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PRODUCTION-CONSUMPTION BUDGET IN AN ESTUARINE BAY: HOW ANOXIA IS PREVENTED IN A FORCED SYSTEM

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SUMMARY

Althought the generation of anoxic situations is a well known fact in estuarine bays, in the southern embayment of the Ebro delta (NW Mediterranean), the Alfacs Bay, oxygen depletion is a rare event. In this paper we examine the processes preventing anoxia in the system through a consumption/production budget. From calculations based upon annual mean values, we conclude that the bay is slightly heterotrophic, that is, that total consumption exceeds autochtonous production by only 10%.

But heterogeneity in both space and time results in a high variance around the mean used in our budget. We have examined the main components of this variance (stratification of the water column, horizontal heterogeneity, phytoplankton production in pulses, etc.) and some of them have been incorporated in a simple box-flux model. From this model, we conclude that only the deep water layer is strongly heterotrophic and that its sources of oxygen are vertical mixing and renovation (50%), diapycnal eddy diffusion (25%) and local production (25%).

The generation of anoxia must be driven by the co-occurrence of events associated with oxygen depletion and/or limitation of oxygen transport (i.e., calm weather period after a phytoplankton pulse; lack of estuarine circulation during a long calm weather period, etc.), what we call the covariance between processes. Such covariance is in general low, and in consequence anoxia must be considered a low probability event.

Comparing Alfacs Bay with other estuaries in the framework of the proposed conceptual model, three features emerge that may be relevant in order to prevent anoxia: low organic loading (produced plus imported); active estuarine circulation forced by high wind frequency; degradation of the organic matter mainly by benthic consumers.

KEY WORDS: Estuaries, eutrophication, anoxia, oxygen budget.

INTRODUCTION

The estuaries of developed countries have suffered dramatic changes in the last few decades. While they preserve the characteristics of transit systems between a continent that contributes and an ocean that dilutes, the processes have accelerated. Human action increases energy and matter flows, upsets the natural equilibrium and leads to situations that may compromise the existence of the estuarine ecosystem in its current form.

Each estuary has its own features that determine its functioning and define the extent of the possible fluctuations in the system's variables of state; beyond certain limits of these variables, important qualitative changes take place. Standing out amongst these are the processes of eutrophication, implying local or overall oxygen depletion, with consequences both for the general functioning of the system (loss of biological diversity, fall in production, etc.), and for activities of economic interest (fishing, aquaculture).

The current study is the first attempt at a functional synthesis, undertaken after more than eight years of research in the Alfacs Bay (Ebro delta, Tarragona, N.E., Spain), and is based on the results of diverse studies either published or in preparation, and on data from doctoral theses either already completed or in the process of elaboration (DELGADO, 1986; PÉREZ, 1989; MARTÍNEZ, 1990; VIDAL, 1991; CAMP, 1991).

This database represents precise analytical and quantitative knowledge of the most relevant processes in the ecological dynamics of the bay (primary production, nutrient cycling, etc.) and, in spite of the gaps for a complete and comprehensive general model, it permits a functional approach to the ecosystem of the bay.

The current study proposes a simple model that describes the overall ecological dynamics of the bay in terms of a budget between autotrophic and heterotrophic processes, using dissolved oxygen concentration as the main system descriptor. The model explains the series of field values obtained from repeated measurements of this variable, gives an indication of the processes that maintain the oxygen concentrations relatively high and allows some speculative discussion about the possible limits of these mechanisms and some peculiarities of interest in the bay under study.

THE STUDY AREA

The zone is a semi-confined mass of sea water, with a surface area of 49 km^2 and an average depth of 3.13 m ; the mouth of the bay is 2 km width (Fig. 1). The edges are surrounded by a shelf or platform (18 km^2), which falls in a gentle slope from 0 to 1.5 m, with an average depth of 0.64 m and which connects via a more pronounced slope to the muddy central basin, with an average/maximum depth of 4.16/6.5 m and an area of 31 km^2. The northern part of the shelf occupies 6 km^2, has a silty sediment and is almost totally covered (90 %) by dense beds of macrophytes, mainly *Cymodocea nodosa*; sediments of the eastern and southern sides of the shelf, which together extend over 12 km^2, are sandy, with a vegetation cover of 10 % (PÉREZ & CAMP, 1986).

The bay receives freshwater inputs from the northern edge of about 275x10^6 m^3 per year between April and October, and much less during the rest of the year, a seasonality caused by the needs of rice cultivation. This water brings considerable quantities of inorganic nutrients and organic matter into the bay (CAMP & DELGADO, 1987; PRAT *et al.*, 1988; MUÑOZ, 1989).

