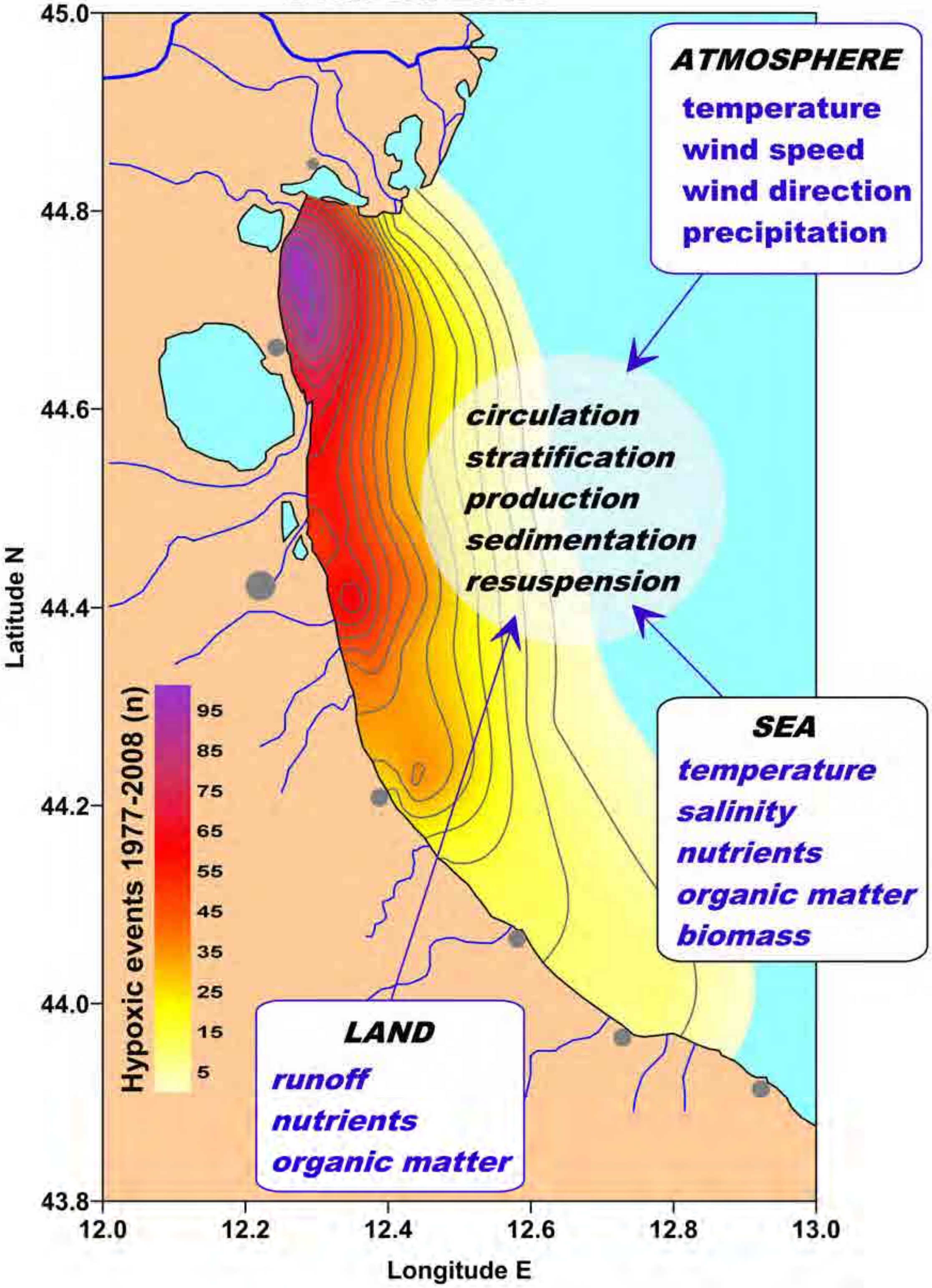
*Graphical Abstract

Hypoxia in Emilia Romagna Coastal Zone



Highlights

- hypoxia is still a frequent phenomenon in ERCZ, in particular south of Po River delta
- seasonal widespread hypoxia changed in periodic, short, local hypoxia
- hypoxia is favoured by different environmental conditions at a seasonal scale
- long-term changes of environmental and oceanographic conditions are detected in ERCZ
- future climate changes could deeply affect the dynamics of hypoxia in ERCZ

CAPTIONS

Fig. 1 – Bathymetry (m) of the Coastal Zone of the Emilia Romagna (ERCZ) with the monitoring stations of ARPA-ER.

Fig. 2 – Total number (n) of hypoxic events recorded in 1977-2008: (a) spatial distribution in the ERCZ, (b) monthly distribution of hypoxia and strong hypoxia.

Fig. 3 – High-Low-Close plot of (a) monthly distribution (+ = median; box = 1°- 3° quartile; vertical bar = range of values) of daily average air temperature (T_A; C) at Porto Tolle in presence and absence of hypoxia in the coastal waters. (b) Difference between median values of temperature (ΔT_A) in the presence and absence of hypoxia.

Fig. 4 – Bar chart of daily-integrated precipitation (P; $dm^3\ m^{-2}\ d^{-1}$) at Porto Tolle in presence and absence of hypoxia in the coastal waters and frequency (%) of hypoxic events for each precipitation class.

Fig. 5 – Bar chart of daily average wind speed (W_S; $m\ s^{-1}$) at Porto Tolle in presence and absence of hypoxia in the coastal waters and frequency (%) of hypoxic events for each wind class.

Fig. 6 – Polar diagram of hourly wind direction (W_D; sectors of 45°) at Porto Tolle in concomitance to hypoxia in coastal waters.

Fig. 7 – Bar chart of the frequency of the days with hypoxia (%) in the coastal waters as a function of Po River flow (daily average; $m^3\ s^{-1}$) during the four seasons in the periods 1977-1988 and 1989-2008.

Fig. 8 – High-Low-Close plot of monthly distribution (median and 1° - 3° quartile) of oceanographic parameters in surface coastal waters in the absence and presence of hypoxia.

Fig. 9 - Annual integrated freshwater load of Po River (km^3 yr-1) and precipitation (P; $mm\ yr^{-1}$). High-Low-Close plot of annual median and 1° - 3° quartile of air temperature (T_A; C), wind speed (W_S; $m\ s^{-1}$), seawater temperature (T_{SW}, C) and salinity.

