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"Trophic Changes in the North Adriatic Sea Since 1911: Evidence and Control"

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Please note: These are preliminary notes intended for internal distribution only.

TROPHIC CHANGES IN THE NORTH ADRIATIC SEA SINCE 1911: EVIDENCE AND CONTROL

1. RECENT EVENTS

2. A CHANGE IN DISSOLVED OXYGEN SINCE 1911 ?

3. EVIDENCE FOR A CORRESPONDING CHANGE IN NUTRIENT INFLOW

4. WHEN WILL THE PHYTOPLANKTON BLOOM PRODUCE MAXIMUM DAMAGE ON THE BOTTOM <=> THE LOWEST DO CONTENT ?

5. DAMAGE AND RECOVERY

6. CONTROL: REDUCTION OF P IN DETERGENTS

   IN 1985 FROM 8 % TO 5 %
   1986 FROM 5 % TO 2.5 %
   1988 FROM 2.5 % TO 1 %

7. ANY EFFECT OF THE CONTROL ?

8. IS A MORE RADICAL CONTROL NEEDED ?

Trends in Oxygen Content 1911–1984 and Occurrence of Benthic Mortality in the Northern Adriatic Sea

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Keywords: oxygen content; long-term changes; surface; bottom; regression analysis; benthic organisms; Adriatic Sea

Trends of dissolved oxygen content of the surface and bottom layers of the northern Adriatic Sea are analysed for the period 1911–1984. An increase in the surface layer and a decrease in the bottom layer are observed in all seasons except winter. Although the oxygen content of the water column as a whole has not changed significantly, it is inferred, from the increasing difference between the surface and the bottom layer, that the primary productivity of the northern Adriatic Sea is increasing. As the average midsummer oxygen content of the bottom layer decreases, the frequency of mass mortality in the benthic fauna is expected to increase, especially in the northern and western subareas.

Introduction

In the shallow northern Adriatic Sea, phytoplankton blooms are known to have occurred from time to time for centuries (see Fonda-Umani, 1985 for a review). Recently, extensive bloom formation has been reported more frequently. Moreover, during the last 20 years a number of investigators have observed that anoxic conditions in the near-bottom layer occur during summer in certain areas of the northern Adriatic Sea. In 1969 a dinoflagellate bloom in the coastal waters near Rimini (Figure 1) caused oxygen depletion and mass mortality of benthic fauna (Piccinetti & Manfrin, 1969). In spring 1971, a red-tide-like phenomenon was observed in the Lagoon of Venice (Voltolina, 1973). In September 1974 mass mortality of benthic macrofauna was recorded in the central part of the Gulf of Trieste (Fedra *et al.*, 1976). Similar events were observed north of Rimini in September and October 1975 (Chiaudani *et al.*, 1983*b*). In the Gulf of Trieste, mass mortality of benthic animals was again observed in September 1980 and in September 1983, when the affected area was estimated to cover about 50 km^2 (Stachowitsch, 1984; Faganeli *et al.*, 1985). Except for the reports of mass mortalities, and hypotheses that these phenomena are due to the combination of climatic and hydrologic conditions, no studies linking mass mortality to the long-term environmental changes have so far been presented.

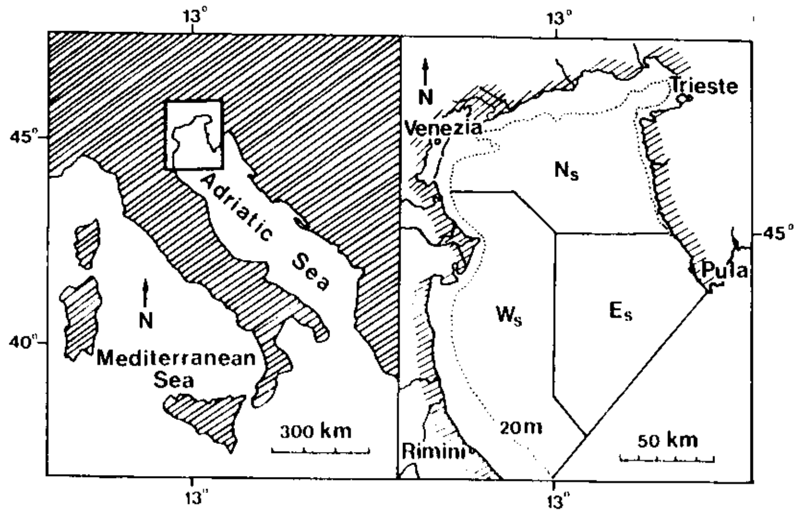

Figure 1. The investigated area of the northern Adriatic Sea. E_s, W_s and N_s indicate eastern, western and northern subareas, respectively, characterized by different hydrological properties.

In this paper the long-term trend in the oxygen content of the northern Adriatic Sea is analysed and the origin, historical development and ecological significance of this phenomenon are discussed.

Area of investigation

The northern Adriatic Sea, extending from the Gulf of Trieste southward to the Ancona-Pula line is a shallow, semiclosed basin with a mean depth of about 30 m (Figure 1). Strong freshwater discharges from the north Italian rivers and high temperature amplitudes cause great spatial and temporal variability in oceanographic properties (Grancini & Gescon, 1973; Malanotte-Rizzoli, 1977; Franco 1982). During winter, the general surface circulation pattern is cyclonic: in the surface and intermediate layers the principal current flows northward along the Yugoslav coast to the Gulf of Trieste and then westward to become an outflowing southerly current (Zore, 1956; Mosetti, 1967). Toward summer the cyclonic circulation loses its intensity and during summer it is absent. Water movements are strongly modified by northerly (bura) and southerly (jugo) winds (Mosetti & Lavenia, 1969). Distinct hydrological features also include a strong summer thermocline and a spring–autumn halocline, both of which cause a marked vertical density stratification (Franco, 1970). The winter–spring period is characterized by isothermal and isopicnic conditions (Franco, 1972). Shallowness and nutrient-rich freshwater inflow (Štirn *et al.*, 1974) make the northern Adriatic Sea one of the most productive areas in the Mediterranean (Sournia, 1973; Relevante & Gilmartin, 1976).

The northern Adriatic Sea can be subdivided into three subareas based on differing coastal inflows. The northern subarea, denoted by N_s (Figure 1) is under the influence of discharges from urban settlements, primarily Venezia and Trieste (Štirn *et al.*, 1974). The western subarea (W_s) is strongly influenced by the Po River discharge, while the eastern subarea (E_s) is influenced mainly by the oligotrophic waters of the middle Adriatic Sea. The coastal inflow to the eastern subarea is small compared to inflows into N_s and W_s (Cescon & Scarazzato, 1979).

Table 1. Sources of data on oxygen in the northern Adriatic Sea: symbols N_s, W_s and E_s refer to the northern, western and eastern subareas, respectively (Figure 1)

Data source	Investigated period	Subarea N_s	W_s	E_s
Brückner (1914)	1911–1914	*	*	*
Picotti & Vatova (1942)	1929–1933	*		
Vatova (1948)	1937–1943	*		
Picotti (1960)	1955	*	*	*
Trotti (1969)	1965–1966	*	*	*
Franco (1970)	1965	*	*	*
Franco (1972)	1966	*	*	*
Gilmartin *et al.* (1972*a*)	1972	*	*	*
Gilmartin *et al.* (1972*b*)	1973	*	*	*
Cescon & Scarazzato (1979)	1971–1973	*	*	*
Franco (1982)	1978–1979	*	*	*
Hydrographic Institute of the Yugoslav Navy (1982)	1974–1976	*	*	*
Marine Research Center – Piran (unpubl. data)	1972–1984	*		
Center for Marine Research – Rovinj, 'Rudjer Bošković' Institute (unpubl. data)	1974–1981	*	*	*

Methods

Oxygen measurements 1911–1984

Assessment of the existing data collected in the northern Adriatic Sea revealed that oxygen content, temperature and salinity data have been collected for extensive periods using identical methodology from 1911 onwards. Dissolved oxygen determinations have all been based on the Winkler technique (Winkler, 1888) which has remained unchanged from the earliest measurements. Careful examination of the reports containing the data revealed no significant differences in sample collection and treatment from one cruise to another. Hence, when using oxygen data it will be assumed that the same systematic error is introduced in different years. As the systematic error of the Winkler method is smaller than 5% (Golterman, 1983), this has been neglected.

