OBSERVATIONS ON THE STRUCTURE OF RED TIDES IN NEW HAVEN HARBOR, CONNECTICUT[1]

By

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Abstract. Observations were made on noncatastrophic red tides in New Haven Harbor, Connecticut, in the summers of 1952 and 1953. Hydrographic, chemical, and biological factors were measured and weather conditions were taken into account. Oxygen production-consumption experiments and nutrient enrichment experiments were also carried out. High concentrations of red tide organisms, here two species of *Goniaulax*, were found to be associated with stable water masses of inner harbor origin. The configuration of the harbor permits the development and retention of water masses; this tendency is reinforced by large volumes of nutrient-rich fresh water entering the inner harbor, by certain wind patterns, and by high radiation values. Adequate time, illumination, nutrients, and favorable temperatures are essential for red tide development. Stable, discrete, nutrient-rich water masses in the sea adequately meet these conditions.

Introduction and Methods. In July 1952 and June and July 1953, noncatastrophic red tide blooms of *Goniaulax* spp. were observed in New Haven Harbor, Connecticut. Similar blooms are known to have occurred in other years. Cursory examinations were made through most of the bloom periods and more detailed observations were obtained on three occasions at stations shown in Fig. 1.

At a few stations serial observations were made, but at the rest only surface samples were taken. Salinity, temperature, chlorophyll, cell counts, dissolved oxygen, phosphate, and nitrate-nitrite were measured in some or all of the samples. Temperatures were taken with a bucket thermometer; a bathythermograph was also used at some stations. Salinity titrations were made by means of the simplified silver nitrate method suggested by Harvey (1928). Raw water samples were filtered through Whatman No. 42 paper filters and were extracted overnight in 90% acetone for chlorophyll measurements. The amount of chlorophyll was determined by reading the sample in a Klett-Summerson photoelectric colorimeter with a No. 66 filter and comparing the result with a known chlorophyll standard. Raw water samples were preserved with formalin to determine phytoplankton

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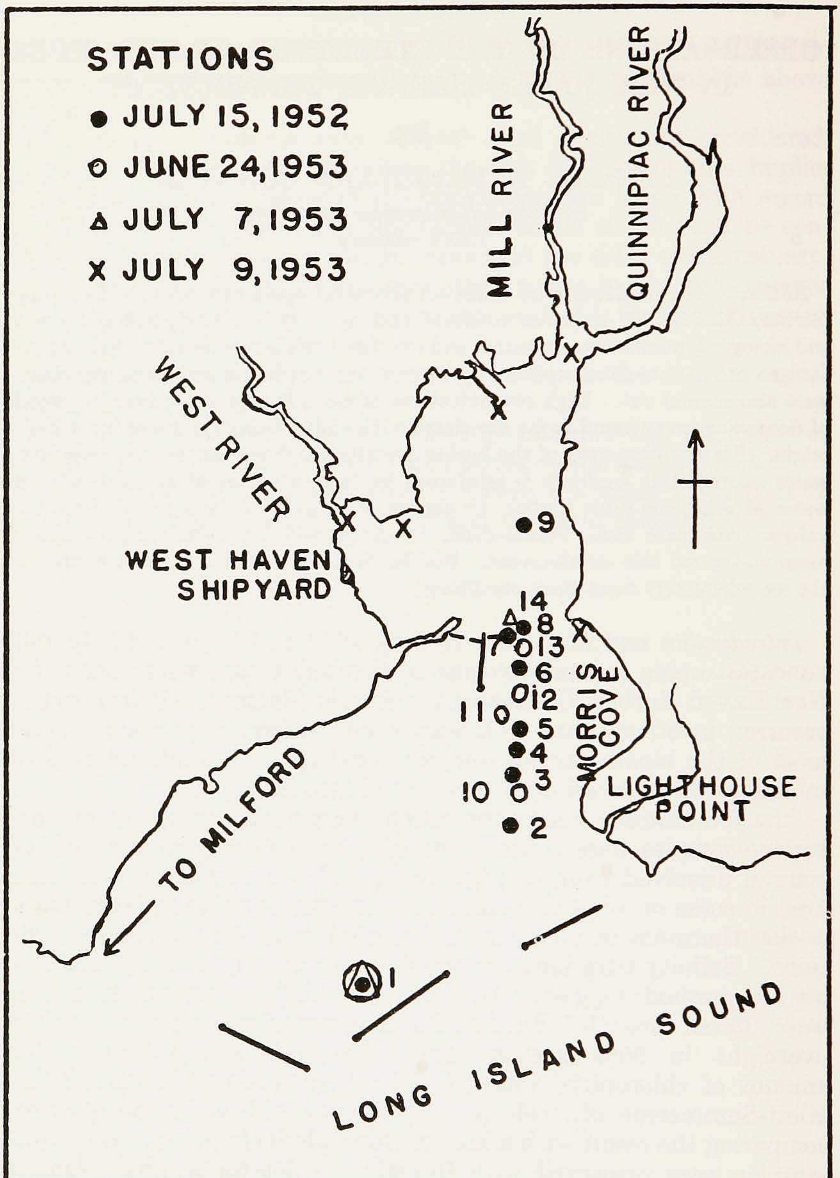