The hydrographic structure of the bay habitually presents a salinity dominated stratification, with a superficial layer (0 to 2-3 m depth) of low salinity (30-35 ‰) and a more or less pronounced outward movement, and a deep, salty (36-38 ‰) layer with an inward movement. Total

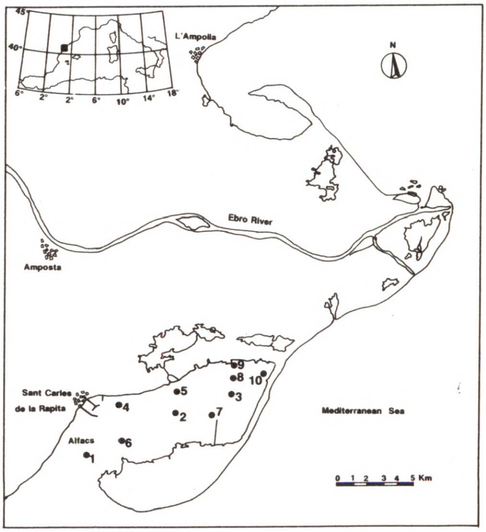

FIGURE 1. Location of Ebro Delta and map of the study area. Situation of the sampling stations is also given.

TABLE I. Some morphological and hydrological features of the Alfacs Bay relevant to the present work.

SURFACES (km^2)	
Total	49
Platforms	18
Northern	6
Southern and Eastern	12
Central basin	31
VOLUMES OF WATER (m^3)	
Total of the bay	153 x 10^6
Annual freshwater inputs	275 x 10^6
DEPTHS (m)	
Average of the bay	3.13
Maximum of the bay	6.50
Average of the platforms	0.64
Average of the central basin	4.17
HYDROLOGICAL FEATURES	
Water temperature (annual mean)	18.2 °C
Water temperature (April-November)	22.0 °C
Salinity 0-2 m (annual mean)	35 g.l^{-1}
Salinity 2-4 m (annual mean)	37 g.l^{-1}

mixing of both layers is rare and occurs in the case of very strong north-western winds, which blow with an average frequency of 12 days and a duration of 2-3 days (FONT, 1986). Re-stratification occurs within 48 hours after the wind dropping. This implies an export of the mixed water, which is substituted by sea water from outside the bay. In the absence of strong wind there is still an exchange between the bay and the open sea, either following a sequence of dilution with a periodicity of ca. 10 days (CAMP & DELGADO, 1987) or through a typical estuarine circulation with a volume exchange of 5-15 x 10^6 m^3 day^{-1}. Some of the general features of the bay are summarized in Table I.

FIELD DATA FOR THE MODEL

Primary production in the bay (Table II) is mainly due to phytoplankton, the activity of which does not show apparent seasonality. This production is higher in the upper, diluted nutrient-rich and well illuminated layer (DELGADO, 1986). Microphytobenthos production is more intense in the shallow water of the shelf and does not show any marked seasonality (DELGADO, 1989). Among macrophytes, the phanerogams show production maxima between March and October (PÉREZ, 1989), while macroalgae growth peaks between January and June (MARTÍNEZ, 1990). Other significant organic carbon inputs come through the water from irrigation channels (Table II).

TABLE II. Organic carbon inputs to the Alfacs Bay. The data are expressed on a surface basis (in mg C m^{-2} day^{-1}, averaged throughout the year) and as total inputs to the bay (in Tm C y^{-1}). From DELGADO (1986); PÉREZ (1989), MARTÍNEZ (1990) and unpublished data.

	mg C m^{-2} day^{-1}	Tm C y^{-1}
PHYTOPLANKTON		
Upper layer (0-2 m)	273	4874
Bottom layer (2-4 m)	64	725
MICROPHYTOBENTHOS		
Shallow waters (platforms)	96	631
Deep waters (central basin)	48	543
MACROPHYTES		
Seagrasses	1080	1643
Macroalgae	610	493
ALLOCHTHONOUS INPUTS		
Discharge channels (only POC)	62	1100

An important part of the total input (produced plus imported) is consumed in the sediment, as reflected in its oxygen uptake rates (VIDAL *et al.*, 1989; see Table III).

The data for dissolved oxygen concentration come from diverse sources. One data set was obtained from chemical analysis (Winkler) and the other from polarographic sensors (Orbisphere models 2608-2609, Syland Simplair and WTW OXI-196).

