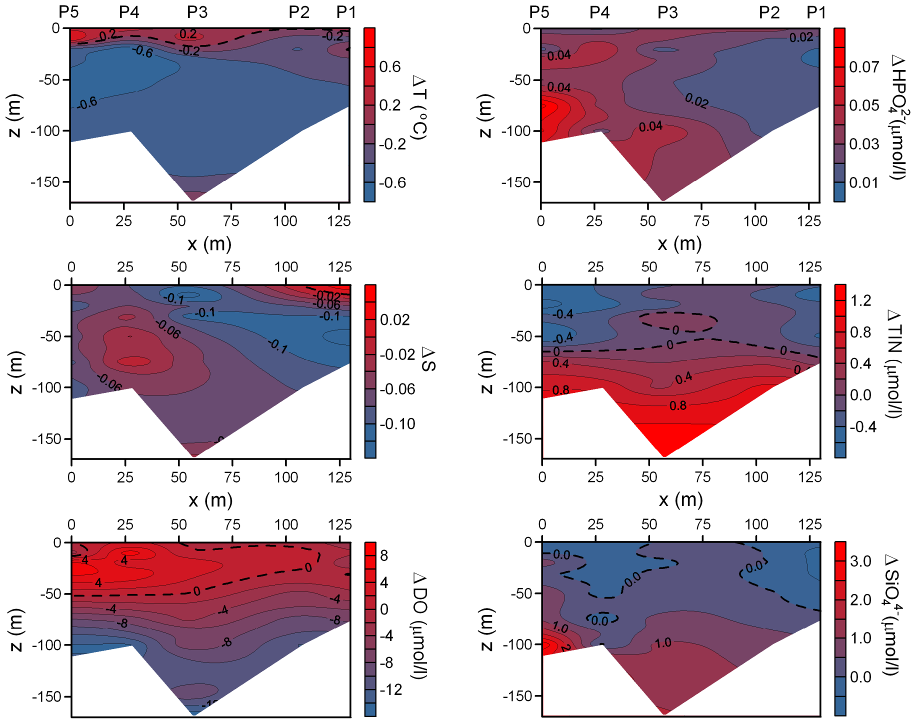

Fig. 7. As in Fig. 6, but for difference between 1991–1998 and 1960–2010 period.

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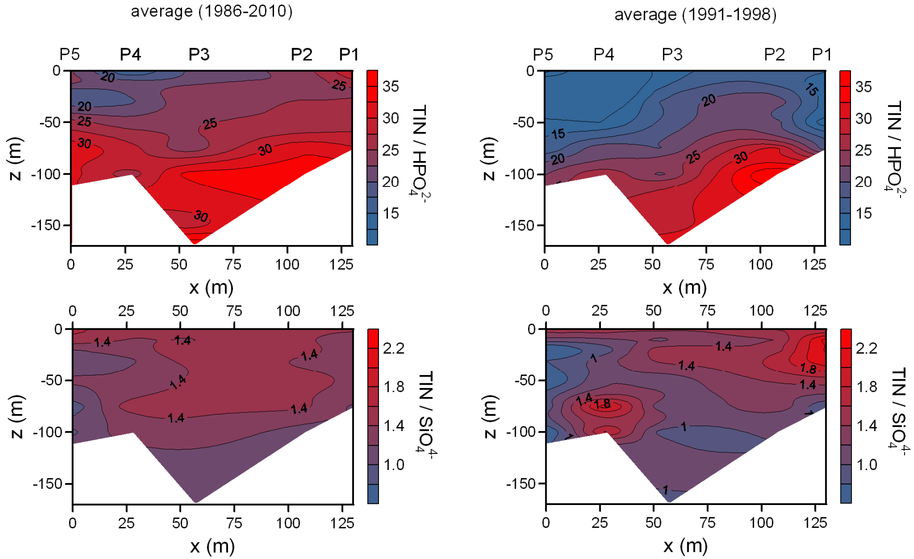

Fig. 8. Palagruža Sill profiles of TIN to HPO_4^{2-} and TIN to SiO_4^{4-} ratios averaged over common period of measurements (1986–2010, left panels) and over 1991–1998 (right panels).