Data sources

Original data on dissolved oxygen content have been taken from publications and unpublished data reports (Table 1). Data on temperature, salinity and Secchi-disc depth from the same sources were also used as a reference to this analysis.

Data grouping

The data were divided into four groups according to the four seasons. Analyses were performed separately for subsurface water (0·5 m below the surface) and for near-bottom water (2·0 m above the sea floor). Data from the area shallower than 20 m were not considered in order to avoid the larger variability arising from local sources. This means that for the eastern side along the Yugoslav coast only the data collected farther than 0·5 to

5 km from the coast were used. On both the western and northern sides, the 20 m isobath is between 5 and 15 km off the coast.

Analysis of trends

Linear and nonlinear regression analyses were performed. It was assumed that 1911 is the zero-point for the x-axis. From the set of potential functions (logarithmic, exponential and polynomial), a function which minimizes standard regression error (Spiegel, 1975) was chosen:

$$s=\left[\sum_{i=1}^{n}(O_{2i}-\hat{O}_2)^2/(n-k)\right]^{1/2}$$

where s is the standard regression error, O_{2i} is the ith measured oxygen content, $\hat{O}_2$ is the value of the function, n is the number of data, and k is the number of parameters of the function. The function which minimized the error was found to be linear: $\hat{O}_2=a+b\,\bar{t}$ where $\bar{t}=t-1911$. As the quantity of data was large, a 95% probability interval around the regression line was approximated by $\hat{O}_2+2s$ and $\hat{O}_2-2s$. The significance of the regression coefficient (b) was tested by a Student's t-test for $n-2$ degrees of freedom (Rohlf & Sokal, 1969).

Results

Winter

The oxygen content in the surface layer increased at the rate of 0·005 $cm^3\,O_2\,dm^{-3}\,y^{-1}$. On the other hand, no significant rate of change was observed in the near-bottom layer (Figure 2). The data scatter around the regression line remained the same throughout the investigated period. The very narrow 95% probability interval indicates low variability in the data.

Spring

The oxygen content in the surface layer increased at a rate of 0·021 $cm^3\,O_2\,dm^{-3}\,y^{-1}$, while a decrease in the near-bottom layer averaged 0·010 $cm^3\,O_2\,dm^{-3}\,y^{-1}$ (Figure 3). The width of a 95% probability interval exhibits an approximately two-fold increase when compared with a situation in winter. If the investigated period is split into two periods, 1911–1955 and 1965–1984, it is clear that the variability of oxygen content around the mean is higher for the second period.

Summer

The average oxygen content in the surface layer increased at a rate of 0·015 $cm^3\,O_2\,dm^{-3}\,y^{-1}$. In the bottom layer the oxygen content decreased at a rate of 0·030 $cm^3\,O_2\,dm^{-3}\,y^{-1}$ (Figure 4). The width of the 95% probability interval of the oxygen content in the near-bottom layer showed an approximately three-fold increase when compared with the width of the winter probability interval. Moreover, its lower limit is at the present time below 2 $cm^3\,O_2\,dm^{-3}$.

Autumn

The oxygen content increased in the surface layer at a rate of 0·012 $cm^3\,O_2\,dm^{-3}\,y^{-1}$, while the decrease in the near-bottom layer averaged 0·020 $cm^{-3}\,O_2\,dm^{-3}\,y^{-1}$ (Figure 5).

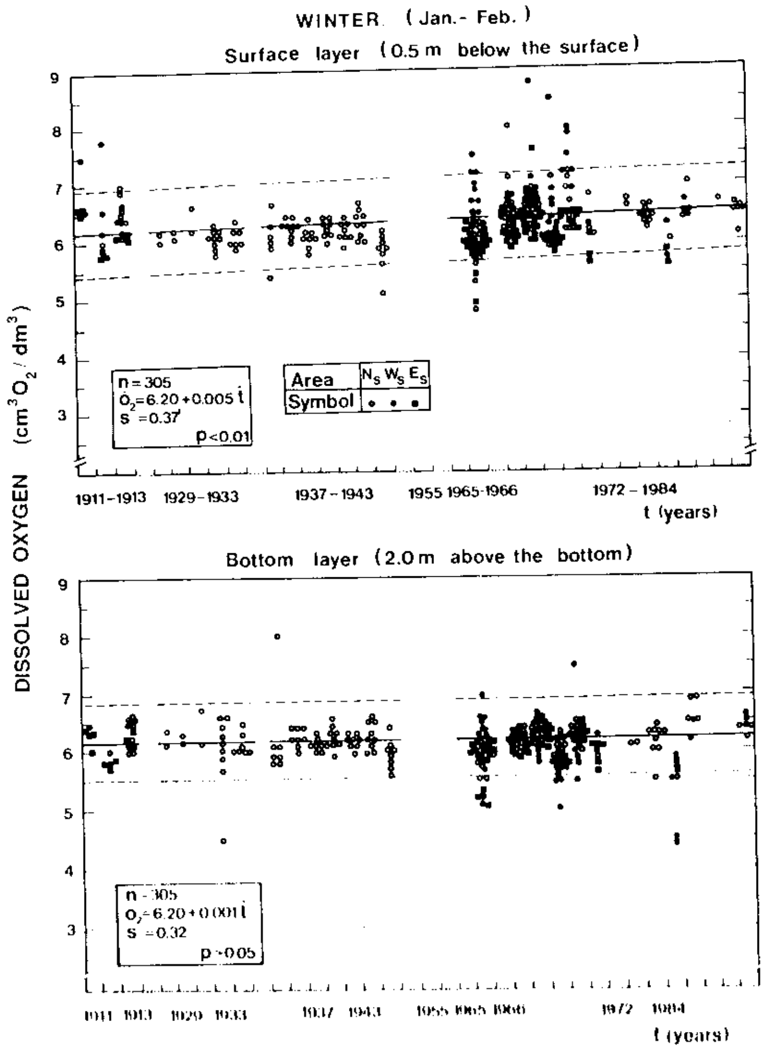

Figure 2. Oxygen content of the northern Adriatic Sea in January and February, over the period 1911–1984. Full line indicates the best fit ($\hat{O}_2$); t is taken to be zero at 1911, i.e. $\bar{t}=t-1911$; parallel broken lines are the limits of the 95% probability interval; n is the number of data points, s is the standard regression error in oxygen content, and p is the significance level. Symbols N_s, W_s and W_s refer to the data collected in the northern, western and eastern subareas, respectively. The periods without data are cut out.

Variability in the data was about four times higher when compared to probability intervals in the winter.

Mean yearly rates

Taking the slopes of the linear regression equations from Figures 2, 3, 4, and 5, the mean trend of increase of oxygen content in the surface is 0·013 $cm^3\,O_2\,dm^{-3}\,y^{-1}$, while in the

