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AN ANALYSIS OF FACTORS AFFECTING OXYGEN DEPLETION IN THE NORTHERN ADRIATIC SEA

ANALIZA FAKTORA KOJI UVJETUJU POJAVU HIPOKSIJE U SJEVERNOM JADRANU

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In the northern Adriatic Sea the occurrence of hypoxic conditions and related benthic mortalities have considerably increased in frequency for the last 20 years. The causal relationship of factors which create conditions near the bottom favourable for the development of hypoxia is discussed.

The main causative agent of the northern Adriatic hypoxia is sedimentation of organic matter from the pelagic strata and subsequent benthic respiration on the bottom. During winter, the entire water column is well saturated in oxygen. Towards summer, the oxygen demand at the bottom increases with the increasing sedimentation and temperature while the reoxygenation through the pycnocline decreases with the increasing stability of the water column. As a consequence the oxygen content at the bottom decreases. The oxygen content of the bottom "cold pool" decreases also due to the fact that pycnocline gradually progresses towards the deeper parts of the water column. On occasion, it may lie just few metres above the bottom. The phenomenon of near bottom pycnocline is important in the shallower northern and western subareas. Interestingly, it is regularly associated with the occurrence of hypoxia in the Gulf of Trieste. The development of hypoxic conditions at the bottom coincides with the periods of low wind frequency. Apparently, the pronounced hypoxia may develop only if the wind speed at the surface is not higher than 4 m/s. Stronger wind tends to destroy stratification and this process seems to progress linearly with the increasing wind speed.

Accordingly, the wind faster than 8 m/s is able to mix the water column down to the depth of 30 m, which is an average depth of the northern Adriatic Sea.

To analyze relative importance between a set of factors which create conditions near the bottom, favourable for the development of hypoxia, a two-box mathematical model has been used. The model describes decay of organic matter as a function of primary production at some earlier time, where the time lag is caused due to the sinking of detritus from the euphotic zone to the bottom. The balance equation for oxygen is given as the difference between the resupply of oxygen across the pycnocline and the oxygen consumption due to benthic and epibenthic respiration. The decay constant depends primarily on ambient water temperature. Vertical oxygen flux is estimated from Fickian diffusive model where the vertical eddy coefficient has a nonlinear dependence on the stability of the water column. The model has been calibrated on the basis of 10-year data series. Comparing measured oxygen concentrations and the simulation results one can see that the model complies with the data relativelly well. Simulations of perturbed dynamics gave an indication of relative importance of a set of ecological factors in formatuion of hypoxia.

INTRODUCTION

Mass mortalities of benthic animals, as a consequence of hypoxic conditions near the bottom, have been reported from the coastal and estuarine areas worldwide (e.g. Dethlefsen and Westerhagen, 1983; Officer *et al.*, 1984: Stachowitsch, 1984). In the northern Adriatic Sea this phenomenon is known to have occurred for centuries, but during the last 20 years it apparently has become more frequent and more widespread than before (Piccinetti and Manfrin, 1969; Voltolina, 1973; Fedra *et al.*, 1976; Chiaudani *et al.*, 1983; Stachowitsch, 1984; Faganeli *et al.*, 1985; Zavodnik *et al.*, 1989). Recently, several papers attempted to relate the increasing occurrence of hypoxia to the long-term eutrophication (Justić, 1987, 1988). However, there has been no attempt to analyze the relative importance of various environmental variables which create conditions favourable for the development of hypoxia. In this paper the causal relationship of factors affecting oxygen depletion in the northern Adriatic Sea is discussed.

METHODS

In the northern Adratic Sea, the data on oxygen content, temperature, salinity and nutrient concentration have been collected for extensive periods using identical methodology from 1964 onwards (see Justić *et al.*, 1987 for data sources). In this paper the data for the period 1972-1982 were used. Examinations of the reports containing the 1972-1982 data revealed no significant differences in sample collection and treatment from one cruise to another. Therefore, it is assumed that the same systematic error was introduced in different years.

