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HYDROGRAPHIC CONDITIONS AND NUTRIENT REQUIREMENTS DURING RED TIDE IN THE KAŠTELA BAY (MIDDLE ADRIATIC)

RED TIDE U KAŠTELANSKOM ZALJEVU (SREDNJI JADRAN) OSVRT NA HIDROGRAFSKE PRILIKE I POTROŠNJU HRANJIVIH SOLI

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Under the conditions of persistent and substantial input of nutrients and organic matter of anthropogenic origin to a semi-enclosed middle Adriatic basin (Kaštela Bay), summer red tide with the dominance of the species *Lingulodinium polyedra* (Stein) comb. nov., has become quite ordinary phenomenon in its most heavily loaded part.

An analysis of hydrographic, chemical and biological parameters recorded at four stations during monitoring in 1989 shows surface temperature to be of great importance controlling bloom intensity. Their correlation could be described by an exponential equation applicable to all studied stations.

Of nutrients, nitrate was an important bloom factor in the vicinity of input sources, whereas no correlation could be established at the most offshore station.

INTRODUCTION

The role and importance of defined hydrographic factors and nutrients for the initiation and persistence of intensive monospecific dinoflagellate blooms ("red tide") recorded all over the world have not yet been fully understood irrespective of the fact that they have been intensively studied.

Sea water temperature plays a specific role among hydrographic factors, particularly in the bottom layers as an initiating factor of cyst activation (Marasović, 1990, 1991). There are also some reports of its positive effects on bloom intensity in the surface layer (I w a s a k i , 1979; F o n d a U m a n i , 1985).

The attitudes concerning nutrients, their required concentrations and individual forms indispensable for red tide development greatly differ, from their total negation (S w e e n e y , 1979) to definite indicators of preferential uptake of nitrate in relation to other nutrients, for the species *L. polyedra* (B l a s c o , 1977). It still appears that, as to the nutrients, the basic prerequisite is the availability of minimum quantities meeting half-saturation constant-K_s of dominant red tide species (E p p l e y *et al.*, 1969). Presumably, the disturbed N:P ratio supports the dominance of individual species A u b e r t *et al.*, 1984).

Nitrogen sources for bloom development may be of anthropogenic origin (H o l m e s *et al.*, 1967), the upwelling (W a l s h *et al.*, 1974; T a k a h a s h i *et al.*, 1977), whereas some species take the advantages of active migrations in the water column (H o l m e s *et al.*, 1967) even in the case of opposite water mass motions (B l a s c o, 1978).

The occurrences of red tide are not unusual in the Adriatic and the best known locations are in its northern eutrophic part for which F o n d a U m a n i (1985) gave a historical review of bloom occurrences. In the middle Adriatic (an oligotrophic area) the red tide is still limited to a microlocation (Vranjic Basin-VB) in the eastern part of the Kaštela Bay (Fig. 1). Basic hydrographic properties of VB are positive summer and negative winter gradient of surface temperature, as well as reduced surface salinity in the offshore direction. Since the Kaštela Bay is a semi-enclosed bay with 12 flushing periods a year (Z o r e - A r m a n d a , 1979), nutrient budget in the VB is greatly affected by untreated sewage effluents of the town of Split, industrial waste waters and river Jadro, so that their concentrations in less saline surface layer might reach very high values (M a r a s o v i ć and V u k a d i n , 1982).

To distinguish the effects of different factors on the blooms, a monitoring programme was started in the VB in 1988. The first results concerning basic hydrography of the area during blooms have already been published (M a r a s o v i ć *et al.*, 1991).

MATERIAL AND METHODS

Sampling and measurement stations (Fig. 1) were selected on the basis of earlier bloom occurrences. Four stations were sampled at two depths (0.5 m and near the bottom) at approximately weekly intervals from June to September 1989. Since the order of magnitude caused by tides and storm surges is 10 cm in the middle Adriatic (M o s e t t i and M a n c a , 1972) tidal state component was neglected during sampling, regularly performed between 9 and 11 a.m. Measurements included temperature; salinity; oxygen; pH; nutrients: NO_3 - N, NO_2 - N, NH_4 - N, PO_4 - P and SiO_2 - Si; phytoplankton and bacterial numerical abundance and phytoplankton species composition.