Fig. 10 - As in Fig. 9 for chlorophyll “a” (Chl a; $\mu g\ L^{-1}$), dissolved oxygen saturation (DO_{sat}; %), concentrations of nitrate (NO_3^-; $\mu mol\ N\ L^{-1}$), ammonium (NH_4^+; $\mu mol\ N\ L^{-1}$) and reactive phosphorus (PO_4^{3-}; $\mu mol\ P\ L^{-1}$) and N/P molar ratios.

Tab. 1 – Number (n), duration (days; median and range of values) and ratio of strong hypoxia (sHy; $DO < 1\ mg\ L^{-1}$) and hypoxia (Hy; DO = 1-3 $mg\ L^{-1}$) in the ERCZ in 1977-1988 and in 1989-2008.

Tab. 2 – Inventory of river water (Q_y; $km^3\ yr^{-1}$) and nutrient ($t\ y^{-1} \cdot 10^3$) discharges of Po and the other ER rivers (TN = total nitrogen, TP = total phosphorus, DIN = dissolved inorganic nitrogen, SiO_2 = reactive silicon).

Tab. 3 - Difference (Δ) between monthly median value of oceanographic parameters in surface coastal waters in the presence and absence of hypoxia.

Tab. 4 - Median (med.), 1° - 3° quartiles (Q_1, Q_3) and range of values (min., max.) of meteorological (1990-2008), Po River flow (1977-2008) and oceanographic (1981-2008) datasets considered in this study. Mann Kendall Z-test (MKT) and Sen's test were applied to time-series of annual median data.

Seasonal dynamics and long-term trend of hypoxia in the coastal zone of Emilia Romagna (NW Adriatic Sea, Italy)

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Abstract

Long-term series of meteorological, hydrological and oceanographic data were compared with hypoxia occurrence, in order to define characteristics and trends of this phenomenon in the Emilia Romagna Coastal Zone (ERCZ) in 1977-2008. During this period, hypoxia was recorded at all sampling stations, up to 20 km offshore. In winter, spring and late autumn, hypoxia appearance was matched to significant positive anomalies of air and surface seawater temperatures (up to +3.6 C), whereas this effect was less pronounced in August-October. Hypoxia generally occurred with scarce precipitation (0-2 $dm^3\ m^2\ d^{-1}$) and low wind velocity (0-2 $m\ s^{-1}$), suggesting the importance of stable meteo-marine conditions for the onset of this phenomenon. Nevertheless, wind direction resulted to be an hydrodynamics seasonal changes indicator in the area and thus an hypoxia regulator. In winter, spring and autumn, hypoxia was favored by large increases of biomass induced by river freshets. In contrast, summer hypoxia occurred during periods of low runoff, suggesting that pronounced stratification and weak circulation of coastal waters were more important in this season.

Since the 1990s, a shift from widespread summer hypoxia to local hypoxia irregularly distributed across the year has occurred. This process was concomitant to long-term increases of air temperature (+0.14 C yr^{-1}), wind speed (+0.03 $m\ s^{-1}\ yr^{-1}$) and salinity (+0.09 yr^{-1}), and decreases of Po River flow (-0.54 $km^3\ yr^{-1}$), oxygen saturation (-0.2 % yr^{-1}) and PO_4^{3-} (-0.004 $\mu mol\ P\ L^{-1}\ yr^{-1}$) and NH_4^+ (-0.04 $\mu mol\ N\ L^{-1}\ yr^{-1}$) concentrations in surface coastal waters. Despite several of these changes suggest a ERCZ trophic level positive reduction, similar to that reported for the N Adriatic, the concomitant climate warming might further exacerbate hypoxia in particularly at shallow shelf locations. Therefore, in order to avoid hypoxia development a further mitigation of anthropogenic pressure is still needed in the area.

Keywords: coastal hypoxia, eutrophication, meteorology, river discharge, time-series, long-term trend.

1. Introduction

Declines of oxygen levels in coastal waters during modern historical times were reported in Europe and USA at least since the early 1900s (Diaz, 2001; Zhang et al., 2010), but the number of coastal zones subjected to hypoxia increased by 5.5 % yr^{-1} in 1916-2006, with an exponential rise after the 1960s in coincidence to the largest marine ecosystem eutrophication (Vaquer-Sunyer and Duarte, 2008). In Europe, the systematic appearance of coastal hypoxia was observed in the Baltic Sea since the 1930s (Fonselius, 1969), in the North Adriatic (NAd) since the 1960s (Justič et al., 1987), in the Kattegat since the 1970s (Baden et al., 1990) and in the Black Sea since the 1980s (Mee, 1992). In the Mediterranean, several coastal zones other than the NAd are frequently affected by hypoxia and anoxia such as the lagoons of Orbetello in Italy (Lardicci et al., 2001) and Thau in France (Souchu et al., 1998), the delta of Ebro in Spain (Camp et al., 1992) as well as the Amvrakikos Gulf and the Aetoliko lagoon in Greece (Friedrich et al., 2014).

Despite the existence of natural oxygen-depleted coastal zones, like the upwelling regions receiving oceanic waters from persistent Oxygen Minimum Zones, the most frequent cause of coastal hypoxia increase in the recent past was the supply of nutrients and organic matter originated by human activities (Rabalais et al., 2010). During the human history, coastal populations settled preferentially in semi-enclosed coastal zones like deltas, barrier islands and gulfs determining a deep impact on their natural landscapes as a result of their large conversion to agriculture, silviculture, aquaculture, as well as to industrial and residential uses (Valiela, 2006). These transformations have increased the production of wastewater, the transport of fertilizers associated to runoff and soil erosion and the atmospheric deposition of biogenic elements originated by pollution and fossil fuel burning. Many studies worldwide have demonstrated a direct correlation between population growth, increased nutrient discharge, primary production and frequency of coastal hypoxia (Howarth et al., 1996; Diaz, 2001; Zhang et al., 2010).

Climatic oscillations have also modulated hypoxia in estuarine (Pearl, 2006) and coastal (Meire et al., 2013; Rabalais et al., 2010) ecosystems over temporal scales ranging from decades to millennia, but only in the last century their combination with anthropogenic pressure has become a crucial aspect for hypoxia development (Zillén et al., 2008; Rohling et al., 2015). Temperature increases, altered regimes of wind, precipitation and runoff can deeply affect the fate of nutrient loads in continental margins. Seawater warming and ocean acidification can increase the susceptibility of marine organisms to low oxygen levels and to shift of marine systems towards heterotrophy and jellyfish proliferation (Altieri and Gedan, 2015).