The causal relationship of factors affecting oxygen depletion was investigated by means of regression methods and simulations of a simple box model. Basic description of the model structure was included in the text. The rest will be presented elsewhere (Justić, in preparation).

RESULTS AND DISCUSSION

Conceptual considerations

In the northern Adriatic Sea hypoxia has been rarely observed in the southeastern section while it is almost regular seasonal phenomenon in the western subarea and in the Bay of Trieste. Based on the data collected during summers between 1972 and 1982, the oxygen saturation lower than 20% occurs within the 95% probability interval in the area from the Po Delta southward to Rimini and in the Bay of Trieste (Fig. 1). Since these

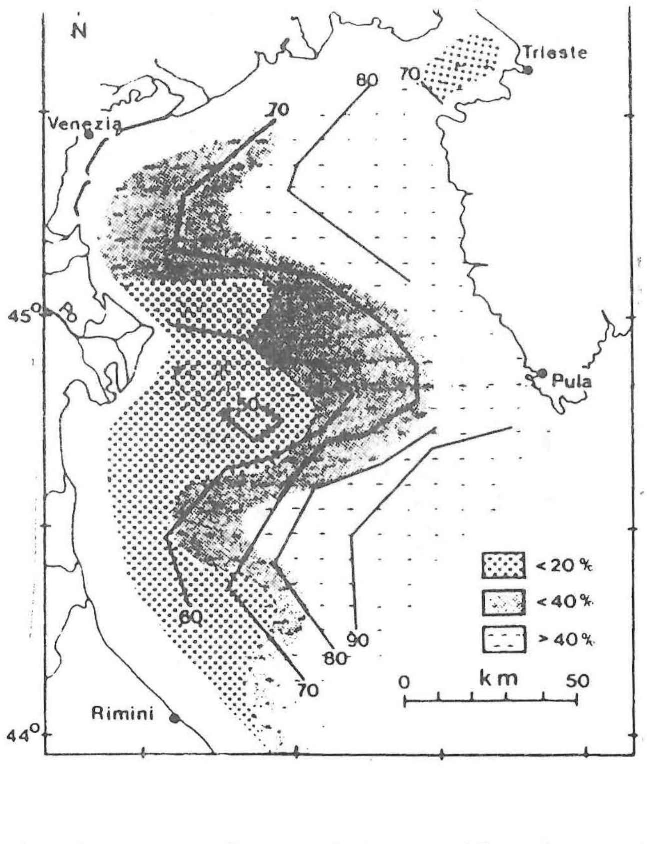

Fig. 1. Distribution of oxygen saturation means in August and September, over the period 1972-1982. Indicated are areas where the oxygen saturations lower than 40% and lower than 20% occur within the 95% probability interval

areas have considerably higher pelagic primary production than the rest of the region one can hypothesize that the main causative agent of the northern Adriatic hypoxia is sedimentation of organic matter from the pelagic strata and subsequent respiration at the bottom. The seasonal cycle of primary production is characterized by three periods of bloom; January-April, June-August and September-November (G i l m a r t i n and R e v e l a n t e , 1980). The integrated yearly primary production ranges from 55 gC/m^2 in the easternmost section to 120 gC/m^2 in the section approaching the Po Delta (G i l m a r t i n and R e v e l a n t e , 1983). In the middle Adriatic Sea, the average sedimentation rate at the depth of 50 m accounted for about 28% of the primary production (S t a r e š i n i ć *et al.*, 1983). Since the mean depth of the northern Adriatic Sea is only about 30 m, the 0.3 is probably the lowest coefficient of sedimentation that can be expected on a yearly basis. Assuming that the respiratory quotient is 1 this means that between 44 and 96 gO_2/m^2/year can theoretically be consumed by the benthic respiration processes. The latter value is obviously high enough to maintain hypoxia in the bottom waters during a part of the year.