Figure 1. Diagram of New Haven Harbor, showing station positions and other points of reference. Scale: one inch = 1.4 miles.

species and total numbers. Some samples were counted directly; others were allowed to settle and were concentrated before counting. Dissolved oxygen was measured by the Winkler technique. Phosphate was determined by the Denigés-Atkins ceruleomolybdate method; the treated samples were read in the Klett with the No. 66 filter. Water treated with strychnidine-sulfuric acid reagent (Zwicker and Robinson, 1944) was read in the Klett with the No. 54 filter to estimate nitrate-nitrite concentrations.

The light bottle-dark bottle technique was used in 1953 to determine photosynthetic oxygen production. Other experiments were designed to determine the effect of nutrient enrichment and altered salinity on the 1953 blooms. The nutrients were *P*, added as KH_2PO_4, *N*, added as $NaNO_3$, and a soil extract. Since the total *P* and *N* present in the soil extract was not determined, *P* and *N* values in these bottles are marked questionable in Table IV. Salinity was increased by adding more saline Long Island Sound water to the experimental water and was decreased by adding a small quantity of distilled water. All of the experimental bottles were suspended to a constant depth of 0.5 m in Milford Harbor, Connecticut, for two days prior to analysis.

Weather data were obtained from the New Haven Weather Bureau.

General Description. The first red tide, already well developed, was reported on July 14, 1952. On the following day observations showed that it occurred in patches and streaks from the mouth of New Haven Harbor north to the mouth of the West River, where the maximum concentration was found (Fig. 1). From New Haven southwest along the coast to Milford additional streaks were seen in tide rips. The major organism of the bloom was *Goniaulax* sp., probably *Goniaulax africana* Schiller. On the next day (July 16) the bloom appeared as one large patch in New Haven Harbor along the east shore from the mouth of the Quinnipiac River to Morris Cove. At the West Haven Shipyard workmen observed red tide on the west shore and reported that contact with it produced a skin irritation. However, no injury to the marine organisms of the area was observed.

On June 24, 1953, one discrete patch of red tide was observed south of Lighthouse Point; from there into the harbor the concentration of organisms gradually increased, and, so far as could be observed, was greatest off the mouth of West River. This organism, smaller than that observed in 1952, resembled closely the descriptions of *Goniaulax cochlea* Meunier.

The third bloom, again *Goniaulax africana* (?), was observed in its initial stages on July 7, 1953. The water in the main channel of New Haven Harbor was slightly discolored in several places; one small red

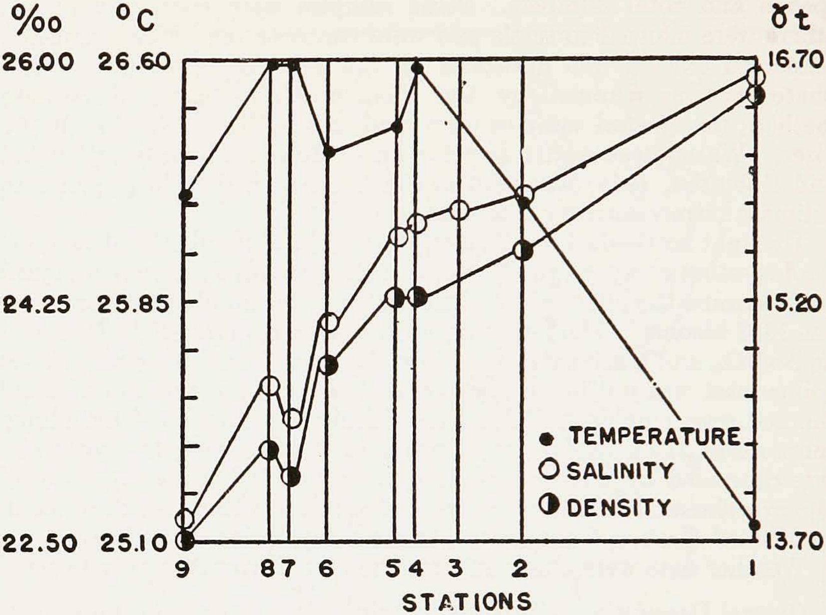

Figure 2. Temperature, salinity, and density data, July 15, 1952.

