

# 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  $18 \times 10^3 \text{ km}^2$  (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 Degobbi, 1994).*

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

The river Po is the largest single freshwater input with  $50 \times 10^9 \text{ m}^3 \text{ y}^{-1}$ . 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 pycnocline 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.*, 1972a, 1972b). 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).

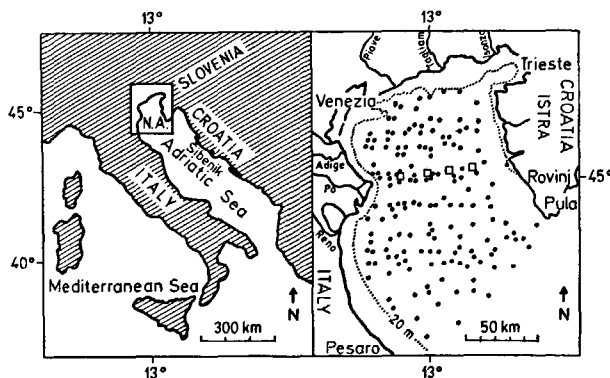


Figure 1

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; Smolaka, 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,  $z_s$ :

$$PI = \int_0^{z_{eu}} P(z) dz,$$

$$\text{where: } P(z) = PP \exp(-kz)$$

$$\text{and } k = c/z_s. \quad (1)$$

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<sup>-2</sup> y<sup>-1</sup>.

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<sup>-1</sup> at the beginning of the phytoplankton bloom and to 1.0 day<sup>-1</sup> at the end of the bloom (Starešinić *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<sup>-1</sup>, 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. Starešinić *et al.* (1980, 1982) determined that the sedimentation flux in the northern Adriatic varies from 40 in the eastern to 140 mgC m<sup>-2</sup> day<sup>-1</sup> in the western part. Thus, between 25 and 30% of primary production is sedimented on the bottom.

The sedimentation process is described by:

$$S(t) = \alpha PI(t - \varphi) \quad (2)$$

where  $S(t)$  is the sedimentation flux to the bottom (mgC m<sup>-2</sup> day<sup>-1</sup>),  $PI$  is the daily integrated primary production (mgC m<sup>-2</sup> day<sup>-1</sup>),  $\alpha$  is the sedimentation coefficient (between 0.25 and 0.30),  $t$  is time in days and  $\varphi$  is the time required for the biomass to reach the bottom.

#### Benthic respiration

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

$$R(t) = 2.01 k_b(T, DO) S(t) \quad (3)$$

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

$$k_b(T, \text{DO}) = k_0 (T/T_{\text{max}})^a$$

if  $\text{DO} \geq 1.5 \text{ dm}^3 \text{DO m}^{-3}$

$$k_b(T, \text{DO}) = k_0 (T/T_{\text{max}})^a (\text{DO}/1.5)^b$$

if  $\text{DO} < 1.5 \text{ dm}^3 \text{DO m}^{-3}$  (4)

$T_{\text{max}}$  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  $1.5 \text{ dm}^3 \text{DO m}^{-3}$  (Pamatmat, 1971).

The seasonal cycle of temperature is represented by:

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

where  $\tau$  is a phase shift in days. The maximum value of temperature in the bottom layer is around  $20^\circ\text{C}$ .

When the temperature is around  $20^\circ\text{C}$  and the concentration of oxygen is above  $1.5 \text{ dm}^3 \text{DO m}^{-3}$ , the value of the  $k_b$  function is close to  $k_0$  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  $40 \text{ gC m}^{-2} \text{y}^{-1}$ , benthic respiration is between  $0.05$  and  $0.11 \text{ gC m}^{-2} \text{day}^{-1}$ . Using the Redfield ratio, the mean value of oxygen consumption varies between  $0.14$  and  $0.32 \text{ g DO m}^{-2} \text{day}^{-1}$ . 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  $1 \text{ g DO m}^{-2} \text{day}^{-1}$ . 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:

$$V = -k_z \partial(\text{DO})/\partial z \quad (6)$$

where  $V$  is the flux of oxygen ( $\text{dm}^3 \text{DO m}^{-2} \text{day}^{-1}$ ),  $k_z$  is the coefficient of vertical turbulent diffusion ( $\text{m}^2 \text{day}^{-1}$ ). 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):

$$k_z = 86400 a_0 N^{-1}$$

where  $a_0 = 1.1 \cdot 10^{-7} \text{ m}^2 \text{s}^{-2}$  (7)