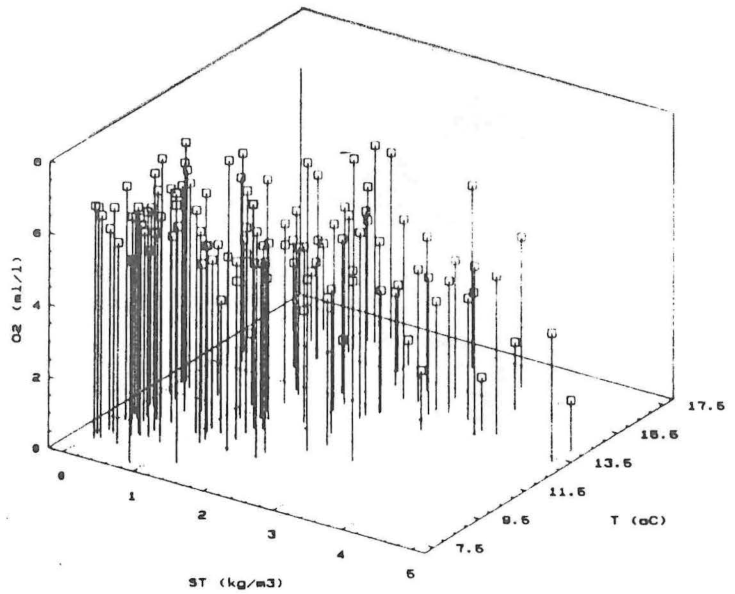

Fig. 2. The oxygen concentration in the bottom layer as a function of bottom temperature and stability of the water column between the depth of 10m and the bottom. The data are collected in the western subarea of the northern Adriatic Sea, over the period 1972-1982. The variations in bottom temperature and stability of the water column can explain 40% and 20% of the variations in the oxygen content, respectively

In the northern Adriatic Sea hypoxia is a seasonal phenomenon occurring only during summer and autumn months. Towards summer, the benthic respiration rate increases with the increasing temperature. The importance of temperature in the precipitation of hypoxia is indicated by the fact that about 40% of the variations in oxygen content may be explained by the variations in temperature (Fig. 2). Contrary to the benthic respiration, the reoxygenation through the pycnocline decreases towards summer with the increasing stability of the water column. On the average, about 20% of the variations in oxygen content may be explained by the variations in stability of the water column (Fig. 2). Moreover, as the stability increases the pycnocline gradually progresses towards the deeper parts of water column and often approaches bottom on less than 10 m (Fig. 3). On occasion, it may lie just 1-2 meters above the bottom which substantially

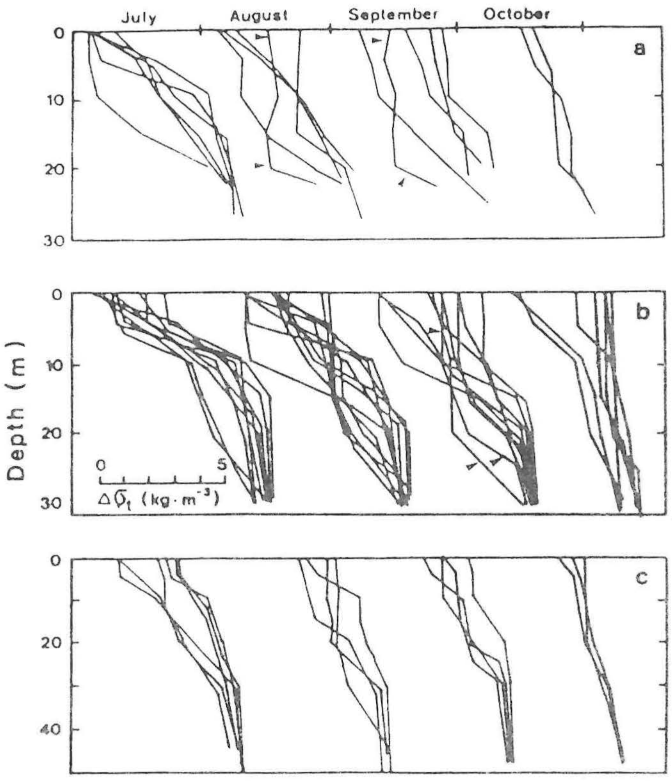

Fig. 3. Plots of density anomaly ($\Delta\sigma_t$) versus depth during July-October, in the northern Adriatic Sea from 1972-1982; a - northern subarea, b - western subarea, c - eastern subarea. Arrows indicated near-bottom pycnoclines

reduces the oxygen reserve in the lower water mass. This phenomenon of "near-bottom pycnocline" seems to be one of the important causative agents of the northern Adriatic hypoxia. Importantly, it is regularly associated with the occurrence of hypoxia in the Bay of Trieste (F a g a n e l i *et al.*, 1985).