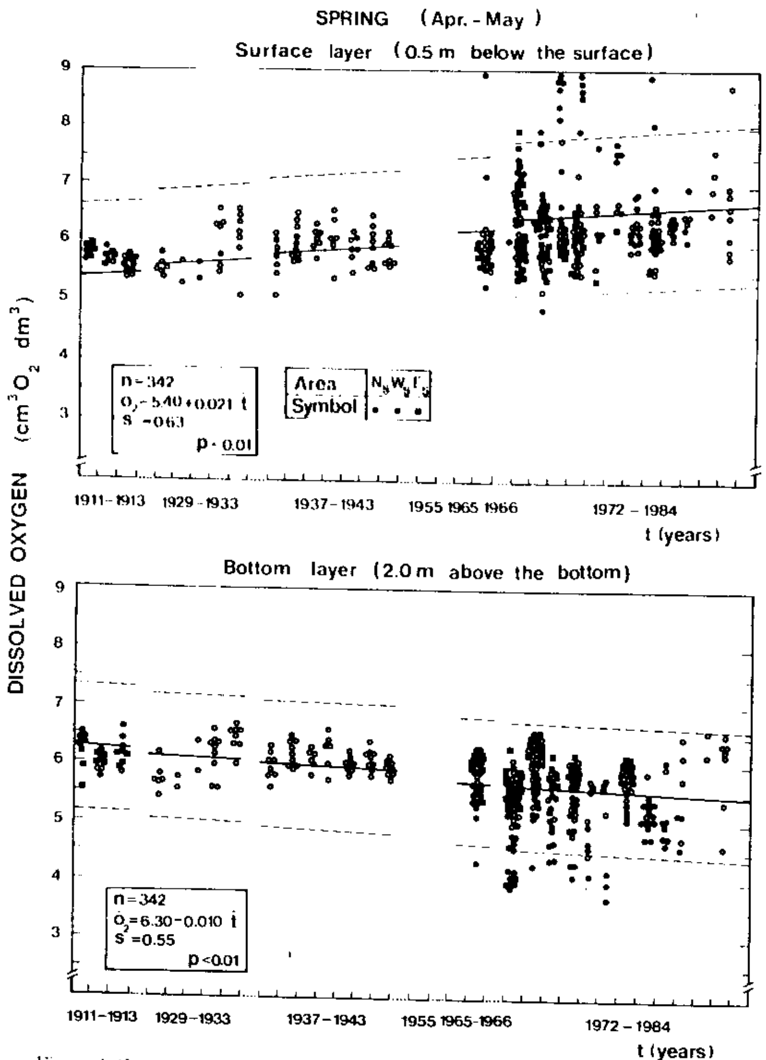

Figure 3. Oxygen content in the northern Adriatic Sea during April and May over the period 1911–1984. See Figure 2 for additional explanation.

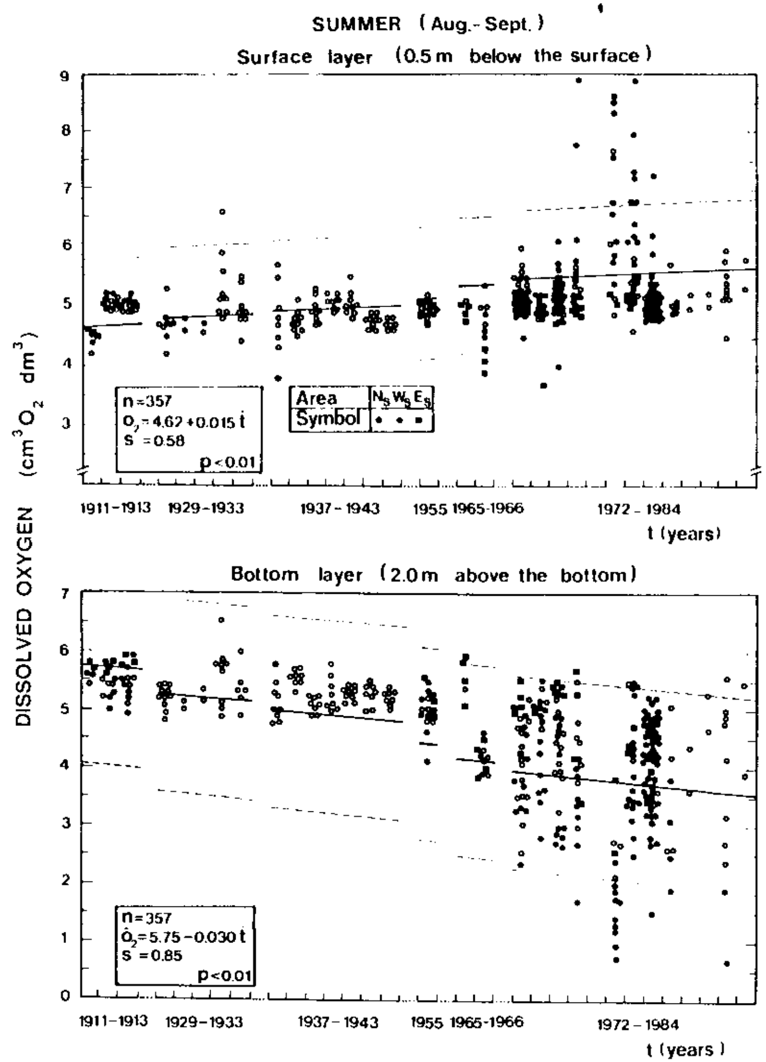

Figure 4. Oxygen content in the northern Adriatic Sea during August and September, over the period 1911–1984. See Figure 2 for additional explanation.

bottom the mean trend of decrease is 0·015 cm^3 O_2 dm^{-3} y^{-1}. The net oxygen content decrease of 0·002 cm^3 O_2 dm^{-3} y^{-1} appears to be insignificant.

Discussion

From the regression analysis it can be seen that the oxygen content increases in the surface layer and decreases in the bottom layer. An increasing difference between O_2 content at the surface and at the bottom is particularly evident during summer periods when both vertical and horizontal water exchange is small. Using the same patterns of data arrangement and statistical treatment, no significant trend in temperature or salinity changes was found for the period 1911–1984. This fact indicates that the principal current flow and wind regime must have remained unchanged on a broad scale within the investigated period. After all, the only reasonable explanation for the observed trends in O_2 content is an increasing primary production in the surface layer and consequently a higher respiration near the bottom. The increasing primary production is a consequence of high nutrient enrichment from the land-based sources. This conclusion is further reinforced by two factors.

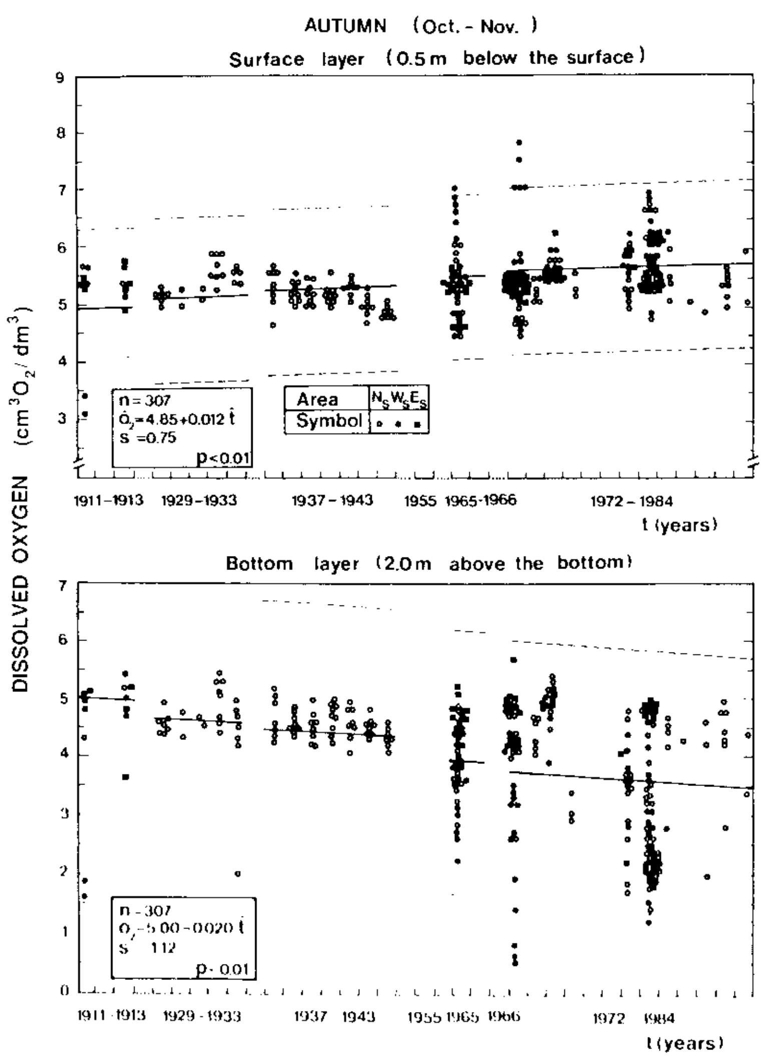

Figure 5. Oxygen content in the northern Adriatic Sea during October and November, over the period 1911–1984. See Figure 2 for additional explanation.