To date, 23 % of the world's population lives within 100 km distance from the coast and the population density in coastal regions is about three times higher than the global average (Small and Nicholls, 2003). Therefore, hypoxia may have a significant socio-economic cost in the coastal zones, with negative consequences on human activities from local to international level (Mee, 1992). The deterioration of water quality causes a loss of value for recreational activities and tourism, as well as a threat for human health. The alteration of benthic invertebrate and bottom fish communities often led to a replacement of highly valuable benthonic fishes with less desirable planktonic omnivores (Caddy, 1993; Wu, 2002; Diaz and Rosenberg, 2008). Strong hypoxia may also cause an impoverishment of bottom fauna that in extreme cases lead to a complete defaunization (Wu, 2002; Vaquer-Sunyer and Duarte, 2008; Stachowitsch, 2014).

The Emilia Romagna Coastal Zone (ERCZ) is a key area in the NAd to study the relationships of hypoxia with meteorological forcing, river inputs and oceanographic conditions. This shallow coastal ecosystem is characterised by a large river discharge of nutrients and organic matter (Marchetti and Verna, 1992; Cozzi and Giani, 2011) and by highly variable meteorological conditions, which modulate its hydrology and biogeochemistry (Zoppini et al., 1995; Artegiani et al., 1997; Ursella et al., 2007). As a result, eutro- and hypertrophic conditions were observed to cause, since the 1970s, an increased frequency of hypoxia and anoxia (Montanari et al., 1984; Rinaldi and Montanari, 1986). This serious degradation of the coastal marine environment pointed out the need of a better assessment of the dynamics of this ecosystem, which is still underway, in order to plan a more effective mitigation of the anthropogenic pressure in the area (Vollenweider et al., 1992).

The aim of this study was to analyse and compare time-series of environmental data and observations carried out in the ERCZ in order to better understand seasonal behavior and long-term evolution of hypoxia (DO = 1-3 mg L^{-1}) and strong hypoxia (DO < 1 mg L^{-1}). The records of hypoxia occurrence and extension in 1977-2008 were compiled in a dataset, which was afterwards compared to the time-series of meteorological parameters, river loads and oceanographic characteristics of surface coastal waters. The long-term evolution of coastal hypoxia was also analysed with respect to the information recently published in the literature concerning the trends of runoff (Cozzi and Giani, 2011), ecosystem and sea floor conditions (Giani et al., 2009; Giani et al., 2012; Alvisi et al., 2013) and offshore hypoxia in NAd pelagic and benthic compartments (Djakovac et al., 2014; Stachowitsch, 2014).

2. Materials and methods

2.1 Study site

The ERCZ is located along the NW Adriatic Sea (Fig. 1), extending approximately 130 km from the Southern edge of the Po Delta (44.8 lat. N) to the town of Cattolica (43.9 lat. N). The beaches and the coastal shallow shelf sediments are sandy until 1 km off the coastline, whereas offshore sediments are progressively enriched in mud (Frignani et al., 2005). The bathymetry is characterised by a very low gradient up to 20 km off the coast (1 m km^{-1}), with the exception of the inner belt where the 5-m bathymetric line is parallel to the shoreline at 1 km offshore (Correggiari et al., 2005).

The hydrological characteristics of this area are mainly affected by the presence of the coastal front originated by the spreading of Po River plume, which is modulated by meteorological conditions and intensity of the Southward flowing Western Adriatic Current (WAC; Cushman-Roisin et al., 2001; Ursella et al., 2007). However, the presence along the coast of several other watercourses, jetties and other human-made structures affects hydrodynamics and biogeochemical characteristics of coastal waters at a local scale (Chiaudani et al., 1980; Russo et al., 2002).

In summer, pronounced water column stratification with a 5-6 m deep thermocline usually develops under stable meteo-marine conditions. Po River plume often spread eastward, the circulation is weakened and local anticyclonic gyres are formed along the coast, causing prolonged inshore water retention. During winter, cooling periods and NE winds determine the mixing of the water column and push the haline fronts toward the coast enhancing the circulation (Vollenweider et al., 1992).

In the ERCZ, frequent eutrophic conditions originate from the large input of land-borne nutrients and dissolved organic matter (Zoppini et al., 1995; Marchetti and Verna, 1992; Cozzi et al., 2002), as well as by the resuspension and diffusion of bottom reactive organic particles (Giani et al., 2009; Alvisi et al., 2013). As a result, the ERCZ is the most productive area in the NAd, holding intense fishery and large fish and shellfish farming activities. However, since the 1970's, these characteristics also favored the development of recurrent dinoflagellate blooms, mucilage phenomena and hypoxia (Rinaldi and Montanari, 1988; Vollenweider et al., 1992; Rinaldi et al., 1995).

Fig. 1

2.2 Hypoxia records

Since 1977, after a period of exploratory studies, the Daphne Oceanographic Structure of ER Regional Environmental Protection Agency (ARPA-ER; URL: http://www.arpa.emr.it/daphne/) established a regular monitoring network in order to evaluate the rise of the eutrophication in this area. The number of monitoring stations increased in 1977-1983 as to cover the whole coastal area with a network of 34 stations sampled weekly throughout the year (Fig. 1). The presence of hypoxic conditions was assessed through CTD casts, water sampling and visual observations. Based on this activity, a description of hypoxic events was included in the Annual Report Series "Eutrophication of the coastal waters of the Emilia Romagna". The analysis of these reports allowed the compilation of a dataset on timing and extension of hypoxia in 1977-2008. Moreover, two levels of hypoxia were distinguished in the reports: concentration of DO = 1-3 mg L^{-1} was referred as hypoxia, while concentration of DO < 1 mg L^{-1} was considered as strong hypoxia, a condition that may include anoxia in bottom waters, death or mass migration of marine organisms, as well as formation of toxic chemical compounds in the water column (Wu, 2000). The records of ERCZ hypoxia were used: (i) to analyze the spatial and temporal dynamics of this phenomenon in 1977-2008 and (ii) to perform distinct statistical analyses of other available environmental parameters in presence/absence of hypoxia.

2.3 Time-series of meteorological and hydrological data

Weather conditions in ERCZ were analysed using the data acquired in 1989-2008 at the Pradon Porto Tolle station (44°54.99' Lat. N, 12°22.16' Long. E; 3 m AMSL) by the Meteorological Centre of Teolo - Regional Environmental Protection Agency of Veneto Region (ARPAV; URL: http://www.arpa.veneto.it/). Hourly averaged data included air temperature (T_A; C), precipitation (P; dm^3 m^{-2} h^{-1}), wind speed (W_S; m s^{-1}) and wind direction (W_D; 16 sectors). This time-series covered 7305 days, 974 of which (13% of the data) concomitant to hypoxia in the ERCZ.