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

$N$  is the Brunt-Väisälä frequency ( $\text{s}^{-1}$ ),  $g$  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:

$$d(\text{DO})/dt = (V - R)/L \quad (9)$$

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  $0.5 \text{ m}$  below the surface during 1911-1913 and 1974-1982 are shown in Figure 2a. 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 ( $2 \text{ m}$  above the bottom) between 1911-1913 and 1972-1982 periods are shown in Figure 2b. 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.

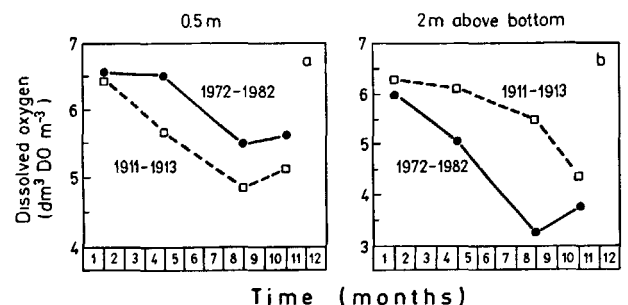


Figure 2

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 ( $\text{dm}^3 \text{ DO m}^{-3} \text{ y}^{-1}$ )	Summer	Autumn
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 <sub>4</sub>	SiO <sub>2</sub>
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 than 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.

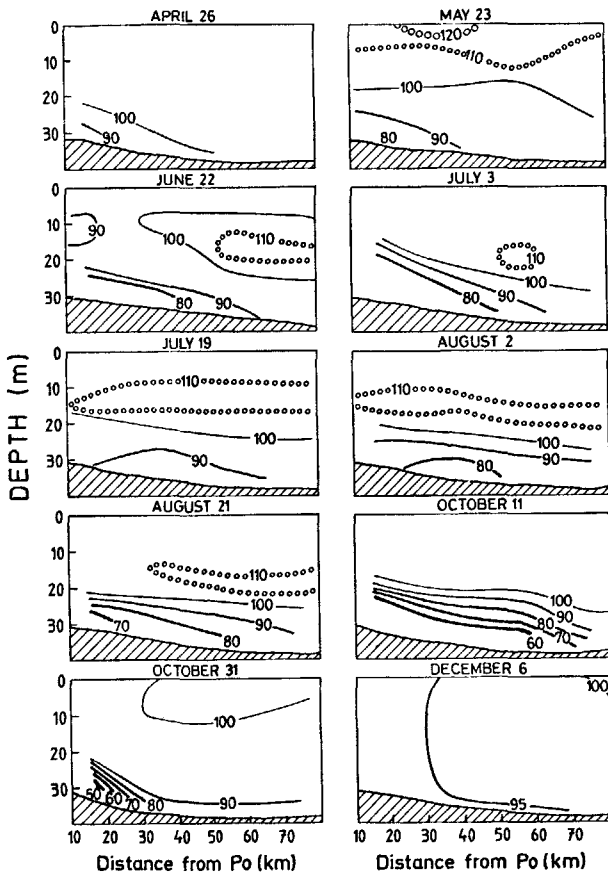


Figure 3

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 4a and 4b, 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 4b 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 Jetic and Smodlaka, (1978) one finds:  $DO = 87.2 + 5.43 \text{ Chl-}a$ ,  $R = 0.91$ , where DO is expressed in % of the saturation and Chl-a in  $\mu\text{g l}^{-1}$ .