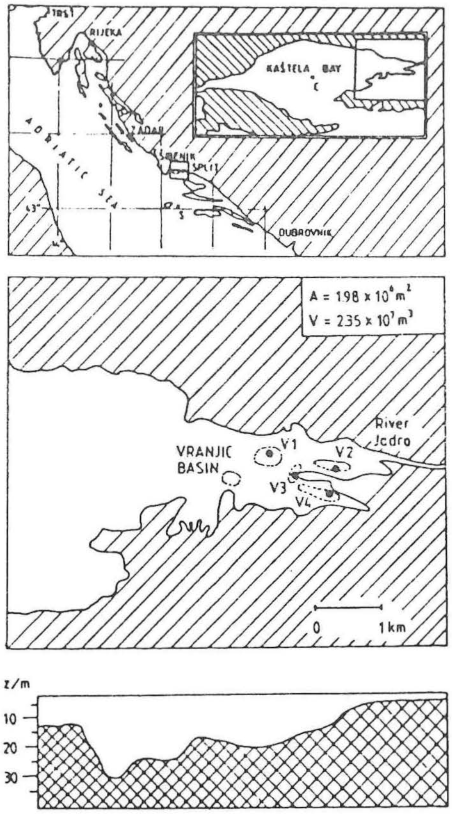

Fig. 1. The Kaštela Bay with the Vranjic Basin V1-4 stations; C: Central Kaštela Bay station; S: Open sea station; Encircled area: Bloom centers

Chemical parameters were analyzed by standard oceanographic method (Armstrong, 1967; Grasshoff, 1965; Head, 1971; Solorzano, 1969; Strickland and Parsons, 1968).

Phytoplankton was analyzed by Utermohl method on an inverted microscope after sample preservation in 2% formaldehyde solution and 24 h sedimentation.

Total counts of bacteria were made by using the acridine orange direct count (AODC) technique (Hobbie *et al.*, 1977).

Meteorological observations were carried out daily as well as the Jadro River and waste water flow rate and the results of their quantitative composition.

RESULTS

Intensive phytoplankton blooms (N/L^{-1} to $7x10^7$) were recorded from the surface layer at stations V1, V2, V3 and V4 in summer 1989. Counting of main present species showed that a dinoflagellate species *L.polyedra* was highly represented (over 90%) in the total bloom population.

The other important biological group - bacteria (expressed as AOCD) followed closely the phytoplankton bloom with high coefficients of correlation between their abundances.

Hydrography

During the entire measurement period negative vertical concentration gradient of both biological parameters were particularly marked, as well as that of chemical indicators of biological activity, that is dissolved oxygen content and pH of the sea water. On several occasions during blooms this lead to the occurrence of anoxia and fish kills. In general, the effects of hydrographic factors on the initiation and persistence of the bloom as well as the reflexive response to them were identical to those of the preceding year (Marasović *et al.*, 1991). On the basis of the ranges of several parameters, characteristic of the surface (sl) and bottom layer (bl), given in Table 1, it may be concluded that the parameters are greatly variable in the VB in summer.

Table 1. Ranges of measured parameters

	T/°C	$s x 10^{-3}$	O_2/%	pH
(sl)	19.2-27.6	22.61-37.06	59-277	7.97-8.74
(bl)	16.4-23.9	37.20-38.84	14-144	7.79-8.21

	N_{TOT} mmol m^{-3}	PO_4-P mmol m^{-3}	AODC x 10^6 ml^{-1}	Phytoplankton N x $10^3 dm^{-3}$
(sl)	41.145-93.65	0.040-0.6	0.27-19.6	1.5-70000
(bl)	0.822-50.725	0.045-0.6	0.16-3.39	0-980

The influence of surface sea water temperature on bloom intensity in the surface layer is shown in Fig. 2. It is quite obvious that the temperature of 20°C is of crucial importance for the development of *L. polyedra* bloom, whereas phytoplankton positively responded to further temperature increase, as well.