In consequence, comparisons in absolute terms are difficult; but the several Winkler/sensor intercalibration experiments performed showed that although differences in absolute values are evident, the concentration gradients (e.g. following a vertical profile) are faithfully reproduced independently of the method used or the calibration of the sensor. This justifies our preference for emphasizing differences rather than absolute values, especially when data from different authors are presented

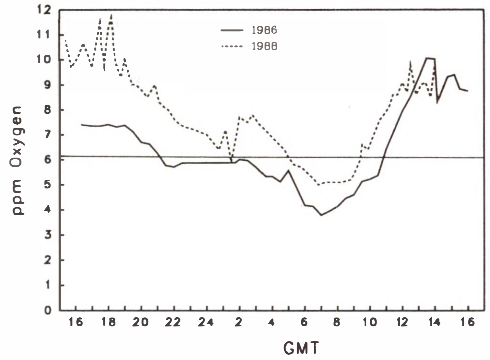

FIGURE 2. Daily evolution of oxygen concentration in the water over the shallow, northern platform, corresponding to two different years. Horizontal line represents an approximate value for oxygen saturation.

together.

Data on dissolved oxygen concentration can be grouped in the three following categories:

a) two daily cycles on the shallow shelves with continuous measurements by sensor (Station 10 in figure 1).

b) vertical profiles distributed throughout the bay and measured in three consecutive years by different authors (Fig. 2; Table IV). The frequency distribution of the surface/bottom differences (that is, the difference in oxygen concentration between 0 and 4 metres) appears in figure 3.

c) a smaller set of chemically determined values, which serve as a reference for items (a) and (b) (see Table IV).

There is a lack of systematic and reliable data for consumption in the water column (BOD). The only available information indicates that the BOD_5 values are in general lower than 2 ppm (C. Lleti, pers. comm. and J. Camp, unpublished data).

TABLE III. Oxygen consumption in the sediment, in g m^{-2} day^{-1}. From VIDAL *et al.* (1990) and VIDAL (1991).

	Minimum	Maximum	Average
Northern platform	1.76	2.30	1.80
Southern platform	0.23	1.02	0.61
Central basin	1.23	1.84	1.54
Average for the bay			1.53

Likewise, the data from deep water consumption in short incubation experiments (3 hours) never indicates significant oxygen uptake (VIDAL, 1991), which, given the precision of the method, results in a maximum consumption of less than 1 ppm day^{-1}.

THE MEAN: AN ANNUAL OVERALL BUDGET

The first approach to this model is in terms of a production/consumption balance on an annual basis.

The primary production in the bay can be estimated at 8,900 Tm of C, while the external contribution from channels is 1,100 Tm of C in particulate form (Tables I and II). To these must be added the dissolved organic carbon (DOC), the magnitude of which, estimated according to sporadic analysis (MUÑOZ, 1990), oscillates between 1,500 and 3,500 Tm. Therefore, the total input (produced plus imported) of organic carbon oscillates between 11,500 and 13,500 Tm C y^{-1}.

The oxygen consumed in the sediment is 27,364 Tm O_2 y^{-1}. This can represent, in terms of organic matter consumed, between 7,885 and 10,287 Tm C y^{-1}, depending on the oxidation pathways involved, aerobic (106 C:138 O_2) or anaerobic (basically

TABLE IV. Data of oxygen concentration (ppm) at 0 and 4 m depth, averaged throughout complete studies for different stations, numbered as in figure 1. For Stations 1, 2 and 3, data from an annual cycle (12 months) by DELGADO (1986) obtained through Winkler titration. For Stations 9, 8 and 3, data from an annual cycle (16 months) by CAMP (1991), obtained by polarographic sensor. For Stations 4, 5, 6 and 7, data from an annual cycle (12 months) obtained by a polarographic sensor (unpublished data from Departament d'Agricultura, Ramaderia i Pesca). Vertical gradient (difference) is also given.

Station	1	2	3	9	8	3	4	5	6	7
0m	8.12	8.20	8.24	9.64	7.80	7.83	6.2	6.4	7.3	6.9
4m	7.88	7.52	7.27	-	6.60	6.82	5.5	5.4	6.7	6.3
Difference	0.24	0.69	0.97	-	1.20	1.01	0.7	1.0	0.6	0.6

sulphate reduction, in which case the molar ratio is close to 1 C:1 O_2).

These data show that the primary production of the bay and the carbon consumption in the sediment are of the same order of magnitude and give a positive balance between inputs (+) and outputs (-) ranging from 1,000 to 5,500 Tm C y^{-1}, the indetermination mostly being due to the scarcity of values of DOC. The excess of organic carbon may be exported towards the exterior of the bay, accumulated in the sediment or consumed in the water column. Even in the case of a total consumption of the maximum value of 5,500 Tm C in the water column, the average BOD_5 would not be over 1.5 ppm, which is consistent with the existing data.