patch was located in the channel off the mouth of West River. By July 16 a major bloom had developed, and it either continued or recurred throughout the next month.

Hydrography. Examination of the data for July 15, 1952, graphed in Fig. 2, shows that gradients of temperature, salinity, and density existed from the innermost harbor stations to Station 1, where the greatest admixture of Long Island Sound water occurred. The regularity of this gradient was marred, however, by the existence of two patches of high temperature water at Stations 8–7 and 5–4, the first having a distinctly lower salinity as well. These patches were without doubt intrusions of inner harbor water which maintained their identity as discrete water masses by virtue of their density relative to the surrounding waters.

On June 24, 1953 salinity increased and temperature decreased in regular horizontal gradients from the inner harbor to the harbor mouth, uncomplicated by the existence of discrete water patches. Salinity and temperature data for July 7, 1953 suggested a situation similar to that of June 24, but not enough data were obtained to warrent a definite conclusion. Subsurface observations at Station 13 on June 24, 1953 showed that vertical gradients in salinity, temperature, and density were very large (Table I).

TABLE I. Vertical Section at Station 13, June 24, 1953

Depth, m	Temperature, °C	Salinity, ‰	Sigma-*t*	Extinction coefficient	Chlorophyll, µg/l	Total phytoplankton cell count; millions/l.	Total *Goniaulax cochlea* (?) cell count; millions/l.	% red tide organism / total phytoplankton	Oxygen, % saturation	*P*, µg at/l	*N*, µg at/l
0.5	19.04	23.80	16.49	2.2	75.8	45.6	44.4	97	131	.66	.20
2.5	17.95	24.37	17.32	1.6	65.6	33.5	31.5	94	117	.68	.23
4.0	16.00	24.95	18.09	1.3	31.0	10.3	8.6	86	86	.83	.08

New Haven Harbor is so shaped that the narrow waist could effectively separate the outer harbor from the inner, thus reducing the active circulation in the latter. The fresh water discharged from the Quinnipiac, Mill, and West Rivers into the inner harbor may have a long period of relative stagnation before it enters active harbor circulation. This would be particularly true if the winds are southerly and hold the water in the inner harbor. Other things being equal, the larger the volume of fresh water entering the inner harbor the larger the discrete water mass and the longer its life. The presence of large horizontal and vertical gradients described above suggests that mixing in any direction would be slow under such stable conditions.

Five days before July 15, 1952 and ten days before June 24, 1953 there were heavy rainfalls; winds on the intervening days were all southerly sea breezes or gentle easterlies. Rainfall and wind data were similar both before and after July 7, 1953. During all of these periods radiation was unusually high, and the average monthly radiation values for July 1952 and for June and July 1953 were close to 120% of normal. In short, weather conditions in New Haven Harbor were optimal for the formation and maintenance of discrete stable water masses during the periods when red tides developed.

Phytoplankton Description. By comparing Fig. 2 with Fig. 3 it is evident that high concentrations of phytoplankton organisms, as measured by plant pigments, total cell counts, and numbers of red tide organisms, were associated on July 15, 1952 with the water masses of inner harbor origin. An additional isolated concentration of organisms was found at Station 2; this might represent either a water mass that had lost its identity in all but organisms or simply a concentration of organisms in a tide rip. Phytoplankton data for June 24, 1954 revealed a regular dilution gradient; the highest con-