First, in the western subarea (W_s), which is under the strongest influence of the River Po, the difference between the surface O_2 content and the near-bottom O_2 content is the largest, as can be seen from Figure 4. Recently, the annual total phosphorus loading to the northern Adriatic area was estimated to be about 30 000 tonnes or about 2·37 kgPha^{-1}. Direct assessments have shown that the Po River contribution is as high as 60% of the total (Chiaudani *et al.*, 1983*a*). By using enrichment experiments, Pojed and Kveder (1977) have demonstrated that phosphorus rather than nitrogen is the most important nutrient controlling phytoplankton production in the northern Adriatic Sea.

Second, from our results (Figure 4) it is clear that, until 1955, the tendency of an increase of O_2 content in the upper layer and a decrease in the lower layer is small or insignificant. The data after 1955 have a much larger rate of change than shown by a common regression line. After World War II the detergent industry using phosphorus compounds, and intensive agriculture started to develop. As a probable consequence, an increase in primary production is visible from 1955 onward.

The two above findings suggested that an increase in the limiting nutrient inflow is the cause; more specifically, it is probably attributable to run off from agricultural areas and wastewaters containing phosphorous compounds. It is interesting to see how the difference in O_2 content between the surface and the bottom layer changes seasonally and how this difference has changed over the last 74 years. The change is not only a quantitative but also qualitative. In the spring and summer of the years 1911–1913, the O_2 content of the bottom layer was greater than the O_2 content of the surface layer (Figures 3 and 4). The opposite case was seen for the same seasons during the last 20 years, which were characterized by a much higher O_2 content of the surface layer than of the bottom layer. In fact, the bottom layer contains less oxygen due to two factors: (1) smaller primary production because of a decrease in light penetration [increased turbidity of the layer above (Justić & Legović, in prep.)], and (2) increased oxygen consumption due to the decomposition of organic matter.

Oxygen content and benthic mortality in the northern Adriatic Sea

According to our results, it is clear that the probability of a low oxygen content, which may be deleterious to benthic fauna, has increased during the period investigated. Although the average oxygen content at 2 m above the bottom in summer has decreased from 5·7 in 1911 to 3·5 cm^3 O_2 dm^{-3} in 1984, this alone does not represent a threat to benthic animals (Theede *et al.*, 1969). However, as is evident from Figure 4, variability of the oxygen content between 1911 and 1984 increased by a factor of five. This means that hypoxic conditions in the near-bottom water are more likely to occur now than previously. Furthermore, as our data cover only the section down to 2 m above the bottom, lower oxygen content may be expected nearer the bottom. In this respect, August and September are particularly critical months.

The course of the benthic community destruction during mass mortality in the Gulf of Trieste (Figure 1) has been described in detail by Stachowitsch (1984). Within a few days, virtually all benthic organisms, with the exception of some anemones, died in the area affected. The changes in oxygen content discussed above may have had significant ecological effects on meroplankton species in the northern Adriatic Sea (Benović *et al.*, 1987). If the observed trends in oxygen content continue, we expect that the frequency of mass mortality in the benthic fauna will increase, especially in the northern and western subareas.

Conclusions

During the period 1911–1984, the oxygen content of the surface layer of the northern Adriatic Sea increased by about 1·0 cm O_2dm^{-3} on average. The maximum increase in the surface layer of about 1·6 cm^3 O_2 dm^{-3} was calculated from pooled data collected during April and May. For the same period, the average oxygen content of the bottom layer decreased by about 1·1 cm^3 O_2 dm^{-3}. The greatest decrease of 2·2 cm^3 O_2 dm^{-3} was recorded for the period August–September.

The anoxic episodes in the northern Adriatic Sea have reached their present state in recent historical time. As long-term changes in temperature, salinity and general circulation are not significant, the only remaining hypotheses is that increased nutrient enrichment from land-based sources has caused this phenomenon. This hypothesis is consistent with the dynamics of increasing difference between the surface and bottom layers and the fact that the difference is largest in the subarea closest to the main sources of nutrients. If the observed trends in oxygen content continue, and there is no reason to believe that they will not, mass mortalities of bottom animals will increase in frequency in coming years, especially in the northern and western parts of the northern Adriatic Sea.

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DISSOLVED OXYGEN FROM 1979 UNTIL AND INCLUDING 1992

The last processed data on DO in Justić, Legović and Rottini-Sandrini were for 1984. In order to see what happened to DO in latter years let us turn to results of the analysis by Ivančić, 1995.

I. Ivančić in her dissertation analyzed data including 1992 but only on the transect between Po delta and Rovinj. With regard to seasons and surface versus bottom, she followed the same procedure but instead to look for trends she separated data in several multi annual intervals. Using her results we can construct the following table. In the table a "decrease" means statistically significant decrease, and "no change" means that statistically a change in DO concentration has not been detected.

Data from the interval [1979, 1992]

Season	Surface	Bottom
February - April	decrease	no change
May - June	increase	decrease
July - August	increase	decrease
September - November	no change	decrease

If we view these results as a continuation of DO in Justić, Legović and Sandrini-Rottini, 1987, we see that at least from May to August DO continued to increase in the surface layer and it continued to decrease in the bottom layer. However, a more detailed quantitative analysis shows that in early spring and late autumn DO are about to level off soon.

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When do phytoplankton blooms cause the most intense hypoxia in the northern Adriatic Sea?

Hypoxia
Phytoplankton blooms
Nutrients
Eutrophication
Adriatic Sea

Hypoxie
Floraison phytoplanctonique
Nutriments
Eutrophisation
Mer Adriatique

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ABSTRACT

Eutrophication of the northern Adriatic Sea was investigated using data on dissolved oxygen (DO) from 1911 to 1982. Beginning in the period 1955-1965, DO concentrations increased in the surface layer and decreased close to the bottom in all seasons except winter. These changes are attributed to an increase of the anthropogenic nutrient inflow.
The occurrence of hypoxia near the bottom and its disappearance were investigated using the vertical distribution of DO on the transect from the Po delta to Rovinj during 1973. Horizontal distributions of DO close to the surface and near the bottom show prominent gradients from the Po delta towards the middle of the northern Adriatic Sea.
Application of a simple box model indicates that phytoplankton blooms which occur in July cause the lowest DO concentrations near the bottom. For DO concentrations near the bottom to increase, anthropogenic nutrient inflow into the northern Adriatic Sea must be significantly reduced.

RÉSUMÉ

Quand la floraison du phytoplancton provoque-t-elle la plus intense hypoxie dans le nord de l'Adriatique?

L'eutrophisation du nord de la mer Adriatique a été étudiée à partir des concentrations en oxygène dissous, mesurées de 1911 à 1982. À partir des années 1955-1965, la concentration en oxygène dissous augmente dans la couche de surface et diminue vers le fond, à toutes les saisons sauf en hiver. Ces variations sont dues à une augmentation de l'apport de nutriments d'origine anthropique.
L'apparition et la disparition du phénomène d'hypoxie dans la couche de fond sont étudiées en examinant la répartition verticale de l'oxygène dissous entre le delta du Pô et Rovinj en 1973. Les répartitions horizontales de l'oxygène dissous en surface et près du fond présentent des gradients importants entre le delta du Pô et le milieu de la partie nord de l'Adriatique.
L'application d'un modèle simple indique que la floraison du phytoplancton, observée en juillet, provoque les plus faibles concentrations d'oxygène dissous vers le fond. Pour élever la concentration de l'oxygène dissous près du fond, il faut réduire notablement les rejets de nutriments d'origine anthropique dans le nord de la mer Adriatique.

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INTRODUCTION

The first attempt to analyse long-term changes of DO concentrations in the Adriatic Sea was made by Štirn *et al.* (1974). They studied data from 1911 to 1973 and concluded that during the period 1960-1973 the frequency of low concentrations near the bottom increased while the frequency of high concentrations decreased.

Justić *et al.* (1987) analysed data from 1911 to 1984. In the surface layer they found significant increasing trends in DO concentrations in every season except winter, while in the bottom layer they found decreasing trends.

We compare the data from the period 1911-1913 to those from 1972-1982, and discuss the evidence of hypoxia dynamics and the horizontal distribution of DO. A simple box model is presented and applied to investigate the effects of changes in primary production and stratification on DO concentrations near the bottom.