The exportation depends on the exchange rate with the open sea. Calculations from successive balances of salt in distinct periods of time (CAMP & DELGADO, 1987) give an average exchange rate of 60 x 10^6 m^3 every ten days. Assuming that the concentration of total organic carbon (dissolved plus particulated, TOC), is close to 3.6 mg l^{-1}, and that the coastal sea water has a TOC concentration of the order of 1.5 mg l^{-1}, a net annual export around 4,000 Tm C can be estimated. The maximum surplus carbon loading to the bay is therefore of 1,600 Tm, which can either be consumed in the water column (yielding an average BOD_5 of 0.5 ppm) or increase the carbon pool in the sediment. In an ideal situation in which daily production and consumption values would be equal to the respective average values throughout the year, net loss of oxygen to the atmosphere would not be expected, and therefore the creation of oxygen deficits would only be related to the balance between input by channels and export to the open sea. As shown, this balance yields a maximum surplus of 500 Tm C inside the bay, the consumption of which would give daily oxygen deficits of the order of 0.05 ppm, easily balanced by influx from the atmosphere. In conclusion, and regarding the mean, the situation reveals very slight heterotrophy, if any.

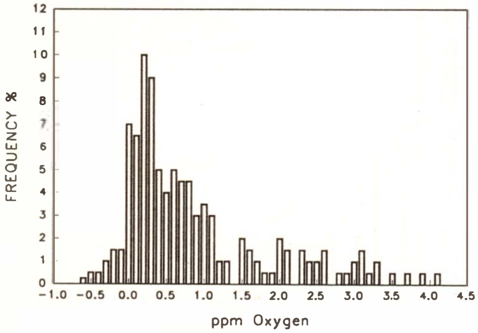

FIGURE 3. Frequency distribution of the oxygen concentration depth gradient observed in data from several years. The gradient is assimilated to the difference between the oxygen concentration at 0.5 m and the one at 4 m. Total number of paired observations, n= 188.

THE VARIANCE: SPACE-RELATED COMPONENTS

Obviously, the balance presented gives a very global picture but with a scarce predictive value, as the processes involved show strong heterogeneity in both space and time. To incorporate both horizontal and vertical spatial heterogeneity into our model, the budget will be recalculated dividing the bay into subcompartments:

(1) shallow northern platform, with a high macrophytic cover;

(2) shallow southern platform, with a low macrophytic cover;

(3) central basin:

(3.1) upper layer, mostly productive due to phytoplankton activity;

(3.2) lower layer, mostly degradative due to sediment activity;

The two layers are separated by a pycnocline, mostly a halocline, situated at 2 m depth.

The water over the platforms is supposed to be in conditions close to the annual average (water temperature 20 °C, salinity 35 ‰, photoperiod: 12 hours, average

TABLE V. Daily oxygen budget in the shallow platforms of the bay. Unless otherwise stated, data are in mg O_2 m^{-2}

	Northern platform		Southern platform	
	Day	Night	Day	Night
Macrophyte production	3340	0	370	0
Microphytobenthos prod.	362	0	362	0
Phytoplankton production	340	0	340	0
Macrophyte respiration	-250	-250	-28	-28
Sediment uptake	-880	-880	-305	-305
Daily change in [O2], ppm	+4.55	-1.77	+1.15	-0.52
Daily budget, ppm	+2.78		+0.63	

TABLE VI. Daily oxygen budget in the central basin. Oxygen consumption in the water column has not been considered. Data, unless otherwise stated, are in mg O_2 m^{-2}

	Day	Night
Upper layer (0-2 m)		
Phytoplankton production	1050	0
Daily change (ppm)	+0.5	0
Deep layer (2-4 m)		
Phytoplankton production	249	0
Microphytobenthos production	181	0
Sediment uptake	-770	-770
Daily change (ppm)	-0.17	-0.38
Net daily change	-0.55	

values of phytoplankton and benthic activities). Production data are taken from Table II; respiration of macrophytes is 15% of its production (PÉREZ, 1989). Consumption in the water column is not considered, neither is exchange with the atmosphere nor exchange with the central water mass. The resulting budget is shown in Table V. Regarding the central basin, the surface (0-2 m) water mass is assumed to be in conditions similar to those of the water over the platforms. The deep (2-4 m) layer has a salinity of 37 ‰. Consumption/production values are the yearly averages (see Tables II and V). The budgets of oxygen per m^2 of basin surface are shown in Table VI.