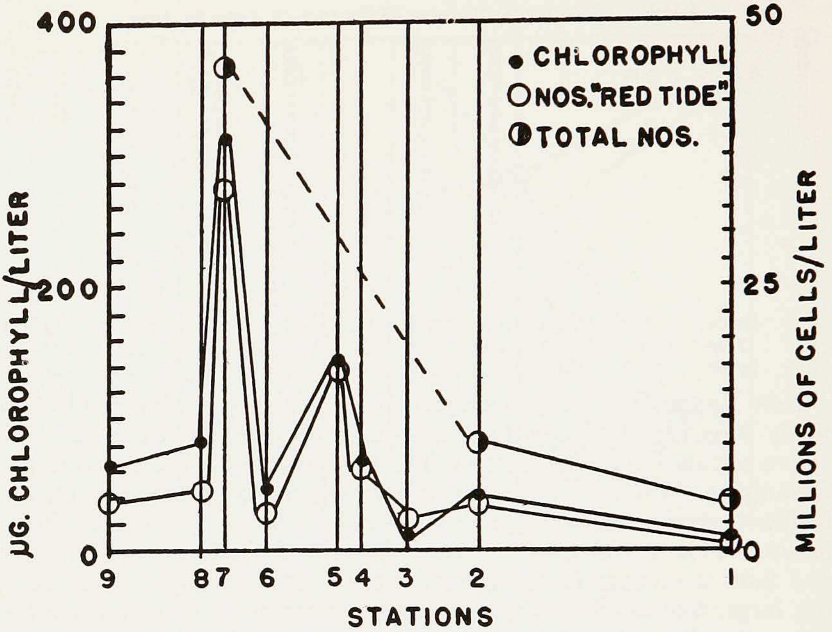

Figure 3. Phytoplankton data, July 15, 1952.

centrations of organisms were found in the inner harbor, with progressive reduction toward the outer harbor entrance.

The data for all samplings have been combined in Figs. 4 and 5, in which micrograms of chlorophyll per liter are plotted against temperature and salinity. The trends in both figures are quite clear; higher phytoplankton concentrations were associated with high temperatures and low salinities.

The phytoplankton cell counts are summarized in Table II. In addition to showing the dilution gradients, these counts show the relationship of the red tide species to other phytoplankton species in the environment. In the inner harbor waters the population was largely made up of red tide organisms while in the outer harbor waters they were only a small proportion of the population, numerically speaking. In Long Island Sound waters, small numbers of these organisms were taken, but it was only in the harbor that blooms developed.

Chemical Description. On July 15, 1952 high phosphate was associated with the fresher waters and with the discrete water masses that contained blooms. Not enough observations were made on

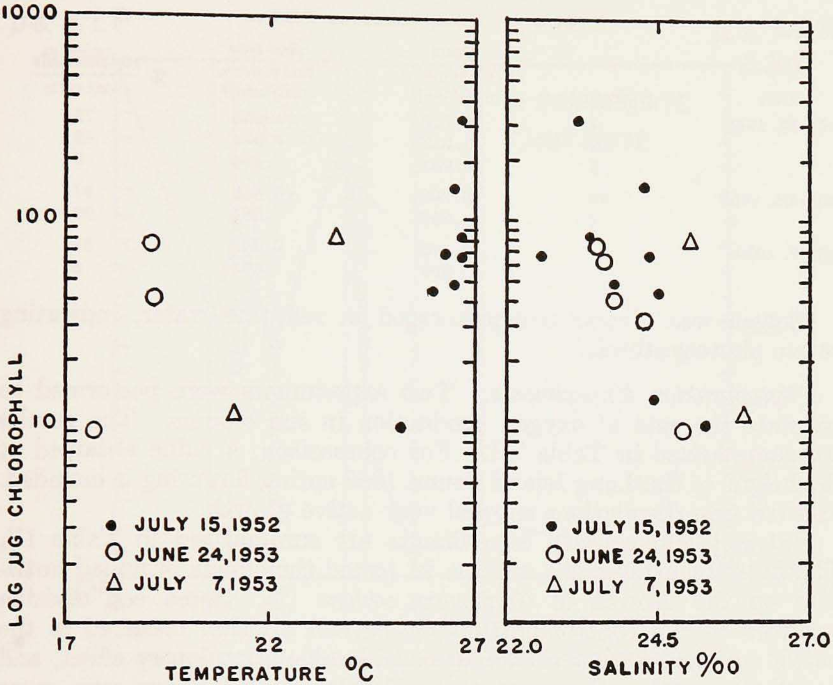

Figure 4 (left) Chlorophyll concentrations plotted against temperature.