The development of hypoxia coincides with periods of calm weather. Apparently, the pronounced hypoxia may develop only if the wind speed at the surface is lower than 4 m/s (Fig. 4a). Accordingly, the wind faster than 8 m/s is able to mix the water column down to the depth of 30 m, which is an average depth of the northern Adriatic Sea (Fig. 4b).

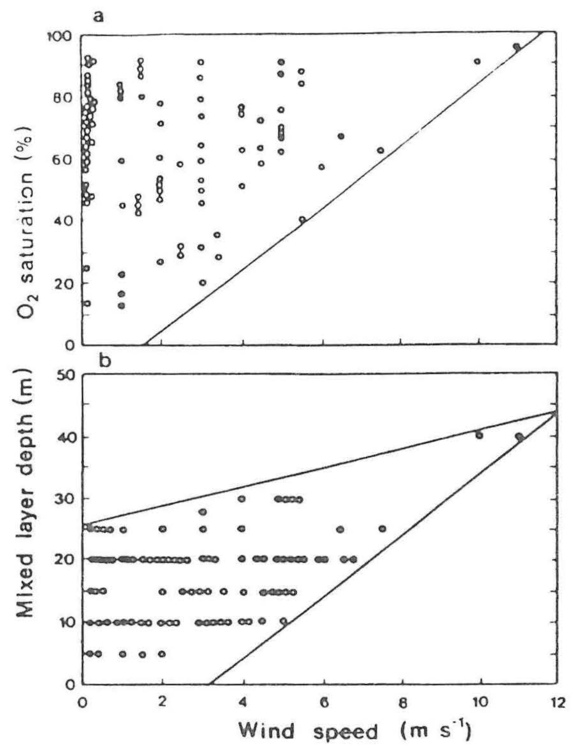

Fig. 4. Oxygen saturation at the bottom (a) and the mixed layer depth (b) versus wind speed at the surface, in the northern Adriatic Sea during August and September 1972-1982. Mixed layer is considered to be a part of the water column saturated in oxygen more than 90%

Model simulations

In order to assess the relative importance of sedimentation, temperature and stability in the development of hypoxia a simple box model has been used. In the model, the sedimentation rate S(t) at any given time (t) is a function of primary production rate at some earlier time (t-φ)

$$S(t) = \alpha P_i(t-\varphi) \qquad (1)$$

where φ is the sinking time of detritus from the euphotic zone to the bottom and α is the fraction of primary production which reaches the sediments. The sedimentation directly contributes to the pool of organic matter at the bottom (F). The balance equation for F(t) may be written as follows;

$$F(t) = \int_{t_0}^{t} [S(t') - R(t')] \qquad (2)$$

where S(t) and R(t) are the sedimentation rate and the benthic respiration rate, respectively. The rate of benthic respiration is given by the equation

$$R(t) = k(T, O_2)\ F(t) \qquad (3)$$

where $k(T, 0_2)$ is the decay constant dependent on ambient water temperature (T) and dissolved oxygen concentration (0_2). Vertical diffusive flux of oxygen across the pycnocline (D) is estimated from the equation;

$$D = k_z \frac{\partial O_2}{\partial z} \qquad (4)$$

where k_z is the vertical eddy coefficient. In the model, the value of k_z is decreasing with the increasing stability of the water column;

$$k_z = a_0 N^{-q} \qquad (5)$$

where N is the Brünt-Väisälä frequency. Finally, the balance equation for oxygen concentration at the bottom is

$$\frac{dO_2}{dt} = -R + D \qquad (6)$$

where R and D are the benthic respiration rate and vertical diffusive flux, respectively.