The shelf budget is clearly positive, and the excess of oxygen is likely to be exported to the atmosphere. The iteration of the basin balance presented in Table VI will lead to the exhaustion of the oxygen in the deep zone in 12-13 days if the consumption in the sediment is independent of its concentration in the water column, or slightly more if we consider that the consumption is depressed below 3 ppm (VIDAL, 1991). Since generalized anoxic situations have never been detected (Fig. 3), an alternative oxygen supply to the deep

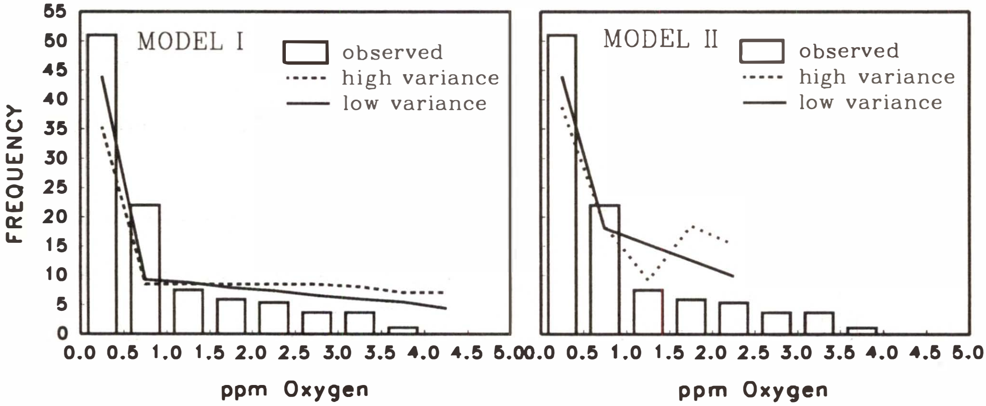

FIGURE 4. Frequency distribution in the oxygen concentration gradient. Observed data (from figure 3) are compared with predicted data from models explained in the text. Model I, without diapycnal eddy diffusion; Model II, including diapycnal eddy diffusion. A certain variance (high, dashed line; low, continuous line) has been assumed for the strong winds frequency.

zone, mainly through hydrodynamic processes, must exist. Two possibilities can be considered: i) water column mixing and/or exchange with the open sea, and ii) eddy diffusion through the pycnocline.

The bay/open sea exchange is controlled by two processes: dilution by fresh water (period around 10 days) and forced vertical mixing due to strong winds (period 10-12 days, duration 2 days). Although the first preserves stratification, the layer of deep (2-4 m) water is substituted by oxygen-saturated surface seawater. The second process implies that the water column loses its stratification, giving vertical profiles of oxygen concentration close to saturation values.

A simple model based on consumption data of Table VI was prepared to predict the oxygen concentration gradient frequency under these two hypotheses:

i) dilution and vertical mixing operate with exactly the same frequency throughtout the year. This means that a sequence of 4 days of vertical homogeneity (2 days of disturbance plus 2 days of re-stratification) followed by a fall of 0.6 ppm day^{-1} during 8 more days would be obtained.

ii) there is a certain variance in the time lag between two consecutive vertical mixing episodes, which means that the dilution cycle can also act.

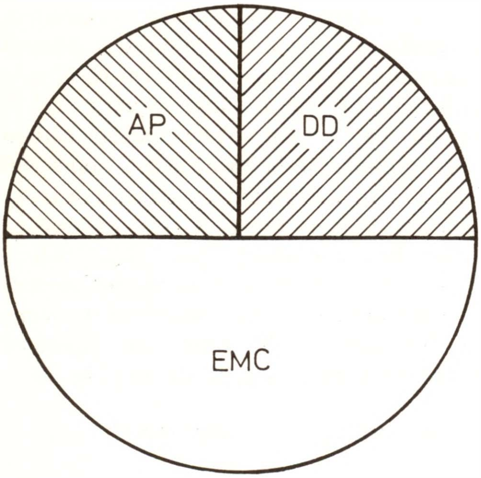

FIGURE 5. Relative contribution of the different processes oxygenating the deep water of the bay. AP, autochtonous production; DD, dyapicnal diffusion; EMC, exchange/mixing cycle.

The results are shown in figure 4a; these predictions clearly do not agree with the observed values, which suggest transport throught the pycnocline.

The magnitude of this process can be summarized by the coefficient of diapycnal eddy diffusion, k, but its estimation raises serious difficulties. k is related to the vertical density gradient and to the energy dissipation rate. LEDWELL & WATSON (1988) discuss an allometric relationship between N (the Brunt-Väisälä frequency) and k, whose parameters bear an error of at least one order of magnitude. From our field values of N, we obtain values of k ranging from 0.1 to 0.01 cm^2 s^{-1}.