Figure 5 (right) Chlorophyll concentrations plotted against salinity.

nitrates to present a clear picture, but it seems likely that high initial concentrations in the inshore area were lowered by phytoplankton activity (Fig. 6). In the 1953 blooms the concentrations of both phosphates and nitrates were much lower than those associated with the 1952 red tide. In 1953 nitrates ranged from 0.30 to 0.0 μg at/l and *P* from 0.8 to 0.5 μg at/l.

A series of samples was taken on July 9, 1953 at the river mouths and at other shore positions (Fig. 1) in an attempt to determine the nutrient supply entering the harbor. Phosphate was approximately 2.0 μg at/l higher at these shore positions than at Station 1. Nitrate reached significantly higher proportions only under West River influence, the concentrations being 1 and 2 μg at/l higher than those in the outer harbor water. However, it seems doubtful that the West River is normally the only source of nitrate for the inner harbor waters. The other rivers and the harbor shore and shallow bottom could also be sources. When water masses are held in the inner harbor they would store increasing amounts of nutrients derived from the river, shore, and bottom sources.

TABLE II. PHYTOPLANKTON COUNTS

Date	Station	Total cell counts, millions/l	Red tide cell counts, millions/l	% red tide cells / total cells
July 15, 1952	7	46.700	34.963	75
	2	10.220	4.944	45
	1	4.965	.464	9
June 24, 1953	13	45.580	44.400	97
	1	.346	.081	23
July 7, 1953	14	10.670	6.198	58
	1	.304	.024	8

Oxygen was always supersaturated in red tide water, indicating active photosynthesis.

Phytoplankton Experiments. Two experiments were performed to estimate the rate of oxygen production in the blooms. The results are summarized in Table III. For comparison, a value obtained at the height of the Long Island Sound 1953 spring flowering is included. The red tide populations showed very active growth.

Nutrient and salinity experiments are summarized in Table IV. The nutrient experiment of June 24 tested the effects of added nutrients on the growth of *Goniaulax cochlea* (?). Some cell division occurred in the control bottle, but no cell division occurred in the bottle enriched with *P*. *N* had considerable stimulatory effect, and enrichment with soil extract and soil extract $+P+N$ was even more effective.

The experiments of July 7 were done on *Goniaulax africana* (?). There was little growth in the control bottle. Phosphate had a slight stimulatory effect and nitrate a greater one. The initial salinity was 25.40 ‰; in one bottle this was raised to 26.12 ‰ and in the other it was lowered to 21.30 ‰; both were enriched with *N*. Greatest relative growth of this organism was found in the increased salinity bottle enriched with *N*. Growth declined when the salinity was decreased.

The experiments clearly indicate that nitrogen was a limiting factor. The need for phosphorus was slight or negligible. The soil extract had the greatest stimulatory effect; it almost certainly supplied nitrogen in an amount equal to that in the *N*-enriched bottle. Whether the additional growth was due simply to more nitrogen in any form or to other nutrients is not known.

There is no evidence that the development of blooms in the inner harbor was due to a preference on the part of the organisms for low salinity. It would be inadvisable to put much confidence in the results of a single experiment, but such evidence as is available suggests a preference for higher salinity. Perhaps, then, blooms of these

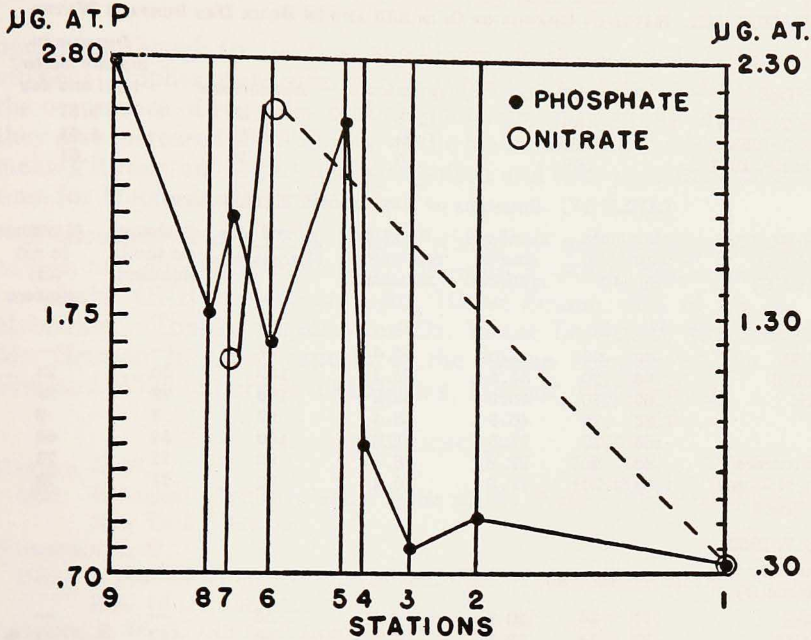

Figure 6. Phosphate *P* and nitrate *N* data, July 15, 1952.

organisms in the inshore waters occur despite low salinity rather than because of it.