Daily average flow rate (m^3 s^{-1}) of Po River at Pontelagoscuro station (44°52.67' Lat. N, 11°36.32' Long. E; 8 m AMSL) were provided by the Ufficio Idrografico e Mareografico of Parma and by the Servizio Idrometereologico of ARPA-ER for the period 1977-2008. This station is 91 km far from the river mouth, but it represents the closing point of the Po drainage basin (71057 km^2) and the best available estimate of the total amount of freshwater that is discharged through the several branches of its delta (Fig. 1). The time-series of Po River flow covered 11688 days, 1779 of which (15% of the data) concomitant to hypoxia. A compilation of available data on nutrient transport by the Po and ERCZ minor rivers was also performed in order to evaluate their influence on coastal ecosystems.

2.4 Monitoring of coastal waters

Hydrological and chemical characteristics of ERCZ surface waters were obtained for the period 1981-2008 by the Annual Reports of ARPA-ER and by the database of Si.Di.Mar. (Sistema Difesa Mare; URL: http://www.sidimar.tutelamare.it/), which is supported by the Italian Ministry of the Environment and Protection of Land and Sea (MATTM).

The oceanographic dataset analysed in this study included CTD parameters and seawater samples (~ 15700 data) collected at each station at 0.5 m of depth. Therefore, these data are representative of the entire water column at inshore stations (3-5 m water depth) and of the upper layer at intermediate and offshore stations (10-27 m water depth). The sampling was carried out weekly, in a number of stations that progressively increased from 8 to 19 in 1981-1990. Afterwards, this network was almost constantly maintained until 2008, covering a coastal belt from 0.5 to 20 km off the coast (Fig. 1).

Seawater temperature (T_{SW}; C), salinity (Sal; psu), chlorophyll "a" (Chl a; µg L^{-1}) and dissolved oxygen concentration (DO; µmol O_2 L^{-1}) were obtained by multi-parametric CTD probes. DO saturation (DO_{sat}; %) was recalculated in the present study according to Benson and Krause (1984). The concentration of nitrate (NO_3^-; µmol N L^{-1}), ammonium (NH_4^+; µmol N L^{-1}) and reactive phosphorus (PO_4^{3-}; µmol P L^{-1}) were determined using standard colorimetric methods applied to auto-analyzer laboratory systems equivalent to those reported in Grasshoff et al. (1999). The N/P molar ratios were calculated as $(NO_3^-+NH_4^+)/PO_4^{3-}$. On the basis of the comparison with hypoxia records, 2660 oceanographic data (17 % of the total) were collected during period of hypoxia.

All time-series of environmental parameters were analysed by non-parametric statistics, grouping the data for presence/absence of hypoxia. Long-term trends were assessed by the analysis of data annual distributions, which do not include repetitive seasonal cycles, using the non-parametric Mann–Kendall Z-test (MKT), whereas the slope of these linear models was estimated by the Sen's test.

3. Results

3.1 Frequency and extension of hypoxia

Over the whole investigated period, hypoxia was recorded at least once at all sampling stations, included those located 20 km offshore (Fig. 2a). The highest number of events was observed in the inner zone South of Po Delta, with a maximum of 97 records. Other zones with frequent hypoxia were located close to Ravenna (n = 64) and Cesenatico (n = 36). The area south of Rimini was gradually less affected by hypoxia until to reach the minimum occurrence in front of Cattolica (n < 9). The temporal distribution of hypoxia showed the presence of a clear annual cycle (Fig. 2b) with a scarce number of events in January - April for both hypoxia (n < 7) and strong hypoxia (n = 1). In June – August, their frequency increased up to the maximum (n = 48) and remained high also in September – October. In November and December, hypoxic events become again less frequent.

Fig. 2

The analysis of the annual frequency of hypoxia indicated that this phenomenon was highly variable in ERCZ across the whole study period (median = 72 d yr^{-1}, range = 23-199 d yr^{-1}). However, two distinct periods were detected by the analyses of periodicity and duration of this phenomenon (Tab. 1):

a) In 1977-1988, hypoxia was basically absent in January-May and in December, but it was frequent in June-November. In these years, the occurrence of strong hypoxia was about half of the frequency of hypoxia (sHy/Hy ratio ~ 0.6) and both types of events were characterised by rather long durations (median from 5 to 8 days). In several cases, hypoxia persisted in the coastal waters for the entire considered month.

b) In 1989-2008, the presence of hypoxia extended to almost all the seasons. In late winter and early spring, the events were not frequent, although they were sometimes characterised by an extremely long duration (up to 31 days). Hypoxia was still frequent from June to November, but it showed a shorter duration (median values 2-6 days) compared to the previous period. Another difference was the increase of the occurrence of strong hypoxia compared to that of hypoxia in summer and in early autumn (sHy/Hy ratio ~ 1.2).

Tab. 1

3.2 Hypoxia and meteorological conditions

The meteorological dataset available for this study covers the second identified period for hypoxia (1989-2008) and thus it can be compared to the more recent dynamics of this phenomenon. Monthly distribution of air temperature clearly showed a pronounced annual warming, with an increase of median values from 3.1 C in January to 23.6 C in August (Fig. 3a). For most of the year, the presence of hypoxia was associated with positive anomalies of T_A (1.1-3.6 C; Fig. 3b) except for August - October, where hypoxia occurred with air temperatures closer to normal values (ΔT_A from -0.2 to 0.7 C). The strong negative temperature anomaly observed during hypoxia in April (-1.2 C) was considered not significant as this value originated by the low number of events recorded in this month (n = 3) and by the presence of a prolonged hypoxia occurred in 1993 in concomitance to low T_A (7.3-15.9 C).

Fig. 3

Over the same period, the precipitation was absent at Porto Tolle during 67% of the time and lower than 1 dm^3 m^2 d^{-1} during 14% of the time, although peaks of rainfall up to 120 dm^3 m^2 d^{-1} were observed (Fig. 4). Hypoxia frequency was 13.5% during the days without rainfall and it decreased almost progressively from 16.0% to 5.2% with an increase of precipitation up to 7 dm^3 m^2 d^{-1}. Above this value, hypoxia was observed with a variable frequency (10.9-14.0%) because of the low number of events recorded in these precipitation classes.