A different approach may be followed based on the salt balance of the bay. The average salinity of the deep layer is 0.8 ‰ less than the water from the open sea and 2‰ less than the surface water (average of 26 profiles in a stratified situation). This implies an exchange of the deep layer with the surface layer of 0.5 m^3 m^{-2} over an average distance of 2 meters every 8-12 days, which can be translated into a diffusion coefficient k of 0.011-0.015 cm^2 s^{-1}. A realistic figure for k must be situated between 10^{-1} and 10^{-2} cm^2 s^{-1}, coinciding with the very general magnitude proposed by several authors of 0.2 cm^2 s^{-1}. Such values are obviously higher than the coefficients of passive diffusion, near 10^{-5} cm^2 s^{-1}.

Oxygen concentration gradient frequencies were recalculated including the diapycnic eddy diffusion. As shown in figure 4b, the expected values become much closer to the field measurements.

Consequently, a tentative summary of the sources of oxygen to fit the deep layer demand can be summarized as in figure 5. As shown there, the deep layer is strongly heterotrophic (75 %) and the main oxygen supply pathway is supported by the mixing/exchange cycle.

Regarding the shelves, the day is not a good time scale for testing the model, as there are no net increases in oxygen concentration at the end of a 24 hour cycle (Fig. 2), due to the loss of oxygen to the atmosphere, which can be estimated at 1,800 mg O_2 m^{-2} per day for the northern shelf and 403 mg O_2 m^{-2} day^{-1} for the southern. The model should be tested on an hourly basis, but in fact, as we will discuss later, the oxygen dynamics of the shelves is scarcely relevant in the overall oxygen dynamics of the bay, due to the close interaction with the atmosphere. Moreover, some of these aspects, mostly concerning seagrass beds, have already been discussed in another study (PÉREZ & ROMERO, in press).

OTHER COMPONENTS OF THE VARIANCE

The relative agreement between the theoretical values obtained under the assumptions described and those observed in the field seems to indicate that the system works, at least in general trends, in accordance with our hypothesis. Even so, since other components of the variance have been neglected, certain doubts may persist on the validity of the model. Some of these possibilities are examined below.

a) SPACE-RELATED COMPONENTS

a1) Spatial heterogeneity in oxygen turbulent advection due to the hydrodynamic and morphological characteristics of the bay. In general, vertical mixing due to NW winds is more intense in the eastern part, but, conversely, estuarine circulation brings more oxygen to the western part of the bay.

a2) Important horizontal differences in planktonic production. Such differences indeed exist (DELGADO, 1986), but this fact is not reflected in the oxygen consumption of the sediment of the central basin (VIDAL, 1991). There is probably a certain homogeneisation of the phytoplankton biomass before its sedimentation.

a3) Spatial segregation of the production and the degradation of macrophytes. Zones of detritus accumulation have been not detected while in the seagrass beds stocks of necromass are built up to 50 % of the foliar biomass in September (M.A. Mateo, pers. comm.). Conversely, dead macroalgae accumulate on the shallow shelves, in which anoxia has been detected in a fine layer (a few cm) close to the sediment; the rest of the water column is oxygenated from the atmosphere. Likewise, these accumulations of dead thalli have also been found at the base of the slope of the northern shelf, although in relatively small areas.

a4) Localised allochthonous contributions. The sedimentation, precipitation and flocculation of materials take place in the northern shelf, which is reflected in the greater oxygen consumption of the sediment there.

a5) Large man-made consumer populations (bivalve cultures). Mussel cultivation concentrates 100 Tm of C in a reduced area with a volume equal to 2.2 % of the bay's total. Their annual carbon consumption can be evaluated at some 700 Tm y^{-1}. In the period of greatest activity (spring-summer) some 5 Tm of oxygen may be consumed per day, which represents 17 % of the total oxygen content of the cultivation area. Data from this zone are included in the field data presented (Stations 4 and 5 in Table IV and Fig. 1).

b) TIME-RELATED COMPONENTS

b1) Time-dependence of allochthonous organic matter inputs. The irrigation channels are open from April to October, inducing higher consumption rates in the water column and, finally, in the sediment.

b2) Pulses of phytoplankton production. Plankton production is likely to be coupled with the passing of meteorological fronts. Strong winds induce both water mixing and sediment resuspension and presumably a massive release of phosphorus (VIDAL, 1991), a nutrient which appears to have a limiting action. The expected result is a phytoplankton growth pulse a few days after the event, ending due to the exhaustion of the limiting nutrient or due to dilution/exportation forced by the following mixing and exchange event. The pulse results in a more active oxygen depletion in the deep zone due both to an enhanced particulated matter sedimentation and to a minimization of autochthonous oxygen production caused by the shadowing of the phytoplankton of the upper layer.

b3) Variability of the exchange frequency with the open sea, especially during the period in which the dilution cycle is not operating due to the closure of the irrigation channels (from October to April).

b4) Variability in the diapycnic diffusion rate, which depends on a wide number of factors ranging from the most local (wind conditions, intensity of stratification) to the most general (internal waves, etc.).