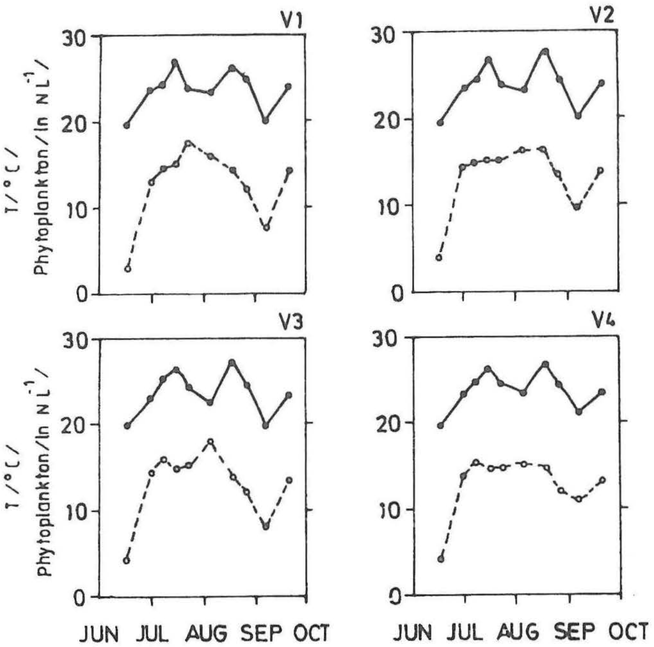

Fig. 2. Temporal distribution of surface temperature (solid line) and the total numbers of phytoplankton (broken line) in the surface layer

The correlation between temperature and bloom intensity might be expressed by a general exponential equation (1):

$$y = exp\ (a + b) \qquad (1)$$

where: y = N - total number of phytoplankton/dm^{3}
x = T - sea water temperature/°C
a,b = coefficients of variables

By a logarithm of the equation (1) and substitution of symbols the equation (2) was obtained:

$$\ln N = a + kT \qquad (2)$$

where: k = linear slope.

Fig. 3 depicts the lines obtained by the application of the equation (2) and the method of least squares, for all four stations. Their slopes and basic statistical elements of the lines are shown in Table 2.

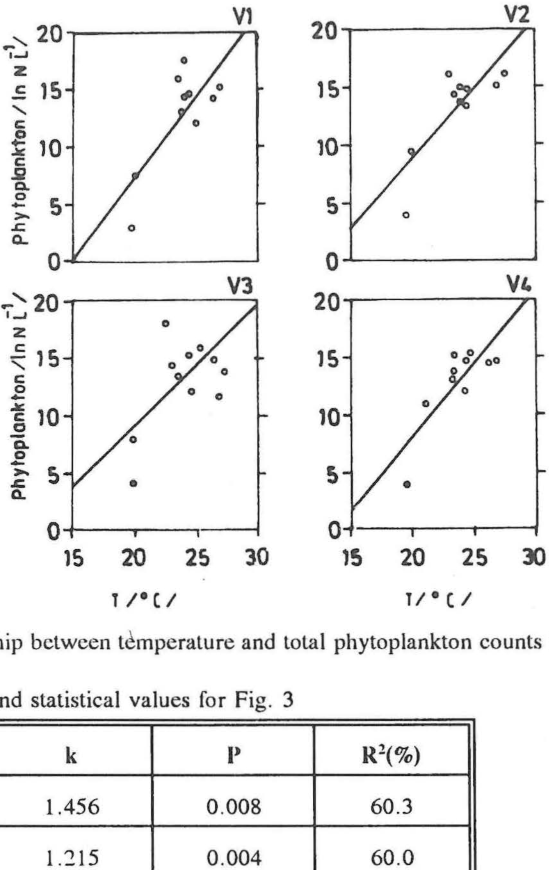

Fig. 3. Relationship between temperature and total phytoplankton counts in the surface layer

Table 2. Slopes and statistical values for Fig. 3

Station	k	P	R^2(%)
V1	1.456	0.008	60.3
V2	1.215	0.004	60.0
V3	1.063	0.044	41.6
V4	1.297	0.004	66.1

The fact that bloom was not reduced with significant surface temperature drop from T_{sl} = 26.3 - 26.9 C (July, 14th) to T_{sl} = 22.4 - 23.4 C (August, 4th) (Fig. 2) is indicative of the effects of other factors on the bloom.

As shown by Fig. 4, reduced salinity values were recorded along with the elevated SiO_2 concentrations in the surface layer on August 4th. This points to the fact that the fresh water input to the VB was intensified. Since, apart from SiO_2, the values of other nutrients were increased, as well, particularly those of NO_3 (up to 92.5 mmol^{-3}), they presumably made possible the elimination of the adverse temperature effects.