Fig. 4

The wind speed showed the highest frequency in the range 0.5-3.0 m s^{-1} (83.1% of the time; Fig. 5), whereas it was weaker than 0.5 m s^{-1} in 2.3% of the cases and, similarly, it was rarely present in the range 5.0-12.7 m s^{-1}. Hypoxia mostly occurred during the days characterised by winds weaker than 2.0 m s^{-1} (12.5-17.4%) and its frequency decreased almost constantly with the increase of wind speed.

Fig. 5

The wind direction showed a very high variability with changes of regime from seasonal to hourly scales. Despite this high variability, the analysis of the prevailing direction concomitant to hypoxia in ERCZ showed significant differences among the seasons (Fig. 6). N-NE winds were associated to hypoxia in all the seasons, with a maximum frequency in winter (31.7 %) and a minimum frequency in summer (19.7 %). During winter, all the other wind directions were scarcely related to the presence of hypoxia. In spring and summer, hypoxia was also common with winds blowing from the sea toward the coast as NE-S sectors represented 54.6 % and 50.1 % of the cases, respectively. On the contrary, in autumn the distribution of wind direction was opposite to the spring and summer ones, with a higher frequency of hypoxia (39.2 %) associated to winds from land to sea. (NW-SW).

Fig. 6

3.3 Effects of river loads

In 1977-2008, Po River discharge was in the range of 168-9520 m^3 s^{-1}, with a median value of 1170 m^3 s^{-1}. Hypoxia in the ERCZ occurred in presence of river flows ranging from 169 to 8010 m^3 s^{-1}, with distinct seasonal distributions in the periods identified in Tab.1 (Fig. 7).

Fig. 7

In 1977-1988, a relatively low hypoxia frequency (1.7-5.3%) was observed in spring at normal or moderately high river water discharges (1600-4200 m^3 s^{-1}). Hypoxia was much more common in summer, with the highest frequency being reached during dry periods (27.5% for 400-600 m^3 s^{-1}). The trend in autumn was opposite to the summer one, showing a high frequency of hypoxia during high river discharges (> 5000 m^3 s^{-1}).

In 1989-2008, hypoxia spread across all the seasons and over a large range of river water flow. In winter, hypoxia occurred up to 3.5% of the cases at normal flows. In spring it was much more frequent than in the previous period and related in particular to high river flow rates (2000-3800 m^3 s^{-1}). In summer and autumn, hypoxia was frequent respectively at low and high river flows, similarly to the previous decade.

Several watercourses contribute to the delivery of nutrients and dissolved/particulate organic matter to the ERCZ (Fig. 1). The inventory of the available literature indicated a Po River transport of DIN and PO_4^{3-} respectively in the range of 49-190·10^3 t N yr^{-1} and 1.4-5.4·10^3 t P yr^{-1} since the early 1970s (Tab. 2). By the comparison between TN and TP with nutrient data, we can estimate that organic N and P constituted respectively about 40% and 60% of the total pool of these elements in 1995-2007. In the case of Po River, the transport of SiO_2 was in the same order of magnitude as that of nitrogen.

Little information is available for the other ERCZ rivers (Tab. 2). A detailed analysis published by Marchetti and Verna (1992) showed that the most important sixteen watercourses located from Po di Volano to Tavollo accounted for 30100 t N yr^{-1} and 2200 t P yr^{-1}, for TN and TP respectively, with the most important contribution observed in the Northern zone due to the presence of Po di Volano and Reno rivers. Therefore, the contribution of the minor ERCZ rivers during the 1980s should have accounted for ~ 20% of Po River transport even though their loads are highly variable, due to the their torrential character.

Tab. 2

3.4 Oceanographic characteristics of surface coastal waters

The analysis of monthly distributions of oceanographic data indicated that hypoxia occur in ERCZ under different surface waters conditions according to different seasons. In winter, early spring and late autumn, hypoxia was characterised by unusual high seawater temperature and low salinity (Fig. 8a,b), with the largest differences (ΔT_{SW} =

1.9 C, ΔSal = -11.1) being observed in February and December, respectively (Tab. 3). These warmer and fresher surface waters were strongly enriched in biomass (ΔChl a up to 31.8 μg L^{-1}) and nitrate (ΔNO_3^- up to 16.9 μmol N L^{-1}). PO_4^{3-} showed a seasonal distribution similar to that of NO_3^-, but its concentration in autumn was lower during hypoxia with respect to the periods in which this phenomenon was absent (Fig. 8g). NH_4^+ was less abundant in seawater during winter and autumn hypoxia (ΔNH_4^+ down to -1.0 μmol N L^{-1}), although the annual trend of this nutrient was not characterised by a clear seasonal cycle.

Fig. 8

Tab. 3

Summer hypoxia occurred in concomitance to opposite characteristics of the surface waters with respect to the other seasons. Seawater temperature was at its highest, but temperature anomalies during hypoxia were minimum (Fig. 8a). This feature was common to that previously observed for air temperature (Fig. 3). Summer hypoxia was still characterised by the presence of fresher water (ΔSal > -3.0) and higher biomasses (ΔChl a up to 2.9) in the upper layer, but these differences were not pronounced like in spring and autumn. The concentrations of NO_3^- and NH_4^+ were low in summer surface waters and similar to those usually found during this season, whereas the availability of PO_4^{3-} was slightly higher during hypoxia (ΔPO_4^{3-} up to 0.019 μmol P L^{-1}).

The annual oscillation of N/P ratio was consistent with the changes of DIN and P availability (Fig. 8h). The highest DIN excess in February-April and October-December concomitant to the largest spreading of river waters increased N/P ratio during hypoxia from 46 to 227 above the values without hypoxia. In June - August, nutrient depletion in surface waters caused an overall decrease of N/P ratios, with little differences in presence of hypoxia (-9 to 11).

DO saturation in surface waters did not show a clear annual cycle, although hypoxia were often associated to a high oxygen saturation in surface waters, a feature that is consistent with the presence of intense phytoplankton blooms (Fig. 8d). The particularly high values of DO observed in February - March were the result of the few events recorded during these months, which included two long periods of hypoxia in 2001 and 2002. Similarly, the low values of DO saturation in December were mainly originated by one strong hypoxia in 1994 (Tab. 1).

3.5 Long-term trends of environmental conditions

The analysis of annual data distributions, which are detrended by the repetitive seasonal cycles, indicated the presence of significant long-term changes of environmental parameters in the ERCZ.