GENESIS OF EXTREME SITUATIONS: SOME REFLECTIONS ON COVARIANCE

The appearance of situations of anoxia will be linked to the degree of coupling amongst the variance components, that is the coincidence in space and/or time of processes enhancing oxygen consumption above the mean. Some of the possible coincidences are briefly discussed below.

In the case of the shelves, in early autumn oxygen budgets can be strongly negative due to: (i) high water temperatures; (ii) scarce macrophyte production; (iii) large amounts of dead leaves (30 g C m^{-2}) decomposing at a rate of 0.1 g C day^{-1} (PÉREZ, 1989); (iv) lack of phytoplankton production; (v) massive contributions from the channels leading to BOD_5 up to 5 ppm. Under these assumptions, daily consumption on the shelves could reach an extreme value of 4.3 ppm. Nevertheless, oxygen concentration does not reach low values since diffusion from the atmosphere, a process estimated at 3.5×10^5 mg O_2 m^{-2} day^{-1} atm^{-1} (HUTCHINSON, 1957) can largely balance the oxygen demand. Moreover, oxygen transport from the atmosphere is accelerated by the high frequency of soft winds (breezes) in the zone. For the same reason, oxygen depletion is not likely to occur at the superficial layer of the central basin, even in extreme conditions (without primary production and with a high BOD_5).

In the deep water layer the situation is far more complex. According to the proposed model, and using the minimum diapycnal diffusion coefficient, it would take 7 windless days of stratification to reach values less than 3 ppm, and 11-12 days to fall to 1 ppm, a value around which the parameter would stabilise. Using a maximum coefficient, 25-30 days of calm would be necessary to reach 3 ppm. Thus, and bearing in mind the "stand-by" times duration of the disturbance + restratification events, the 14-day cycle can lower the oxygen concentration to 50 % of saturation value, while the 10-day cycle can produce values of 60-70%. It seems likely, considering the superposition of both, that there is only a low probability of values of oxygen concentration below 60 % of saturation. Moreover, when the frequency of mixing events is minimal due to calm weather (summer), the channel flows are at their maxima, and the dilution cycle and/or estuarine circulation accelerates; conversely, when the channel flows are minimum (winter) the frequency of strong winds is high. The maximum probability of a lasting stability in the water column would correspond to winter anticyclonic situations

TABLE VII. Variance-covariance matrix between processes affecting oxygen depletion in the deep zone (see explanation in text). Positive covariances are represented by + symbols, negative covariances by - symbols. The number of symbols represents the magnitude of the variance (or covariance).

1) Sediment uptake
2) Organic allochthonous inputs
3) *In situ* production of phytoplankton (pulses)
4) Low frequency of deep water renewal through dilution cycle and/or estuarine circulation
5) Low frequency of vertical mixing due to the absence of strong winds
6) Low rate of dyapycnical diffusion
7) Absence of primary production in the deep zone

	1	2	3	4	5	6	7
1	+	+	+	-	.	.	.
2		++	+	---	.	+	.
3			+++	-	---	.	+
4				++	.	---	.
5					+	.	-
6						?	.
7							+

(typical in January-February). But this situation rarely lasts more than 15 days, and, in addition, the low water temperatures (8-10 °C) in this period would minimize the oxygen consumption rate in the water column.

Consumption in the sediment was not seen to be particulary variable (VIDAL, 1991; see Table III); therefore, departures from the mean in the consumption rates can only be expected in the water column. For a consumption rate of 1 ppm day^{-1} for 5 days an easily degradable organic carbon content of 2 mg l^{-1}, obviously corresponding to much higher TOC contents, would be required. Bearing in mind that the maximum POC values measured in the water of the bay were never higher than 1.2 mg l^{-1}, the above mentioned consumption is unlikely to be reached, except in clearly-defined situations. One of these could be due to a massive resuspension of sediment by a heavy storm, but this would represent a short-lived phenomenon, and besides would bring agitation and oxygenation. Another would correspond to a phytopalnkton bloom, but given that these blooms take place 5-7 days after the passing of the front and implying an oxygen increase in both surface and deep layers, before the enhancement of the consumption rates, the high oxygen demand induced by these blooms will only be relevant in a small part of the mixing/dilution cycles.

All these speculations can be formalised a little more, if necessary, by accepting that the degree of coupling or uncoupling between two processes, on which the oxygen exhaustion depends, can be expressed in terms of covariance. The functioning of the system can be summarised using a variance/covariance matrix, like the one tentatively proposed in Table VII. Since data are not available for a detailed quantification, this matrix represents a purely conceptual and qualitative construction. However, we can accept that if there is a set of processes linked by high and positive values of mutual covariances and independent of the rest, anoxia events are likely to occur, since deviation from the mean will be maximum. Conversely, if such subsets do not exist, the values will be kept closer to the average situations, through compensation among diverging processes.