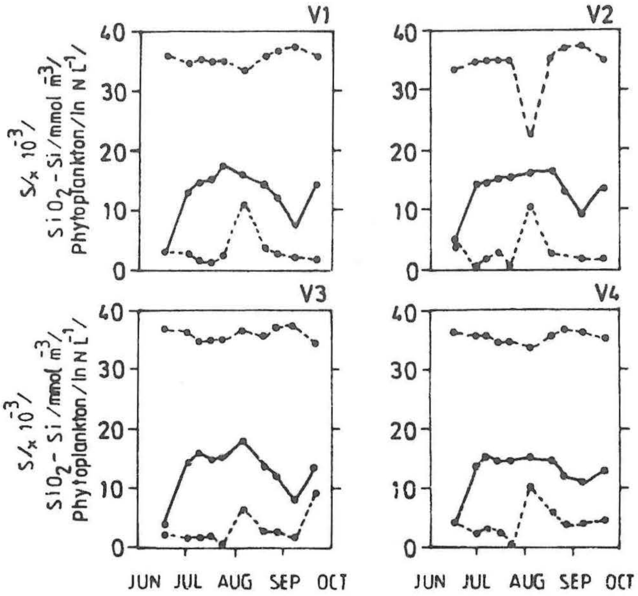

Fig. 4. Temporal distribution of the total phytoplankton counts (solid line), SiO content (double broken line) and salinity (broken line)

Nutrient salts

Nutrient balance is in this area determined by mentioned inputs by the river and waste waters. Annual total input was assessed at N_{TOT} = 340t and P_{TOT} = 84t (B a r i ć 1989), of which about 2/3 originate from the waste water and 1/3 is discharged by the Jadro River. Their impact may be estimated comparing nutrient content in the surface and bottom layer of VB with the data for the stations C and S (Fig. 5).

It may be seen how the occurrence of flux of nutrients released by the processes of sediment remineralization, normally very important in oligotrophic areas of the middle Adriatic - station S, looses in importance at station C in the Kaštela Bay and is totally unimportant component in VB.

Negative vertical nutrient gradient is not particularly marked due to the waste water content where organic matter (BOD_5 values amount even to 1 g dm^{-3}) makes up a considerable proportion. Upon sedimentation and biological degradation they affect an increase in nutrient content in the bottom layer, so that their values considerably exceed those at the central station C in the Kaštela Bay. Mean measured concentrations of individual forms of nutrient in VB are given in Fig. 6.

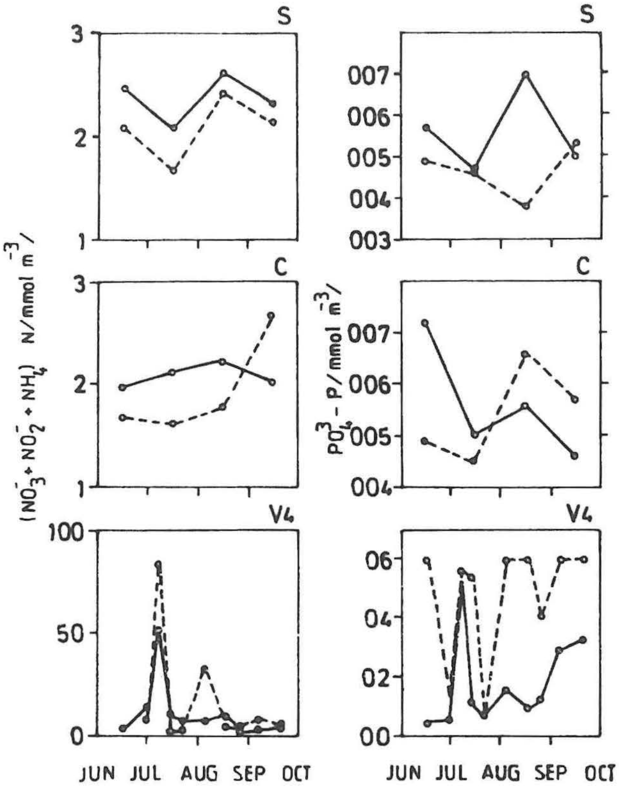

Fig. 5. Nutrient concentrations at stations V4, C and S in the surface (solid line) and bottom layer (broken line). Data for the stations C and S are five year means (1985-1989) for summer

The succession of concentrations was the same in the surface layers of all the stations: $NO_3 > NH_4 > PO_4 > NO_2$, the absolute concentration being highest at stations V3 and V4 (direct impact of waste waters). The concentrations were lower at station V1 presumably due to the process of dilution and elimination of nutrients from the surface layer. Concentrations were lower in the bottom layer, however with the same succession, the percentage proportion of ammonia being many fold increased due to biological processes. Assuming that the nutrient input is constant to a basin which quantitatively satisfies the red tide requirements (with no limitations as to the individual forms of nutrients), it was attempted to correlate present nutrients and red tide intensity by a correlation analysis (Table 3).