For the meteorological parameters, an increase of annual median values of air temperature (+0.14 C yr^{-1}, $p < 0.01$) was observed during the second period of hypoxia in 1990-2008 (Tab. 4). An increase of wind speed was also observed (+0.03 m s^{-1} yr^{-1}, $p < 0.05$), mainly as a consequence of the high values recorded since 2001 (Fig. 9). The annual integrated precipitation was scarce in 1989-1994 (< 666 mm yr^{-1}) and strongly variable in the following years without a clear trend.

Tab. 4

Po River water discharge was constantly high in the early years 1977-1988 and it strongly oscillated afterwards, with low regimes recorded in 1989-1990, 1997-1999 and 2003-2007 (Fig. 9). On the whole, this behavior corresponded to a flow rate decrease of 0.54 km^3 yr^{-1} ($p < 0.05$). Long-term trends of Po River nutrient load were also assessed by the analysis of the available literature (Tab. 2). The river transport of DIN has increased threefold from 1968 to 2007, mainly due to the great increase of NO_3^-, whereas the PO_4^{3-} transport did not increased comparably, thus making the N/P ratio very unbalanced in the riverine inorganic pool. In addition, it should be noticed that the recent sharp fluctuations of river flows have determined total annual nutrient inputs up to three times higher in wet years than in dry years (Cozzi and Giani, 2011).

Fig. 9

The oceanographic properties of ERCZ surface waters were highly variable across the whole investigated period (Tab. 4) with peaks of concentration at least 10-time higher than the median values observed every year for all the parameters. Seawater temperature and salinity were in the range 2.3-30.3 C and 6.0-38.7, respectively. The coastal waters were often enriched in NO_3^- (Q_3 = 22.4 μmol N L^{-1}) and chlorophyll a (Q_3 = 10.0 μg L^{-1}), whereas the concentrations of NH_4^+ and PO_4^{3-} were not systematically high (Q_3 = 2.64 and 0.20 μmol L^{-1}, respectively). As a consequence, the range of values of N/P ratio was extremely wide, in particular during periods of overload of DIN and depletion of PO_4^{3-}.

Despite this high variability, long-term trends were detected also for the parameters in the surface seawater: a) a salinity increase took place in 1981-2008, corresponding to an increment of 0.09 yr^{-1} (Fig. 9); b) oxygen saturation increased in 1981-1986 and then decreased by -0.2 % yr^{-1} ($p < 0.001$); c) the concentrations of NH_4^+ and PO_4^{3-} decreased during the whole considered period (Fig. 10) and, coupled to an absence of trends in NO_3^-concentration, determined a long-term increase of N/P ratio of 2.6 yr^{-1} ($p < 0.01$); d) no significant trends were detectable for seawater temperature and Chl a concentration over the whole period, although lower concentrations of Chl a were observed since 2003.

Fig. 10

4. Discussion

In the ERCZ, periodic and intense eutrophication events driven by nutrient-rich river loads take places leading to well-known unpleasant effects such as strange water colour, bad smell and oxygen deficiency (Montanari et al., 1984). These phenomena usually begin after intense precipitation over Northern Italy that cause the increase of the flows of the

Po and the other minor rivers draining the Northern Apennines, which carry large amounts of nutrients and favour the algal blooms. If stable meteo-marine conditions are present along the coast, these blooms are further enhanced by the water stratification and by the spreading of the coastal front. Afterwards, the biomass quickly falls along the shallow water column and, by reaching the benthic compartment, causes high oxygen consumptions due to bacteria remineralisation. In the presence of prolonged stable conditions, oxygen is rapidly depleted leading to hypoxia/anoxia, a condition that causes mass mortality of the benthic community (Rinaldi and Montanari, 1988).

In this study, the compilation of hypoxia records indicated a long-term presence of a N-S gradient of diffusion of hypoxia (Fig. 2), with a more affected area between the Po delta and the Ravenna and an adjacent area of influence that seems subjected to hypoxia mainly as a consequence of lateral advection of bottom waters, as already shown by previous studies (Montanari et al., 1984; Rinaldi and Montanari, 1988). A second gradient is present from land to sea as hypoxia develops more frequently 1-3 km from the coast, but it is transported near shore to compensate the offshore surface current pushed by Westerly winds (Libeccio and Ponente; Vollenweider et al., 1992). This coastal upwelling of hypoxic waters was identified as responsible of the almost complete disappearance of the near shore oxygenated water belt where generally benthic organisms shelter to temporarily survive hypoxia (Rinaldi et al., 1993). Following the classification of Diaz and Rosemberg (1995), the early period of hypoxia in the ERCZ can be mainly classified as seasonal, with most of the events being observed in summer and autumn. In the second period, hypoxia become periodic (i.e. with intervals shorter than a year), although it is not related in ERCZ to tidal cycles as in other coastal oceanic areas (Haas, 1977). ERCZ hypoxia appears to be otherwise modulated by a combination of irregular oscillations of the environmental conditions.

4.1 Seasonal cycle of temperature and hypoxia in ERCZ

The rise of temperature has several physical effects favoring hypoxia as it reduce the thermodynamic solubility of DO in seawater (-4.76 μM O_2 C^{-1} for T_{sw} = 0-40 C at salinity = 35.0 on average; Benson and Krause, 1984), leading to a de-oxygenation that can be particularly rapid in shallow shelf systems like the ERCZ. Moreover, once the relationship of DO versus T_{SW} is nonlinear, with the greatest de-oxygenation occurring at low temperature, the stress due to oxygen reduction is more pronounced during the coldest seasons than in summer. In addition, high water temperatures favors the development of thermoclines and increases the isolation of the deeper layer, where benthic respiration can cause high DO consumptions especially in the presence of reactive organic-rich sediments (Alvisi et al., 2013). Seawater warming also indicates a high irradiance that stimulates the production of phytoplankton and enhances the accumulation of the biomass (Wu, 2002; Zhang et al., 2010).

The temperature also plays several biological effects on marine organisms that may have direct consequences on hypoxia. Even if the metabolism of autotrophic plankton is generally though to be scarcely affected by temperature, the climate warming can cause shifts in the structure of plankton communities and in blooming periods, in particular in areas characterised by a high seasonality like the NAd (Fonda-Umani et al., 2012). On the other hand, bacterial activity is more dependent by the temperature, included the anaerobic decomposition of organic matter in surface sediments (Matsui et al., 2013). Metabolic rates and respiration of marine organisms increase with the temperature and this process causes a concurrent stress that decreases their tolerance to hypoxia (Vaquer-Sunyer and Duarte, 2008). The control of grazers on phytoplankton can then increases with the temperature, contributing to the shift of eutrophic ecosystems towards heterotrophy (O'Connor et al., 2009). Moreover, seasonal warming in shallow areas like the NAd also involves the bottom waters, thus directly affecting nutrient fluxes, biomass growth and oxygen consumption in the benthic compartment (Bertuzzi et al., 1997; Alvisi et al., 2013).