The model was been calibrated using data on oxygen concentration, temperature and salinity collected during the period 1972-1982 in the western subarea of the northern Adriatic Sea (see J u s t i ć *et al.*, 1987 for data sources). The data on primary production were after G i l m a r t i n and R e v e l a n t e , 1980. The differential equation was integrated by the fourth order Runge-Kutta-Gill method over the interval of 365 days. The integration step was 0.1 day.

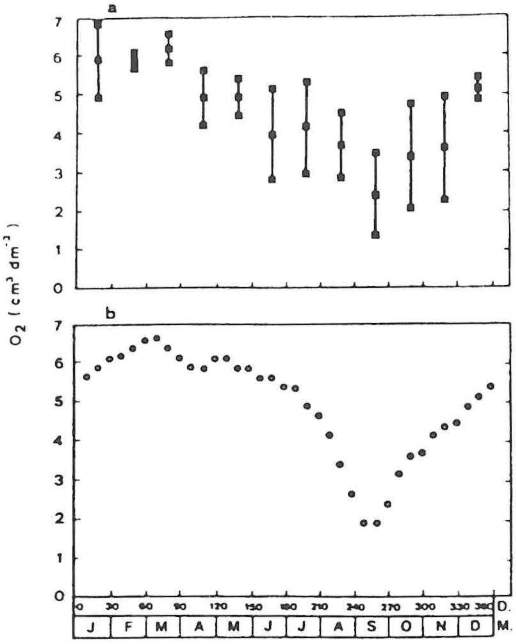

Fig. 5. Seasonal changes in the bottom oxygen content of the western subarea; a - monthly means and standard deviations for the period 1972-1982, b - predictions of the mathematical model. In the model, the integrated yearly value of sedimented organic matter is 34.5 gC/m^2

The results of simulation of nominal model dynamics are illustrated in Fig. 5. Comparing the measured oxygen concentrations and the simulation results one can see that the model complies with the data relatively well. Nominal behaviour of oxygen concetration in the model shows the same dynamical features as measured values. In order to assess the relative importance of sedimentation rate, stability of the water column and temperature in the precipitation of hypoxia, a variety of perturbation experiments were performed. Two of them are illustrated in Fig. 6. They show that pronounced hypoxia during September results from an increase in the sedimentation rate during July or August by approximately 6 gC/m^2. Considering the large variability in

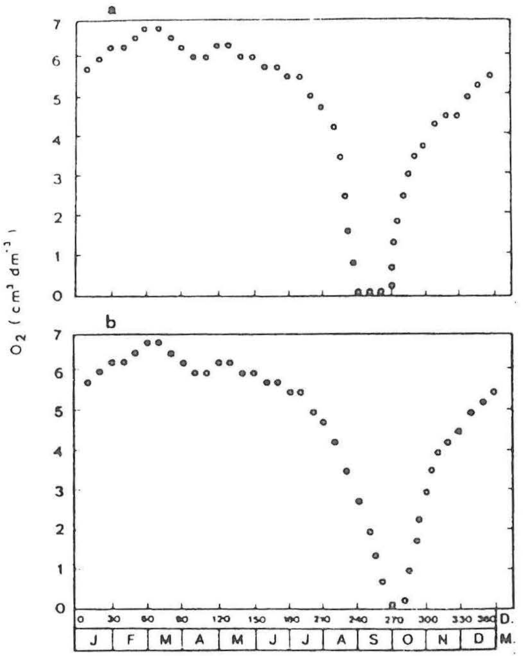

Fig. 6. Perturbation experiments; sedimentation rate during (a) July and (b) August is increased by approximately 6 gC/m^2

the data, these conditions seem to be often satisfied in nature. Thus, it appears that the development of hypoxia may not necessarily be associated with the increasing stability of the water column. However, if stability of the water column is increased too, much lower sedimentation rates would result in hypoxia. The model predicts the duration of hypoxia from 5 to 25 days which is in agreement with the field observations (Stachowitsch, 1984).