Accepting the values proposed for the matrix in Table VII, the prediction for Alfacs Bay appears to be that anoxia is an unlikely event, given that the highest covariances are negative. The maximum probability comes from an intense phytoplankton pulse followed by a long calm period and minimal freshwater inputs, but this combination appears unlikely and, in any case, very localised in time.

An analogous matrix can be constructed paying attention to the space variance/covariance of the processes involved. The most positive covariances would appear between the allochthonous carbon inputs, the chlorophyll values (estimation of phytoplankton activity) and the stock of consumer organisms (mussel beds). These three variables are at their maxima in the northern zone of the bay. Since the shallow shelves are oxygenated from the atmosphere, the anoxia events are most likely to occur at the base of the slope and adjacent deep zones where materials from the shelves (including macroalgal and other organic detritus) can accumulate and where the mussel beds are installed. This is the place where anoxia situations can be generated at particular times of the year, which again takes us back to the time problem and leads us to consider the possibility of a three-dimensional variance/covariance matrix which integrates spatial and temporal elements.

CONCLUSION

The preceding discussion has shown how anoxia is prevented in the system under study. From a more general point of view and apart from emphasizing the close coupling between physical and biological processes, a central question arises: why are situations of anoxia more frequent in other estuaries? An answer based on three properties of the Alfacs Bay can be tentatively proposed; these are:

a) a relatively low rate of external input, from 40 to 70 g C m^{-2} y^{-1}, and a similarly low primary production (180 g C m^{-2} y^{-1});

b) a high wind frequency along with a surface to volume ratio high enough to transform efficiently the wind energy into estuarine circulation;

c) a pathway of carbon degradation and oxygen consumption mainly in the sediment, i.e., dominance of benthos over plankton in the catabolic processes.

These singularities are clearly reflected in the data compiled by NIXON (1981), summarized in figure 6. Considerations a) and b) refer above all to the relatively reduced size of the channel through which the energy of the ecosystem flows, which gives an average situation in which anoxia can be prevented by physical oxygenation processes. c) refers to properties of the subsystem controlling the heterotrophic

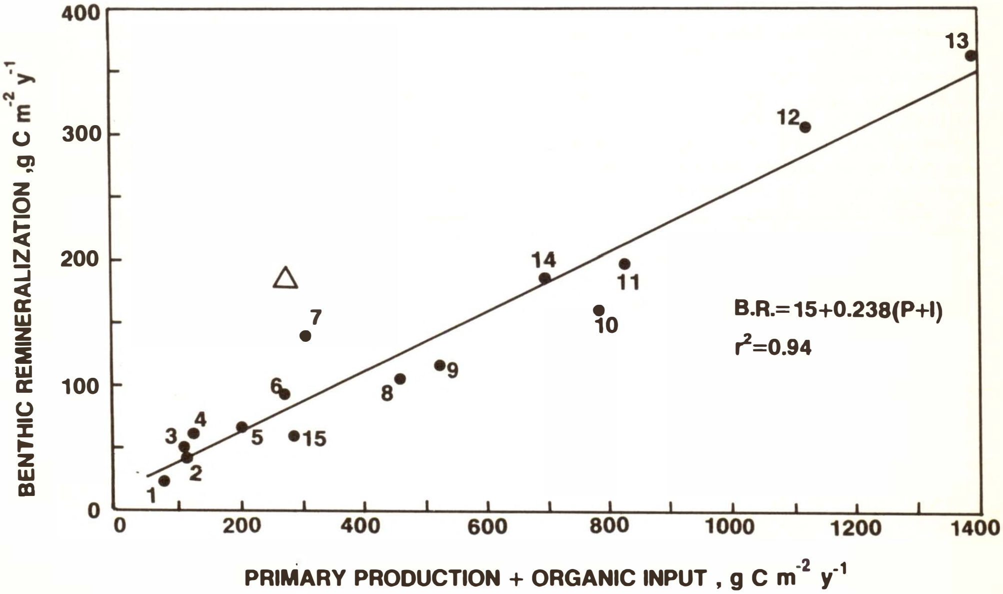

FIGURE 6. Benthic remineralization plotted against total organic carbon input for a series of different estuaries (from 1 to 15; data compiled by NIXON, 1981). Alfacs Bay is also represented (Delta).

aspects. Benthos can be considered as a subsystem of greater inertia and memory, which is able to make the oxygen consumption independent of environmental fluctuations, at least to a certain extent. This in turn produces a lowering in both the variance and the covariance, allowing the system to persist at values not excessively far from the average.

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