The present analyses of air and seawater temperatures suggests that summer warming in ERCZ is usually strong enough to make hypoxia a phenomenon scarcely dependent by temperature anomalies, whereas periods of unusual warming significantly stimulate its appearance during the other seasons. Therefore, a further extension of hypoxia over the whole year due to climate warming should be expected in this area.

4.2 Role of meteorological forcing, runoff and circulation on hypoxia

The analyses of precipitation (Fig. 4) and wind speed (Fig. 5) suggest that hypoxia is often favored by stable weather conditions, which determine a weak circulation and a reduced mixing. During these periods, the increase of residence time of bottom waters along the coast and their isolation from the atmosphere take place favoring the oxygen consumption in the benthic compartment (Vollenweider et al., 1992; Boldrin et al., 2009; Alvisi et al., 2013). However, hypoxia was seldom observed during few extreme precipitation events suggesting that high river water and nutrient loads can enhance this phenomenon, at least at a local scale, even in bad meteo-marine conditions. It should be also considered that the linkage between precipitation and river loads is not simply in the ERCZ. Po River flow is modulated by the overall pattern of precipitation in N Italy and it is characterised by a delay of few days between rainfall and water discharge at the delta mouths. For other minor watercourses along the coast, the linkage between peaks of precipitation and high river discharges is much closer due to the limited extension of their drainage basins. (Marchetti and Verna, 1992; Palmeri et al., 2005).

The analysis of hypoxia frequency as a function of wind direction further highlighted distinct processes involved in the seasonal dynamics of this phenomenon (Fig. 6). N-NE wind (Bora) favors coastal hypoxia during all the seasons, with a particularly prevalence in winter, since it enhances the intensity of the WAC and reinforce the NAd cyclonic circulation at a basin scale with a consequent compression of river plumes toward the ERCZ and their confinement in a null-point water circulation to the South of Po Delta (Cushman-Roisin et al., 2001). Moreover, it is known that Bora wind can also mix weakly-stratified water columns down to a depth of 20-25 m, thus inducing the resuspension of bottom sediments with large releases of nutrients and reactive organic-rich bottom sediments in seawater (Book et al., 2007; Boldrin et al., 2009).

NE-S winds, which blow towards the Italian coast, are connected to hypoxia in spring and summer, as they tend to maintain the river plumes inshore. Among these winds, the Sirocco (SE) was found to have a slow down effect of the WAC intensity and thus to increase the water residence time in the ERCZ (Ursella et al., 2007; Solidoro et al., 2009). Winds blowing seawards, such as Maestro (NW) and Libeccio (W), favor hypoxia almost only in autumn, when hypoxic bottom waters developed offshore in consequence of river freshets are recalled close to the coast as compensation of the current induced by the wind at the surface (Vollenweider et al., 1992; Giani et al., 2009),

4.3 Nutrient enrichment and biomass accumulation

ERCZ is characterised by several entry points of continental waters, whose contribution is superimposed to the main coastal front generated by the Po (Marchetti and Verna, 1992; Ursella et al., 2007). This condition determines the formation of coastal fronts with a complex 3D structure, where nutrient patterns primarily follows the distribution of fresher waters (Cozzi et al., 2002). The cumulative effect is a direct fertilization by Po River in the northern zone that is often reinforced up to 400-500 m from the coast by the other watercourses in the southern sector (Vollenweider et al., 1992). In particular, 90% of the total freshwater input in the ERCZ is delivered within the northernmost 30 km of the coast, between Po delta and Ravenna (Montanari and Rinaldi 1983a, Rinaldi et al. 1995).

The data shown in this study indicate that extreme increases of nutrients are frequent in this area (Tab. 4). However, the highest levels of concentration are probably connected to temporary local discharges of continental waters as, when the whole distributions of values are considered, only the concentration of NO_3^- systematically exceeds the values reported for surface waters in the NWAd (0-8 μmol N L^{-1}; Solidoro et al., 2009). This feature indicates that eutrophication potential due to the overload of land-borne N might be even higher in the ERCZ, if it would not be limited by the P shortage (median N/P ratios from 29 to 469).

In winter, spring and autumn, hypoxia is concomitant to low salinity values and high NO_3^- and Chl a concentrations in surface waters, which clearly point to the presence of large phytoplankton blooms triggered by nutrient river input (Fig. 8). The shallow depth of the area and the weak water column stratification typical of these periods can easily favor a rapid sinking of new-formed biomass and the formation of bottom hypoxia (Vollenweider et al., 1992; Zoppini et al., 1995). Moreover, the rivers are also a source of reactive particulate and dissolved organic matter, whose remineralisation in bottom waters is an additional cause of oxygen consumption (Pettine et al., 1998; Alvisi et al., 2013). During these seasons, hypoxia is also characterised by concentrations of PO_4^{3-} and NH_4^+ lower than in the absence of the phenomenon, which cause an increase of N/P ratios (Fig. 8). This condition suggests that hypoxia occurs when NO_3^- continental loads are in excess, but the utilization of recycled N and inorganic P for the biomass growth is high.

During summer, hypoxia is matched to opposite biogeochemical characteristics of surface coastal waters, such as the depletion of all nutrients, low N/P ratios, low concentration of Chl a and values of salinity similar to those usually observed in this season. These features indicate that oligotrophic surface waters are common both in presence and absence of hypoxia and that hypoxia is mainly favored in this season by the stability of meteo-marine conditions.

The ERCZ is also a shallow coastal area where a close benthic-pelagic coupling drives the evolution of hypoxia. Bottom sediments, mostly sandy mud and clay, are a local reservoir of reactive organic matter and nutrients. Their release in the water column is not directly connected to the processes in the upper layer and therefore it can contribute to maintain eutrophic conditions in the marine environment during periods of scarce mixing (Bertuzzi et al., 1997; Alvisi et al., 2013; Stachowitsch, 2014).