MATERIALS AND METHODS

The area of study

The northern Adriatic Sea extends from the gulf of Trieste southwards to the line Pula-Pesaro. The sea is closed on three sides and open in the direction of the middle Adriatic. The mean depth is 28 m and the surface area is 18×10^3 km^2 (Fig. 1). There is a considerable nutrient inflow from the northern and western coasts (Tab. 1), while oligotrophic waters enter from the middle Adriatic through its southeastern open boundary.

Table 1

Mean annual freshwater and nutrient inflow to the northern Adriatic from the coast (estimates are from Degobbis, 1994).

Inflow to Northern Adriatic	Freshwater (10^9 m^3/y)	Total nitrogen (10^8 mol/y)	Total phosphorus (10^7 mol/y)	Total silica (10^8 mol/y)
N and W coast	84	193	89	79
Istra	6	9	2	4

The river Po is the largest single freshwater input with 50×10^9 m^{3}y^{-1}. The concentration of nutrients in the Po is from fifty to over one hundred times higher than in open waters of the middle Adriatic, and it represents the largest source of nutrients in the northern Adriatic. This is understandable, since the Po river hosts in its basin a far greater human population, and far larger industrial and agricultural areas than any other river entering the Adriatic. As a result, the northern Adriatic constitutes one of the most productive zones of the Mediterranean (Sournia, 1970; Kveder *et al.*, 1971; Štirn *et al.*, 1974).

Intense spring and autumn blooms of phytoplankton appear mostly in the western part, which is under the direct influence of the Po (Revelante and Gilmartin, 1976).

Current measurements in the northern and middle Adriatic, from 1971 to 1982 (Zore-Armanda and Vučak, 1984; Vučak, 1985), suggest a cyclonic circulation during 30 to 70% of the time. Two cyclonic gyres have been identified, one occupying the area north of a line from Pula to the Po delta and the other forming part of the middle Adriatic cyclonic gyre. The first of these is visible on the Coastal Zone Color Scanner pictures from March to August (Sturm *et al.*, 1992). Current measurements indicate that the later cyclonic gyre persists throughout winter and summer.

Vertical mixing in northern Adriatic varies seasonally. During summer, the water column is stratified by the existing thermocline and halocline. Vertical mixing across the picnocline is slower than in the rest of the water column. In this sense, the thermocline "separates" the upper 15 to 20 m layer from the bottom water. During autumn, due to seawater cooling, vertical mixing increases and finally destroys the stratification. This process is practically completed by the end of October, when a vertically homogeneous water column is formed.

Data

Data for the period 1911-1982 and a filtering technique

The following oceanographic parameters have been measured since 1911: temperature, salinity, DO concentrations (at the standard oceanographic depths) and Secchi disc depth. DO concentrations were measured by the Winkler method (for references on data sets see Justić *et al.*, 1987; here we use DO data up to 1982). Measurements were occasional, except during 1973 and 1974 when bi-weekly cruises were organized.

Graphs by Štirn *et al.* 1974 on DO concentrations from 1911 to 1973 for the whole Adriatic reveal an important point: variability is so great that a very careful filtering technique is needed to reveal trends.

The filtering technique used here (Justić *et al.*, 1987) involved the following:

1) Only DO concentrations offshore from the 20 m isobath were considered, so as to decrease the scatter due to variable point sources located along the coast,

2) The four seasons were treated separately in order to distinguish between the different situations: completely mixed water column; the process of stratification; stratified water column; and the process of destratification.

3) Data from the surface were treated separately from data close to the bottom. Oxygen production occurs in the surface layer and oxygen consumption occurs mainly near the bottom; therefore the data were analysed separately. Furthermore, the differences in DO concentrations were more pronounced at the extremes of the two layers, DO concentration close to the bottom being less due to the oxygen demand of the degradation processes and due to low primary production. High primary production near the surface and a high concentration of phytoplankton results in less light being available near the bottom.

Maximum vertical separation of the two data sets also decreases natural variability due to the random nature of vertical turbulent mixing.

For these reasons, only data from the two extreme points were considered: 0.5 m below the surface and 2 m above the bottom.

4) DO concentrations from one year to another were assumed to be cyclic so that a season from one year could be compared to the same season of the following year. A systematic deviation from this assumption would reveal a trend.

Data from the Po delta-Rovinj transect

Hydrographic and nutrient data were taken approximately bi-weekly at the standard oceanographic depths (Gilmartin *et al.*, 1972*a*, 1972*b*). The first station on the Po delta-Rovinj transect is located 20 km off the delta and the last station is located 20 km off Rovinj (Fig. 1). Four stations were located at intervals of 20 km. Approximately monthly transects were available for DO concentrations. Vertical and horizontal oxygen distributions were plotted using objective analysis techniques (Shepard, 1968).

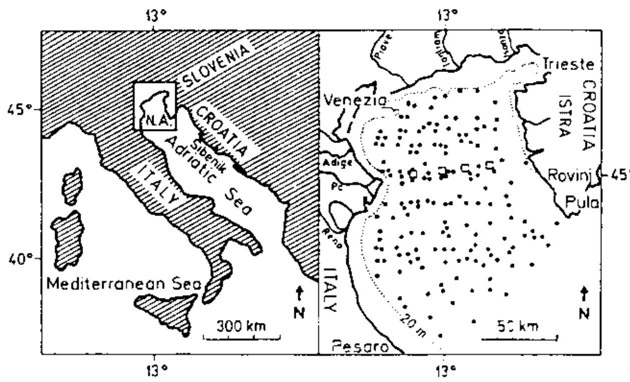

Figure 1

Northern Adriatic Sea, showing the location of stations where measurements of dissolved oxygen were made. Some stations were visited only once while others were visited monthly or seasonally. The four stations on the Po delta-Rovinj transect visited during 1973 are denoted by small squares.

A simple box model

A box model was constructed to study the effects of a change in production near the surface and a change in stratification on DO concentrations near the bottom.

Primary production and sedimentation of organic matter

The seasonal dynamics of primary production in the northern Adriatic is known from detailed measurements in incubators (Gilmartin and Revelante, 1980; Smodlaka, 1986), and from *in situ* measurements (Kveder *et al.* 1971) and from expressions relating the two (Precali, 1983).

The integrated value of the primary production rate (PI) in the euphotic layer was calculated on the basis of potential primary production (PP) in the surface layer. Daily values were calculated for the interval between 6 a.m. and 6 p.m.: based on previous studies (Justić *et al.*, 1986) the daily intensity was assumed to follow a parabola with a maximum at noon. Primary production was assumed to decrease exponentially with depth. The coefficient of attenuation, k, was calculated from the Secchi disc depth, z_s:

$$PI = \int_0^{z_{eu}} P(z)\, dz,$$
$$\text{where}: \quad P(z) = PP \exp(-kz)$$
$$\text{and} \quad k = c/z_s. \tag{1}$$

Value of the constant c is 1.5. For the euphotic depth, z_{eu}, we take $z_{eu} = 3z_s$.

The annual primary production in the western part of northern Adriatic ranges from 90 to 115 gC m^{-2} y^{-1}.

In shallow coastal waters, the sedimentation flux of organic matter was proportional to the integral of primary production (Hartwig, 1976; Smetacek, 1980; Suess, 1980). However, over short time intervals (*i.e.* days) this dependence may not be obvious due to a time lag between primary production and sedimentation.

The ratio between the rate of primary production and sedimentation has been found to range between 0.1 day^{-1} at the beginning of the phytoplankton bloom and to 1.0 day^{-1} at the end of the bloom (Stareŝinić *et al.*, 1982). During winter and spring, diatom blooms sink to the bottom at a relatively rapid rate (Durbin and Durbin, 1981; Smetacek, 1984). During summer, the percentage of organic matter reaching the bottom is smaller, mainly due to the slower sinking of nanoplankton and more intensive zooplankton feeding (Malone, 1980; Hobbie and Cole, 1984). The rate of sinking of organic detritus varies between 0.2 and 100 m day^{-1}, depending on particle size, the ratio between specific weight and surface of the particles, the intensity of stratification and the state of the plankton community. Stareŝinić *et al.* (1980, 1982) determined that the sedimentation flux in the northern Adriatic varies from 40 in the eastern to 140 mgC m^{-2} day^{-1} in the western part. Thus, between 25 and 30 % of primary production is sedimented on the bottom.