Uniform correlation was not obtained for all the VB stations (Table 3). Significant agreement with NO_3 was obtained for three stations in the vicinity of discharges (V2, V3 and V4) whereas the situation at the more offshore station V1 was more complex.

Table 3. Correlation coefficients of N° of phytoplankton and nutrient salts in the surface layer

Station	PO_4-P	NO_3-N	NO_2-N	NH_4-N
1	0.468	-0.183	-0.171	-0.311
2	0.051	0.747*	-0.321	-0.577
3	0.500	0.985**	0.262	-0.124
4	-0.268	0.719*	0.304	0.283

*$p < 0.05$

**$p < 0.01$

DISCUSSION

Hydrography

After the results of this study (Fig. 2) the bloom is initiated by the temperature of the surface layer of 20° C, which confirms earlier hypotheses (M a r a s o v i ć , 1990; M a r a s o v i ć *et al.*, 1991) on the exceptional importance of this boundary temperature. The correlation between phytoplankton density and sea water temperature (Fig. 3) was also established during the measurements in VB.

The extent of temperature effect on phytoplankton is shown by the fact that similar linear slopes and determination coefficients (Table 2) were obtained for all the station which differ as to their hydrography and nutrient content. They point to the fact that temperature variations account for more than 60% of the variation in phytoplankton numbers at the stations V1, V2 and V4 and for more than 40% at station V3. Laboratory results confirmed positive temperature impact on phytoplankton growth. So E p p l e y (1972) in his summary of the results for more than 100 phytoplankton species, reported growth of phototrophic, unicellular algae as a joint exponential