4.4 Long-term changes of hypoxia in NAd and ERCZ

The NAd has been affected in the past by recurrent hypoxia and anoxia, both at offshore and coastal locations. In large open shelf areas, oxygen crises were reported in 1949, 1977, 1983, 1988, 1989 and 2006. These events were concomitant to a general decline of oxygen concentration in bottom waters in 1970-1980 followed by a re-oxygenation in 1990-2012 (Orel et al., 1986; Šimunović et al., 1999; Degobbis, 1989; Giani et al., 2012; Djakovac et al., 2014). Coastal hypoxia was observed in the Gulf of Rieka in 1973 (Orel et al., 1986) and in the Gulf of Trieste almost every year in 1974-1990, with the most destructive anoxia in 1983 (Stachowitsch, 1991; Aleffi et al., 1992; Turk et al., 2007). Recurrent low oxygen levels were inferred since the 1960s in the Po delta offshore area by benthic foraminifers' records (Barmawidjaja et al., 1995) and reported in the lagoon of Venice at the beginning of the 1990s (Tagliapietra et al., 1998). The benthic compartment of NAd was also impacted by hypoxia and anoxia at different levels, which range from the alterations of sediment biogeochemistry to mortality rate, species selection and behavioral response of benthic fauna (Stachowitsch, 2014; and references therein). During the 1980s, hypoxia was also observed in Kastela Bay (Marasović, 1989) and Krka estuary (Legović, et al., 1991) in the Central Adriatic. Despite literature records of hypoxia are affected by uncertainty, these studies indicated an increase of hypoxia frequency in 1950-1990, both in coastal and offshore areas of the NAd followed by its reduction at least in the Central and Eastern areas.

The present study indicated that the ERCZ, the most eutrophic of NAd, was frequently affected by hypoxia over the whole considered period with a clear long-term change of its seasonal character (Tab. 1). During the early-identified period (1977-1988), hypoxia was more frequent than strong hypoxia and, although both events were widespread and persistent, they were mainly observed in summer and autumn. This seasonal character was lost in the most recent period. Since the 1990s, hypoxia resulted exacerbated by its extension over almost the whole year, indicating that highly degraded conditions were frequently and rapidly reached in this coastal area, although now meteo-marine conditions make this phenomenon more localized and shorter.

This evolution of hypoxia in the ERCZ is consistent with the complex long-term changes recently reported for NAd ecosystem. The seasonal and long-lasting hypoxia observed until the late 1980s could have been easily favored by the pronounced air warming observed in the Southern Europe in this period (Alcamo et al., 2007), by the constantly high Po River annual loads until 1988 (Fig. 9), by the two-fold increase of N and P transport by Po River from the first available estimates in 1968 to the late 1980s (Tab. 2) and by the large Po River load of dissolved and particulate organic carbon (Pettine et al., 1998).

Since the 1990s, several changes were observed in the NAd ecosystem such as a further enhanced climate warming and a wide oscillation of Po River load, with recurrent periods of low regime leading to a reduction down to ~ 50 % with respect to the average (Cozzi and Giani, 2011). The anthropogenic N emission still increased in this period (Tab. 2), but that of P decreased as a consequence of phosphate reduction in the detergents introduced in 1986 by Italian regulation (Marchetti et al., 1989; Palmeri et al., 2005). These changes caused the increase of seawater temperature, the decrease of surface salinity, the decrease of PO_4^{3-} and NH_4^+ concentrations (Solidoro et al., 2009; Giani et al., 2012) as well as the decrease of Chl a concentration (Mozetič et al., 2010) in the NW Adriatic waters. The ERCZ was subjected to similar changes (Tab. 4), such as a long-term increase of air temperature, salinity in surface waters and wind speed since the 2000s (Fig. 9). On one hand, the climate warming can easily have favored the spreading of hypoxia across the seasons, but on the other, a more dynamical wind regime might have contributed to the recent shortening of the duration of this phenomenon, due to its effect of mixing of the water column. A decrease of NH_4^+ and PO_4^{3-} concentrations and the shortage of P compared to N suggest a positive reduction of the trophic level in ERCZ that, in turn, may explain the reduction of oxygen super-saturation at the surface. However, they do not seem to have had a substantial effect on standing stocks of biomass and on the reduction of hypoxia, which still remain a frequent phenomenon, probably due to the contribution of remineralisation activity on the sea floor (Giani et al., 2009; Alvisi et al., 2013).

5. Conclusions

The comparison of time-series of meteorology, runoff and oceanographic properties of coastal waters performed in this study provided useful information on seasonal mechanisms and long-term changes of hypoxia in the ERCZ, that are consistent to those recently detected in the NAd. This analysis showed that the ERCZ is still exposed to the threat of hypoxia and of deterioration of the coastal marine environment, although the largest problem due to eutrophication observed in the past seems to be mostly over. The following points were highlighted:

- a N-S decreasing gradient of hypoxia frequency is present in ERCZ, with the most affected area being located south of the Po Delta, due to the coupled effects of river loads and morpho-hydrodynamics. A second gradient is present from land to sea, with the most affected zone at inshore locations;
- hypoxia is favored by stable weather conditions and by wind regimes that weaken the circulation in the area and confine the river plumes inshore (Bora and Scirocco) or that cause the upwelling of offshore bottom hypoxic waters along the coast (Libeccio);
- despite these common forcing factors, the analysis of seasonal processes indicated that hypoxia is favored by two opposite sets of environmental conditions: 1) in winter, spring and autumn, hypoxia occur in the presence of low air/water temperatures, highly positive temperature anomalies, high river loads and surface coastal waters characterised by a low salinity and a high concentrations of nutrients and biomass; 2) summer hypoxia is characterised by high air/water temperatures, low temperature anomalies, scarce river loads and surface waters characterised by a normal salinity and low concentrations of nutrients and biomass. This finding suggested that summer hypoxia often develops during dry periods due to the presence of stable meteo-marine conditions;
- a long-term increase of salinity and oxygen saturation and a decrease of the NH_4^+, PO_4^{3-} and Chl a concentrations suggested a positive lowering of the trophic level, in the ERCZ, which is a common feature with the NW Adriatic;
- this lowering of the trophic level and a more dynamic wind regime might have contributed to the shift from widespread seasonal hypoxia to local irregular hypoxia. However, the contrasting effects of irregular runoff and air warming might have caused the spreading of hypoxia across the year and the increase of the frequency of strong hypoxia.

On the whole, the present study suggests that the response of coastal marine ecosystems to regional climate changes may have unexpected consequences on the dynamics of hypoxia, even if in presence of a positive long-term mitigation of the anthropogenic pressure. For this reason, the management of coastal zones should better consider the long-term consequences of combined climatic and human pressures, in order to plan more effective and cost-sustainable actions.

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