The sedimentation process is described by:

$$S(t) = \alpha PI(t - \varphi) \tag{2}$$

where $S(t)$ is the sedimentation flux to the bottom (mgC m^{-2} day^{-1}), PI is the daily integrated primary production (mgC m^{-2} day^{-1}), α is the sedimentation coefficient (between 0.25 and 0.30), t is time in days and φ is the time required for the biomass to reach the bottom.

Benthic respiration

Benthic respiration, R, is formulated as a first order process:

$$R(t) = 2.01\, k_b(T, \text{DO})\, S(t) \tag{3}$$

where R is in dm^3 DO m^{-2} day^{-1}, k_t is the parameter which describes the dependence of respiration on the temperature and the concentration of oxygen in the bottom layer:

$$k_b (T, DO) = k_0 (T/T\max)^a$$
$$\text{if} \quad DO \geq 1.5\, dm^3\, DO\, m^{-3}$$

$$k_b (T, DO) = k_0 (T/T\max)^a (DO/1.5)^b$$
$$\text{if} \quad DO < 1.5\, dm^3\, DO\, m^{-3} \qquad (4)$$

Tmax is the maximum value of temperature in the bottom layer, while a and b are constants. From experimental data (Hargrave, 1969; Nixon *et al.*, 1980; Officer *et al.*, 1984), it follows that the value of exponent a is between 2 and 3 while that of exponent b is around 2. DO concentration regulates respiration if the value is lower than 1.5 dm^3 DO m^{-3} (Pamatmat, 1971).

The seasonal cycle of temperature is represented by:

$$T(t) = 15 - 6\cos[2\pi(t-\tau)/365] \qquad (5)$$

where τ is a phase shift in days. The maximum value of temperature in the bottom layer is around 20°C.

When the temperature is around 20°C and the concentration of oxygen is above 1.5 dm^3 DO m^{-3}, the value of the k_b function is close to k_o which is between 0.001 and 0.005.

Formulas (1-5) permit the calculation of benthic respiration as a function of the integrated value of sedimentation of organic matter, temperature and DO concentration in the bottom layer. By taking $k = 0.003$ and sedimentation between 17 and 40 gC m^{-2} y^{-1}, benthic respiration is between 0.05 and 0.11 gC m^{-2} day^{-1}. Using the Redfield ratio, the mean value of oxygen consumption varies between 0.14 and 0.32 g DO m^{-2} day^{-1}. Depending on temperature, oxygen concentration and sedimentation of organic matter, the above values may be two to three times larger. Hence, in the most productive areas of northern Adriatic one should expect the maximum of benthic respiration to reach 1 g DO m^{-2} day^{-1}. This value is characteristic of productive marine ecosystems (Officer *et al.* 1984; Jørgensen, 1979).

Vertical oxygen transport

The vertical transport of oxygen is described by Fick's law:

$$V = -k_z \partial(DO)/\partial z \qquad (6)$$

where V is the flux of oxygen (dm^3 DO m^{-2} day^{-1}), k_z is the coefficient of vertical turbulent diffusion (m^2 day^{-1}). The main problem in the application of Fick's law is to determine values for turbulent diffusion k_z. Instead of direct determination, temperature and salinity are often used (Jassby and Powell, 1975; Imboden, 1979; Abott *et al.*, 1984). Since we wish to compute the transport of oxygen to the bottom layer under varying conditions of stability of the water column, we shall use a nonlinear relationship for the dependence of k_z on the intensity of stratification (Gargett, 1984):

$$k_z = 86400\, a_0\, N^{-1}$$
$$\text{where} \quad a_0 = 1.1^* \, 10^{-7}\, m^2\, s^{-2} \qquad (7)$$

$$\text{and} \quad N = [(g/\bar{\sigma})(\partial\bar{\sigma}/\partial z)]^{0.5} \qquad (8)$$

N is the Brunt-Väisälä frequency (s^{-1}), g is the gravitational constant, $\bar{\sigma}$ is average density in the water column, $\partial\bar{\sigma}/\partial z$ is the density gradient computed from data in the northern Adriatic.

Balance of DO

The balance of oxygen near the bottom is described as the difference between oxygen transport to the bottom and benthic respiration:

$$d(DO)/dt = (V - R)/L \qquad (9)$$

where L is a vertical scale of the model.

RESULTS AND DISCUSSION

Changes in DO concentrations near the surface and close to the bottom

Seasonal changes in DO concentrations at a depth of 0.5 m below the surface during 1911-1913 and 1974-1982 are shown in Figure 2*a*. There is no significant difference in DO concentrations between the two periods in winter, while a significant difference is perceived at its largest in spring, and persists throughout the summer and autumn.

Changes in the near-bottom water (2 m above the bottom) between 1911-1913 and 1972-1982 periods are shown in Figure 2*b*. The mean DO concentration in the near-bottom water of northern Adriatic is smaller in all seasons, the difference between the two periods being largest in summer and smallest in winter.

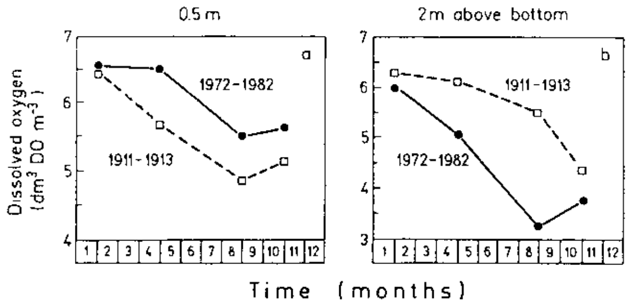

Figure 2

Comparison of mean seasonal DO concentrations in 1911-1913 and 1972-1982 period.

The above results are in agreement with results of Justić *et al.*, 1987. A comparison of DO concentration trends in corresponding seasons of the two periods is shown in Table 2:

Table 2

Trends of DO change from 1911 to 1984. N.S. indicates that the trend is not significant on the 95 % confidence limit. The number of data on which trends are based ranges from 305 for the winter season to 357 for the summer season.

DO trends	Winter	Spring	Summer	Autumn
		(dm^3 DO m^{-3} y^{-1})		
0.5 m	0.005	0.020	0.015	0.012
2 m above bottom	N.S.	−0.010	−0.030	−0.020

Identification of 1955-1965 period. as the start of the significant increasing trend in DO concentration at the surface and a decreasing trend near the bottom, has been linked to a widespread agricultural fertilization and the use of detergents containing phosphorus compounds. In general, increased nutrient availability has led to an increase in the nutrient inflow into the northern Adriatic. From data presented by Justić (1988) concerning increased industrial nutrient production and data from Marchetti *et al.* (1989) on the increase of total mineral nitrogen and phosphate in the river Po, it may be deduced that the Po carries about 20 % of the mineral nitrate and about 1 % of the phosphate contained in industrial fertilizers.

A comparison of nutrient concentration in rivers entering the Adriatic from the northern and western coasts and in the relatively pristine rivers feeding the eastern Adriatic is given in Table 3. Concentration factors were computed from estimates in Gržetić *et al.*, 1991.

Table 3

Comparison of concentration factors for nutrients in rivers entering the Adriatic from the north and from the east. The Krka river enters the mid-Adriatic Sea near Šibenik.

Concentration factor (dimensionless)	total mineral N	PO_4	SiO_2
NA rivers/relatively pristine rivers from eastern Adriatic coast	4	18	5
Po/Krka	9	46	5

It should be pointed out that neither the rivers considered nor the groundwaters of the eastern Adriatic coast are entirely pristine: all of them to some extent contain nutrients of anthropogenic origin. The net conclusion is that the cause of eutrophication in northern Adriatic since 1955 must be anthropogenic, given the magnitude of the increase in the nutrient inflow.

This increase has been responsible for a trend towards higher primary production at the surface that lead to higher DO concentrations.

At the bottom, DO concentrations began to decrease due to the higher flux of organic matter from the upper layer (settling of phytoplankton), reflecting a greater amount, rather than rate, of decomposition, resulting in a higher demand for DO and hence a decline in DO concentration. To a lesser extent, primary production near the bottom also decreased due to reduced light, *i.e.* because of shading from the higher concentration of phytoplankton in the upper layer. This conclusion is supported by the fact that the Secchi disc depth has decreased since the 1911-1914 period (Justić, 1988).