Using the greatest growth rates obtained in these experiments, calculations can be made to determine the time required for the development of populations of the magnitude observed in the harbor. Such calculations are artificial at best, since the growth rate can be altered by any of several physical, chemical, and biological conditions. Even so, the calculated required time agrees rather well with the period of time available for bloom development as indicated by data on rainfall, winds, and radiation. It would have taken 14 days for the observed population of *Goniaulax cochlea* (?) to develop at the experimental rate from an initial concentration of one million cells per liter. Nine days would be required for the development of a population of *Goniaulax africana* (?) from one million cells to the level observed in 1952. A slight increase in either the size of the initial population or the growth rate would make the calculated time equal the available time.

Discussion. Slobodkin (1953) has shown that Florida red tides are associated with fresh water masses of high stability in the sea. The

TABLE III. Rates of Change of O_2 in ml/l and 24 Hour Day Surface Water

Date	*Photosynthesis*	*Respiration*	*Net increase*	*Increase in organic matter, mg/l and day*
June 24, 1953	3.36	1.78	1.58	1.67
July 7, 1953	2.22	1.69	1.53	1.61
March 9, 1953	.68	.10	.58	.61

TABLE IV. Summary of Enrichment Experiments

June 24, 1953 *Goniaulax cochlea* (?)	Nutrients available, µg at/l P	N	Total cell counts, millions/l	Red tide cell counts, millions/l	% red tide / total cells	% change in total numbers	% change in red tide numbers
Initial	.66	.20	45.6	44.4	97	—	—
Control	.66	.20	54.6	54.4	100	20	23
Dark	.66	.20	55.5	55.2	100	22	24
P	1.66	.20	46.9	45.4	97	3	2
N	.66	3.70	71.3	71.0	100	58	60
Soil extract	.66?	.20?	77.8	76.8	99	71	73
P + N + soil extract	1.66?	3.70?	77.5	76.4	99	71	73
July 7, 1953 *Goniaulax africana* (?)							
Initial	.77	.14	10.7	6.2	58	—	—
Control	.77	.14	12.5	6.2	50	17	1
Dark	.77	.14	10.0	5.7	57	–6	–8
P	1.77	.14	14.9	10.0	67	40	62
N	.77	3.64	21.0	11.6	55	97	87
Initial for higher S °/oo	.77	.14	3.6	2.1	58	—	—
Higher S °/oo plus N	.60	3.67	7.8	4.4	57	119	115
Initial for lower S °/oo	.77	.14	9.6	5.5	58	—	—
Lower S °/oo plus N	.69	3.63	11.2	4.4	40	16	–20

present work is essentially in agreement with his conclusions except that New Haven red tide organisms have revealed no physiological preference for low salinity.

Because of the configuration of New Haven Harbor, water masses tend to be held in the inner portion. This tendency is reinforced by the fresh water that enters the inner harbor, by southerly winds, and by high radiation values. Such water masses are reservoirs for land-derived nutrients.

The high radiation and the great stability of the water mass that accompanied the observed red tide blooms also provided conditions of light and temperature favorable for active metabolism and cell division in the organisms. Nutrients were evidently adequate for bloom development, although by the time the blooms were observed the essential nutrient supplies were nearly exhausted. The rains that preceded the occurrence of red tides probably introduced a supply of nutrients; they also increased the stability of the water mass in the inner harbor, making it resistant to physical dissipation and thus providing adequate time for bloom development.

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REFERENCES

Harvey, H. W.
1928. Biological Chemistry and Physics of Sea Water. The MacMillan Co., New York. 194 pp.

Slobodkin, L. G.
1953. A possible initial condition for red tides on the coast of Florida. J. Mar. Res., *12* (1): 148–155.

Zwicker, B. M. G. and R. J. Robinson
1944. The photometric determination of nitrate in sea water with a strychnidine reagent. J. Mar. Res., *5* (3): 214–232.