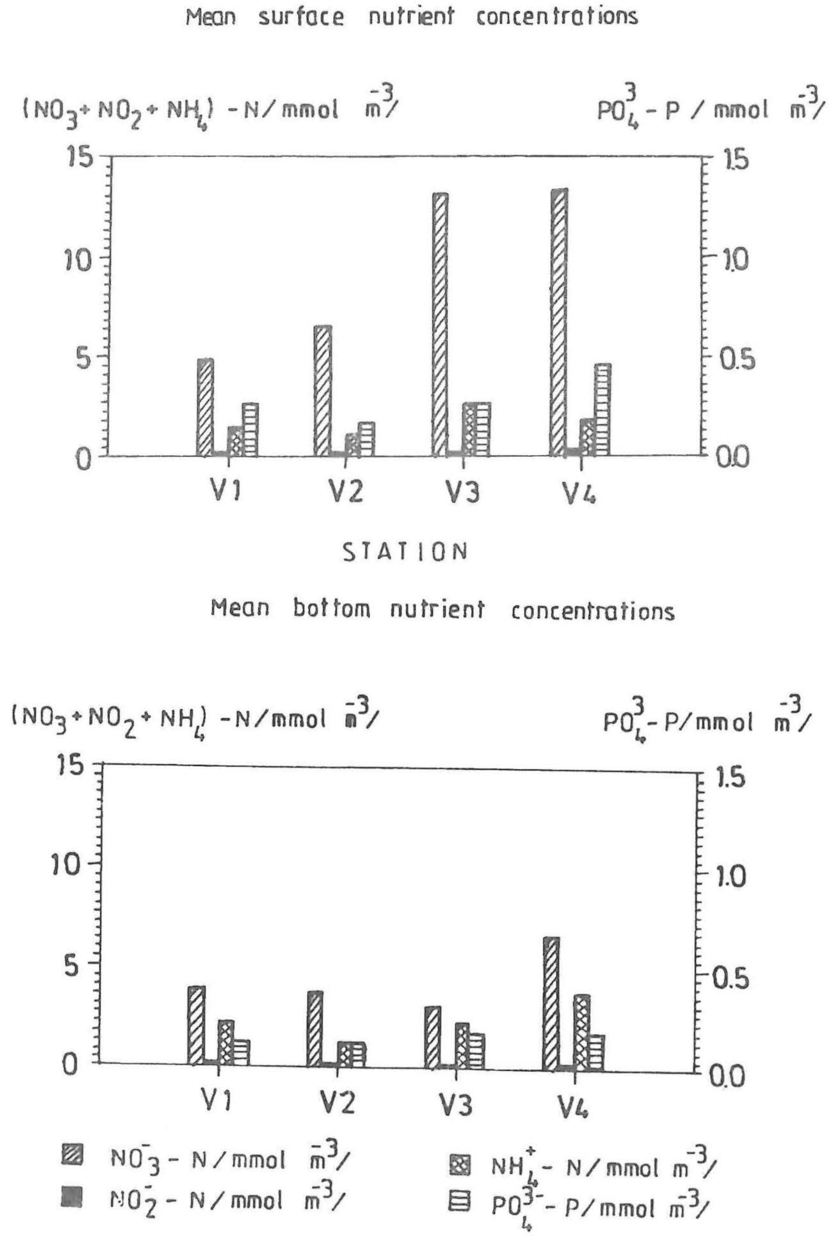

Fig. 6. Mean nutrient values for the surface and bottom layer in VB for summer 1989

response to temperature increase, which may also be expressed with a linear equation (3):

$$\log_{10}\mu = 0.0275\ T - 0.07 \qquad (3)$$

where μ = growth rate (doubling/day) and T = temperature in°C.

Field studies also show the importance of temperature for different blooms. I w a s a k i (1979) reported that in Japan (Seto Inland Sea and Coastal Waters of Shima peninsula) "most red tides have occurred at temperature from 20-27°C, most frequently at 24-26°C". F o n d a U m a n i (1985), studying the hydrography of the Gulf of Trieste reported an increase of surface temperature of 2-3°C which preceded the bloom. V u k a d i n (1990), analyzing the factors which presumably lead to an intensive diatom bloom in summer 1988, which spreaded almost throughout the Adriatic, found that there was a positive sea water temperature difference of 2°C in relation to long-term values.

Nutrient salts

Good agreement of found nitrate concentrations with phytoplankton abundance at stations in the VB may be accounted for by the ability of the species *L. polyedra* to utilize with almost the same efficiency nitrogen compounds other than ammonia as nitrogen source for cell anabolism, particularly NO_3, which it gradually transforms into NH_4 by reductase (H o l m e s *et al.*, 1967). This preferential uptake of nitrates as a source of nitrogen for *L. polyedra* bloom requirements was reported by the studies carried out in the La Jolla Bay (H o l m e s *et al.*, 1967) and in the open sea - Pacific (W a l s h *et al.*, 1974; B l a s c o , 1977). However, the possibility to correlate the bloom at station V1 (most off the source of nutrient input and with considerably lower concentrations in the surface layer, but with the identical bloom intensity as that at other stations) with individual nutrient forms points to the conclusion that nitrate is not an absolute prerequisite for red tide development. Possibility of utilization of inorganic forms of nitrogen salts (NO_2, NO_3) and organic nitrogen (Urea) during growth of natural phytoplankton communities (E p p l e y , 1971) is as well applicable to the species *L. polyedra*. Different relationships between blooms and nitrate may be accounted for by the fact that at the stations V2, V3 and V4, close to the sources of waste waters, they satisfy their nitrogen requirements by the high content of inorganic NO_3 in the sea water whereas at the offshore station V1 they are satisfied by a combined uptake of inorganic and organic forms of nitrogen compounds.

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KRATKI SADRŽAJ

U uvjetima snažnog i značajnog dotoka hranjivih soli i organske materije antropogenog porijekla u jedan poluzatvoreni bazen u srednjem Jadranu (Kaštelanski

zaljev) u njegovom najopterećenijem dijelu postala je uobičajena ljetna pojava "red tide" sa dominirajućom vrstom *Lingulodinium polyedra* (Stein) comb. nov.

Hidrografski, kemijski i biološki podaci zabilježeni na četiri postaje tijekom 1989. godine ukazuju na veliki značaj površinske temperature mora kao regulatora intenziteta cvatnje. Utjecaj temperature mogao se za sve postaje opisati jednom eksponencijalnom jednadžbom.

Na postajama smještenim u blizini dotoka otpadnih voda, nitrat je od hranjivih soli bio najvažniji faktor cvatnje, dok se za najudaljeniju postaju nije ustanovila korelacija intenziteta cvatnje niti sa jednom soli.