As a consequence of higher DO concentrations near the surface, the supply of oxygen from the surface to the bottom as an effect of vertical mixing must have increased. This was obviously not sufficient to compensate for a very large increase in biological oxygen demand near the bottom.

Much of the variance in the data may be explained by vertical mixing between surface and near bottom water. When the difference in DO concentrations between the two layers is small, *i.e.* during the period 1911-1955, the variance is small. As the difference between the two layers widens, the variance in each layer increases.

The small difference in DO concentrations between the winters of the two periods considered may be a result of the following four factors. First, there is probably only a small change in primary production during winter. Phytoplankton production during winter is less dependent on nutrients than on temperature and light. Second, during winter the decomposition rate near the bottom is slower than during the rest of the year, although the flux must have increased. Three, there is an intensive cyclonic circulation in this season which brings oligotrophic waters from the middle Adriatic. Fourth, due to a lack of stratification, vertical mixing is more intensive then in summer. These factors preclude DO build-up near the surface and deficiency near the bottom in winter.

Dynamics of DO content on the Po delta-Rovinj transect

The dynamics of DO content on the transect from the Po to Rovinj during the period from 26 April to 6 December 1973 is shown in Figure 3.

During winter, at the surface, DO concentration is close to the saturation value although slightly higher values were found in the vicinity of the Po. On 26 April 1973, no indication of bloom was found except for the figure of 107 % DO saturation at the station closest to the Po. On 11 May (not shown), 119 % DO saturation was found at a depth of 15 m at the station nearest to the Po, and 110 % was found at a depth of 5 m at the next station. Twelve days later, on 23 May, from 109 % to 128 % DO saturation was found at the surface. During the remainder of spring and summer, higher DO content was observed at depths between 10 and 20 m below the surface.

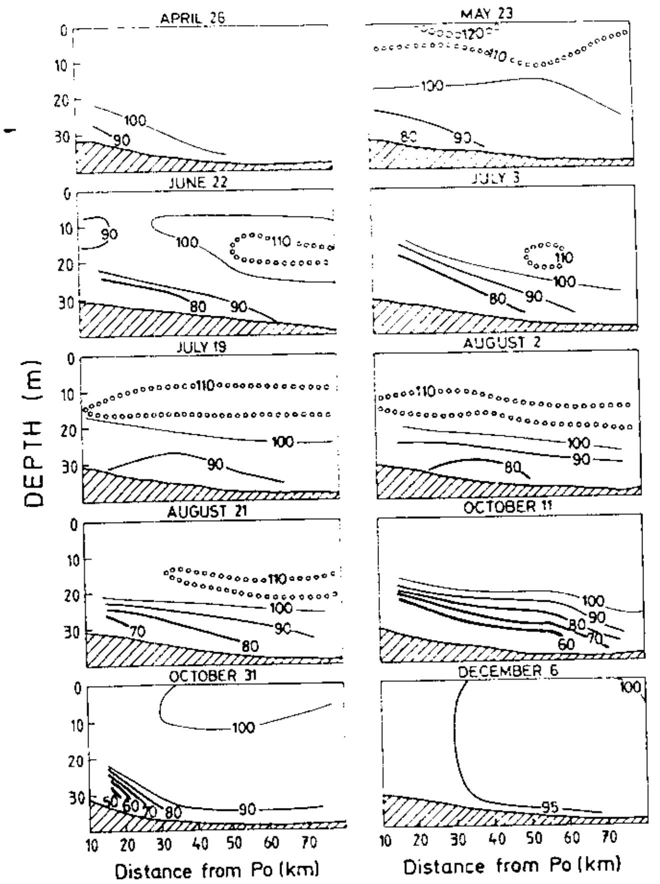

Figure 3

Development and disappearance of DO supersaturation in the water column (in % of the saturation value) and hypoxia near the bottom. Data shown are from 26 April to 6 December 1973 on the transect between the river Po delta (left side) and Rovinj (right side).

Hypoxia close to the bottom begins to develop in the proximity of the Po, and during summer it spreads towards Rovinj. On 11 October, the lowest content for the whole year was recorded. A DO gradient extending from the Po toward Rovinj is clearly visible.

The disappearance of hypoxia is apparent on the final three graphs of Figure 3. Incoming water from the middle Adriatic on the eastern side forces the water outflow on the western side, including the water close to the Po. In addition, vertical mixing, which also intensifies, brings oxygen-rich surface water to the bottom layer.

Horizontal distribution of DO

The horizontal distribution of DO at the surface (0.5 m) and near the bottom (2 m above the bottom) for 19 July 1973 are shown in Figures 4*a* and 4*b*, respectively.

Higher DO content at the surface is often found in the proximity of the Po and extends either towards Rovinj or along the southwestern coast, *i.e.* along the Italian coast, depending on prevailing currents.

Hypoxia near the bottom is often seen as a smeared-out image of the supersaturation close to the surface. The smearing increases with depth since, during sedimentation, horizontal turbulent diffusion spreads the organic material. In the example shown, the lowest DO content is found further south and east from the Po. If the organic material were merely to sink from the Po to the bottom, then the lowest DO content would be much closer to the Po delta. Instead, the distribution in Figure 4*b* indicates that the hypoxia is a consequence of the sinking and decomposition of phytoplankton or phytoplankton-derived matter.

Consequences of the increase of primary production in the upper layer

Three parameters have been measured frequently in the northern Adriatic that represent integrals of primary production in the upper layer: chlorophyll-*a*; dissolved oxygen; and dissolved organic matter. One would expect them to be correlated. Indeed from data in Jeftic and Smodlaka, (1978) one finds: DO$=87.2+5.43$ Chl-*a*, $R=0.91$, where DO is expressed in % of the saturation and Chl-*a* in $\mu g\ l^{-1}$.

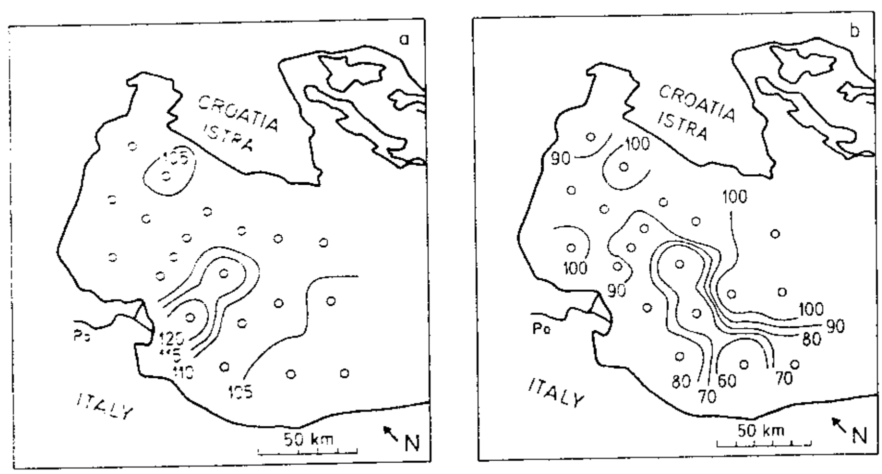

Figure 4

DO content (as a % of saturation) on 19 July 1973: a) 0.5 m below the surface; b) 2m above the bottom.

Dissolved organic matter produced by phytoplankton has been measured as a surfactant activity (Žutić *et al.* 1981). Concentration of dissolved organic matter is higher in northern Adriatic then in the open waters of the remainder of the Adriatic and the Mediterranean (Ćosović *et al.*, 1985). The concentration of surface active organic matter correlates well with DO concentration (R = 0.93, Žutić and Legović, 1990).

The increase in primary production over the long-time interval means that phytoplankton blooms which may occur in spring, summer and autumn, cover a much larger area.

From data at our disposal we were unable to establish that phytoplankton blooms have occurred more frequently in recent years. A model of phytoplankton dynamics (Legović and Justić, 1984*a, b*) showed that, in general, if nutrient inflow to an area increases, a previously nonexistent autumn bloom become a regular event.