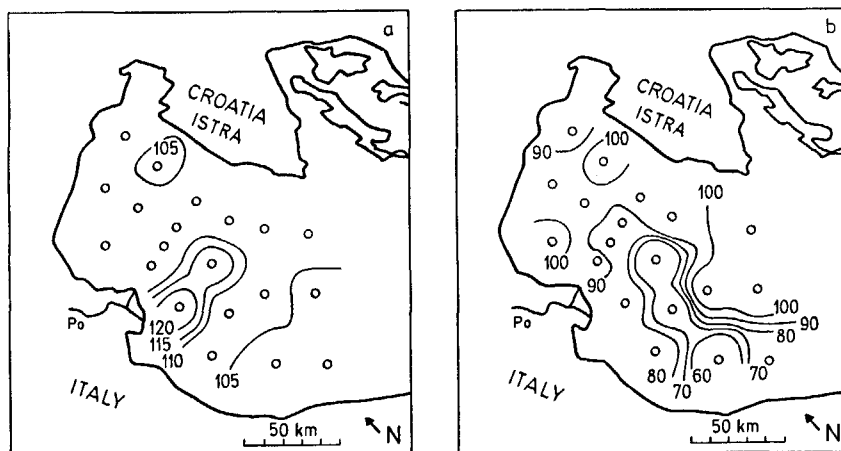


Figure 4

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 than 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, 1984a, 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 ( $\text{gC m}^{-3} \text{s}^{-1}$ ) 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  $1 \text{ dm}^3 \text{ DO m}^{-3}$ ) 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  $0.5 \text{ dm}^3 \text{ DO m}^{-3}$  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. 2a, 2b) 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 5a 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  $90 \text{ gC m}^{-2} \text{ y}^{-1}$ .

#### *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. 5b), July and August (Fig. 5c).

The occurrence of a bloom during May does not cause DO concentration near the bottom to fall below  $2 \text{ mg l}^{-1}$ . 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.

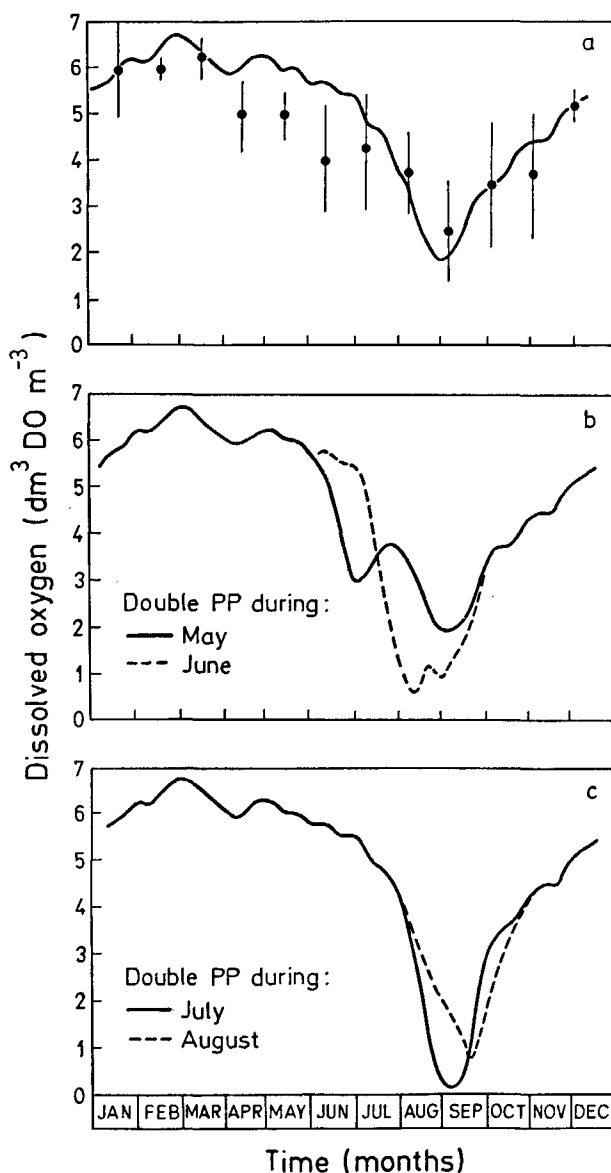


Figure 5

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).

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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 phosphorus 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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