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ANALIZA FAKTORA KOJI UVJETUJU POJAVU HIPOKSIJE U SJEVERNOM JADRANU

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KRATKI SADRŽAJ

Učestalost pojava hipoksije i masovnih pomora bentoskih organizama značajno je porasla tijekom posljednjih dvadeset godina. U literaturi su već ranije izneseni argumenti u prilog hipoteze da je navedeni trend posljedica dugoročne antropogene eutrofikacije ovog akvatorija (npr. J u s t i ć *et al.*, 1987), ali nije bilo pokušaja da se kvantitativnim metodama protumače uzročno-posljedične veze pojedinih faktora koji uvjetuju nastanak hipoksije u pridnenom sloju. U ovom radu taj se problem pojave hipoksije razmatra uz pomoć jednostavnih statističkih i matematičkih modela uzimajući pritom u obzir desetogodišnje nizove podataka sakuljene od 1972 do 1982 godine.

Osnovni mehanizam koji uvjetuje nastanak hipoksije u pridnenom sloju jest porast intenziteta bentičke i epibentičke respiracije, kao posljedice sedimentacije organske tvari proizvedene u eufotičkom sloju. U uvjetima stratificiranog vodenog stupca, potrošnja kisika u pridnenom sloju veća je od transporta kisika procesima miješanja i turbulentne difuzije što dovodi do hipoksije.

Analiza pojava hipoksije u sjevernom Jadranu omogućava da se, osim ove osnovne sheme, uoče i određene specifičnosti kao što je fenomen "pridnene piknokline". Naime, od proljeća prema jeseni piknoklina se postepeno pomiče prema dubljim slojevima te neposredno prije nastupa jesenskog ciklusa miješanja dostiže dubinu od 15-20 m. Imajući u vidu da je pretežni dio područja sjevernog Jadrana plići od 30 m, subpiknoklinalni sloj je najčešće tanji od 10 m što uvjetuje brzu eliminaciju kisika. Tijekom hipoksija u Tršćanskom zaljevu, na primjer, utvrđeno je prisustvo "pridnene piknokline" na svega 1-2 m iznad dna (F a g a n e l i *et al.*, 1985).

Pojava hipoksije poklapa se s razdobljem mirnog vremena. Hipoksični pridneni sloj može se, naime, održati samo ukoliko je brzina vjetra nad površinom manja od 4 m/s; jači vjetar izaziva znatnije miješanje vodenog stupca, dok je vjetar brzine oko 8 m/s u stanju potpuno izmiješati vodeni stupac do dubine od oko 30 m, koliko iznosi prosječna dubina sjevernog Jadrana.

Da bi se procijenila relativna važnost pojedinih faktora koji uvjetuju nastanak hipoksije konstruiran je jednostavni matematički model. U modelu je pretpostavljeno da je proces razgradnje organske tvari na dnu u trenutku t funkcija primarne proizvodnje u eufotičkom sloju tijekom vremena t - t_0. Dinamika koncentracije kisika u pridnenom sloju odražava ravnotežu procesa bentoske respiracije i turbulentne difuzije kisika kroz piknoklinu. U modelu koeficijent bentoske respiracije raste nelinearno u zavisnosti od temperature u pridnenom sloju. Transport kisika u vertikalnom smjeru opisan je Fickovim difuzijskim modelom pri čemu je koeficijent turbulentne difuzije bio nelinearna funkcija stabilnosti vodenog stupca. Model je kalibriran na temelju višegodišnjih podataka o primarnoj proizvodnji, koncentraciji kisika, salinitetu i temperaturi sakupljenim u zapadnom podpodručju sjevernog Jadrana.

Usporedbom osnovne dinamike modela i izmjerenih vrijednosti koncentracije kisika ustanovljena je velika podudarnost.

Simulacijom perturbiranih stanja modela odredjeni su neki od graničnih uvjeta za pojavu hipoksije u subpiknoklinalnom sloju.