The most visible recent phenomenon in the northern Adriatic is the accumulation of massive quantities of gelatinous material or mucilage at the surface. During the largest events, between one and fifty million tons of this material may be present. The cause of this phenomenon has been sought in hydrodynamic and meteorological conditions over the area (Degobbis *et al.*, 1979; Degobbis, 1989). During calm weather and weak currents, phytoplankton can reach higher densities, and in the later stage, a higher flux (gC m^{-3} s^{-1}) of mucilage is generated in a confined area. However, irrespective of the meteorological conditions, high densities of phytoplankton can only occur over a wide area if sufficient amounts of nutrients were previously present. For example, the same meteorological conditions that prevailed in summer 1988 over northern Adriatic when an extensive bloom occurred, also prevailed over the mid-Adriatic, but the concentrations of phytoplankton and, later, of mucilage reached their highest values in northern Adriatic.

Consequences of oxygen decrease close to the bottom

Low dissolved oxygen concentration (0.5 to 1 dm^3 DO m^{-3}) close to the bottom may eliminate organisms living on the bottom or organisms which have a bottom-attached phase in their life cycle. Benović *et al.* (1987) presented a comprehensive data set which shows a correlation between oxygen depletion near the bottom and the disappearance of meroplanktonic hydromedusans from the northern Adriatic. In this respect, the mean oxygen concentration is neither critical nor decisive: it is the minimum oxygen concentration which is significant. Data from Justić *et al.* (1987) indicate that concentrations may fall below 0.5 dm^3 DO m^{-3} at 2 m above the bottom. Since data closer to the bottom do not exist, one may speculate on concentrations there. At all events, smaller oxygen concentrations may be expected and, according to evidence in Stachowitsch (1984), this deficit is sufficient to cause mass mortalities. In 1974, mass mortality of benthic macrofauna was recorded in the central part of the gulf of Trieste (Fedra *et al.*, 1976). Similar events were observed north of Rimini in September and October 1985 (Chiaudani *et al.*, 1983). In the gulf of Trieste, mass mortality of benthic animals was observed in September 1980 and in 1983, when the affected area was estimated to cover about 50 km (Stachowitsch, 1984, Faganeli *et al.*, 1985). Mass mortality has so far been linked to a combination of climatic and hydrological conditions, but data presented above (Figs. 2*a*, 2*b*) indicate a long-term ecological change. Hence we may expect these events to have occurred over a larger area after the 1955-1966 period. Crema *et al.*, (1991) identified a number of effects induced by frequent catastrophic events on the structure of macrofaunal communities. Zavodnik *et al.*, 1994 reported consequences following the autumn hypoxia of 1989 and concluded that 80 to 95% of meiofauna died. Among the macrofauna, sponges, polychaetes, echinoderms and tunicates almost totally disappeared while most actinians survived. According to the same study, two years later meiofauna and macrofauna had not yet stabilized.

Generally speaking, conclusions based on long-term trends may be expected to hold. Because of the far greater nutrient inflow in recent decades, the same natural fluctuations in water inflow and meteorological conditions produce greater interannual differences.

Model results

An average year

Figure 5*a* shows a comparison between data on DO concentration and model simulation. Since the results of the model were mostly within one standard deviation from the data, we judge the correspondence between the model and the data to be acceptable. In agreement with the data, the integrated annual primary production in the model was set to 90 gC m^{-2} y^{-1}.

Effect of doubled primary production during one summer month

When primary production integrated over one month is doubled, this perturbation roughly corresponds to a moderate phytoplankton bloom. Since the effect on DO concentration near the bottom might vary depending on the month in which the bloom occurs, we investigated the appearance of a-bloom during each of the following months: May, June (Fig. 5*b*), July and August (Fig. 5*c*).

The occurrence of a bloom during May does not cause DO concentration near the bottom to fall below 2 mg l^{-1}. However, a bloom during June, July or August will cause severe hypoxia. The bloom which occurs during July is likely to result in benthic mortality of organisms two months later. If primary production in the upper layer increases threefold during July in comparison with the annual monthly average, it will cause anoxia near the bottom.

Effect of higher stratification during summer

Simulations increasing the vertical stratification by one standard deviation above the mean value were carried out to test the hypothesis that hypoxia near the bottom occurs primarily because of calm weather and unusually high stratification which reduces the vertical transport of oxygen to the bottom layer.

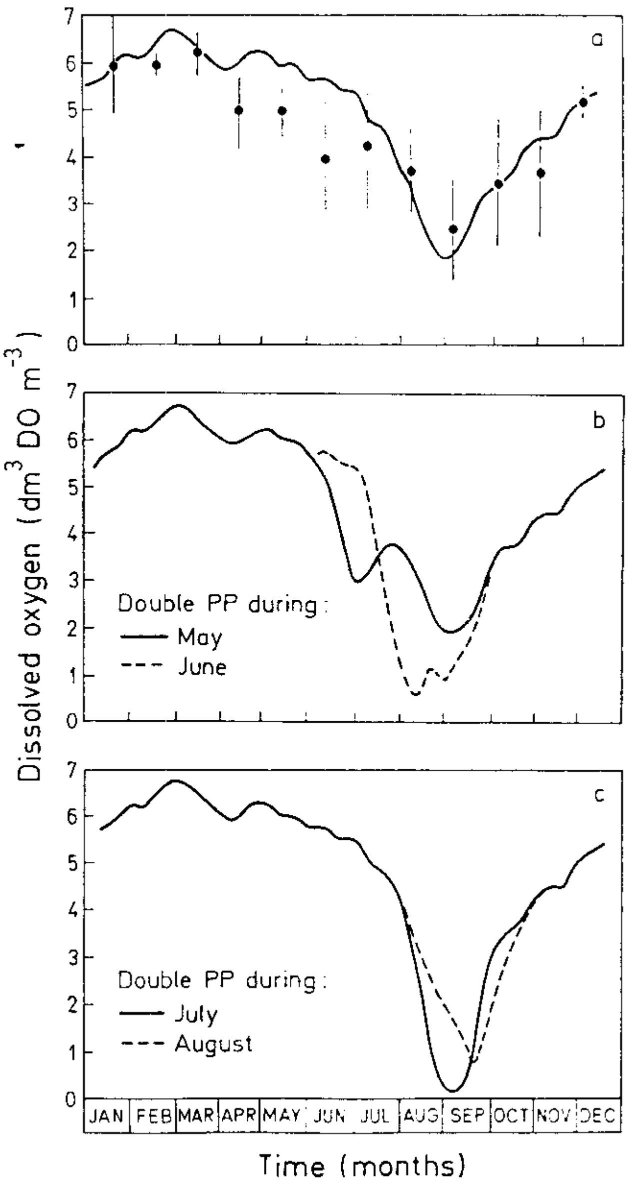

Figure 5

a) Seasonal dynamics of DO concentration near the bottom. Data for average values and standard deviations are taken from the western part of northern Adriatic. Model results are denoted by a line. Where primary production is doubled during May, June, July or August the resulting model dynamics is shown in b) and c).

Results show that the increase in vertical stratification with respect to the normal year does not cause significantly lower DO concentration near the bottom.

In summary, model results suggest that hypoxia occurs primarily as a consequence of a significant phytoplankton bloom above the thermocline, subsequent sinking of organic detritus and decomposition on the bottom. If such a bloom occurs in July, when the detritus has enough time to reach the bottom and decompose prior to destratification, the resulting intensive hypoxia will affect the survival of benthic fauna.

CONCLUSIONS

In comparison to the DO concentrations that existed in the northern Adriatic during 1911-1914 period, surface concentrations have increased, while they have decreased close to the bottom. The most pronounced change is visible in spring, summer and autumn. The change is attributed to an order of magnitude increase in anthropogenic nutrient supply, especially phosphors and nitrogen. The higher inflow of nutrients bring about more extensive phytoplankton blooms causing higher DO concentrations near the surface, while the sinking and decomposition of organic matter cause a decrease of DO near the bottom, to the extent that massive benthic mortalities covering ever larger areas became frequent. Phytoplankton blooms that occur during July cause the most severe hypoxia and anoxia.

A solution to the problems posed by the phenomena described would be to decrease significantly the anthropogenic phosphorus and nitrogen inflow to the northern Adriatic Sea.

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