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Bureau of Commercial Fisheries Symposium on Red Tide

By James E. Sykes

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By

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ABSTRACT

In October 1964, the Bureau of Commercial Fisheries held a Red-Tide Symposium at St. Petersburg Beach, Fla. Purposes were to review progress on red-tide research in recent years, to exchange views on the nature of current investigations, and to determine where emphasis should be placed in further studies. Abstracts of presentations by 14 participating scientists are included in this report. Eleven areas of red-tide research were cited as needing attention in continuing studies.

INTRODUCTION

Sporadic concentrations of the red-tide organism, Gymnodinium breve, are associated with fish mortality and human discomfort. Although outbreaks of red tide are observed in various parts of the Gulf of Mexico, their most frequent occurrence has been noted in the coastal waters of west Florida.

Red-tide research in the Bureau of Commercial Fisheries began on a limited basis in the Gulf of Mexico in 1947. A major research program began at the Bureau's Biological Laboratory, Galveston, Tex., in 1954. Subsidiary stations were established on the west coast of Florida, at Sarasota, Fort Myers, Naples, and St. Petersburg Beach. The objectives of field and laboratory studies on G. breve, were to determine its incidence and distribution in Gulf coastal waters and to increase the knowledge of ecological conditions responsible for starting blooms.

Field data were obtained routinely at stations between Anclote Key and Florida Bay on the west coast of Florida, in both Gulf and estuarine waters. To relate the occurrence of G. breve to its environment, data were collected on temperature, salinity, copper, inorganic phosphate, total phosphate, nitrogen, calcium, silicon, alkalinity, depth, cloud cover, water transparency, and wind speed, duration, and direction. In addition to the survey of Gulf and inshore waters, intensive sampling was carried out during blooms or so-called outbreaks of the organism. Water samples and collections of G. breve also were supplied to the Galveston Laboratory for culturing. Practically all of the data obtained during field work in Florida have been published.

In January 1962 the Bureau of Commercial Fisheries Biological Station at St. Petersburg Beach was detached from the Laboratory at Galveston and made a separate research unit. Funds were appropriated for estuarine ecological research, with particular reference to the effects of engineering alterations on euryhaline organisms, food chains, and, ultimately, commercial fisheries dependent on the estuarine environment. Although the Station's funds were not earmarked specifically for red-tide investigations, research continued from January 1962 to August 1963 in conjunction with the estuarine program. The heavy bloom of G. breve in April 1963 was responsible for the appropriation of new funds for research on red tide in September 1963. Screening of compounds for control of the organism continued at Galveston, but the major research program was shifted to Florida.

The 1963 bloom differed from previous ones in that it infiltrated the inshore waters of Tampa Bay and appeared to kill greater numbers of fish than any bloom previously recorded there. In response to the urgency of the situation, Station personnel cooperated with the Florida Board of Conservation Marine Laboratory in field studies during the outbreak and in recording associated hydrologic, planktonic, and fishery data. These data and some interpretations were assembled in a mimeographed report which was issued jointly by the two laboratories.

The renewed appropriation led to an examination of possible approaches to the red-tide problem with available facilities and specialists. It was imperative that the approach be

[1] Contribution No. 17, Bureau of Commercial Fisheries Biological Station, St. Petersburg Beach, Florida.

planned carefully because several lines of endeavor appeared practical. For example, the characteristics of the toxin from G. breve had never been determined, even though its fish-killing capacity had been well known for several years. Investigation of the toxin could improve the possibilities of controlling the effects of red tide.

After several approaches were considered, the principal program was designed to include a long-term, systematic study of plankton succession in two estuaries, Tampa Bay and Charlotte Harbor, and along offshore transects between the two areas. The purposes were to explore the year-round interrelation of planktonic species and to determine the reaction of these species to the environment and to related organisms during different seasons. Monthly collections began February 1964.

In addition to the field studies, we were concerned with the further examination of past red-tide data that had received only cursory analysis. We felt we could add greatly to the knowledge of G. breve and its relation to hydrography by automatic data computation; also, some of the factors previously measured might prove to have no significant effect on the growth, survival, and multiplication of the organism. With these possibilities in mind, the data are now being programmed for computation to test the dependence of G. breve on single and multiple environmental factors.

Funds were awarded also by contract to the University of Alabama for the assimilation and interpretation of red-tide literature. This work resulted in the completion of an annotated and interpretive bibliography in May 1964, to be used by participants in this Symposium and in future red-tide research. The bibliography is expected to be published at a later date. It includes references to research on red tide and related subjects by Federal, State, institutional, and individual researchers.

This Symposium represents the third segment in the use of red-tide funds in Fiscal Year 1965 and the first phase of a renewed approach to the problem. It had become clear that coordination should be established in planning and conducting red-tide research, and that definite and precise goals should be sought in further attacks on this complex problem.

Participants were chosen to represent the several disciplines usually concerned with red-tide research: microbiology, fishery biology, and oceanography. The purpose was to discuss research already completed by several agencies investigating the red-tide problem and to explore the direction which research should follow in the future. Agencies represented were: Bureau of Sport Fisheries and Wildlife and Bureau of Commercial Fisheries of the U.S. Fish and Wildlife Service; Florida Board of Conservation; Gulf Coast Research Laboratory (Mississippi); U.S. Department of the Navy; St. Petersburg Junior College; Institute of Marine Science (Miami); Oceanographic Institute of Florida State University; Florida Atlantic University; U.S. Army Biological Laboratory; Haskins Laboratories (New York); Florida Presbyterian College; University of Alabama; Gulf Coast Shellfish Sanitation Research Center; and California State Fishery Laboratory.

ABSTRACTS OF DISCUSSIONS

During the first 2 days of the Symposium, opinions were expressed by participants and discussed to establish guidelines and design further research. Comments that were recorded and transcribed are abstracted in the following sections of this report.

ROLE OF VARIOUS FACTORS CAUSING RED-TIDE BLOOMS AS DEDUCED FROM FIELD OBSERVATIONS

By George A. Rounsefell

University of Alabama, University, Ala.

Over a 50-year period, the occurrence of fish-killing red tides in western Florida has been favored by heavy rainfall from March to September. Blooms in some years when precipitation was not heavy indicate that this is only one of the associated factors.

Analysis of extensive data collected in 1954-61 showed that G. breve was abundant in a narrow strip along the coast. The organism is definitely neritic, seldom penetrating far into bays.

The upper limit of water temperature for blooms appears to lie between 28° and 30° C. The organisms were not taken below 10° C.; abundance begins to decrease at about 15° C. The upper limit of temperature is normally exceeded in midsummer; this may limit summer abundance. Lower and upper limits of abundance are at about 24‰ and 34‰ salinity. Salinity range for fish-killing concentrations is about 30‰ to 34‰, but the lower limit of the range is not well defined. Reduced precipitation during the summer usually results in salinity too high for blooms of G. breve.

Winds were heaviest during the spring and early summer, when red tide seldom blooms, and least in August, September, and October, when blooms often occurred. A high number of hours of wind appears to have a definitely limiting effect on the abundance of G. breve. An analysis of phosphorus and G. breve abundance for both red-tide and non-red-tide months showed that usually the linear correlation was slightly negative but not statistically significant.

Although many chemical characteristics have been or could be measured, temperature, salinity, and winds will always be important factors in the development of bloom conditions.

RED-TIDE RESEARCH AT THE FLORIDA STATE LABORATORY

By Robert M. Ingle

Florida Board of Conservation,
St. Petersburg, Fla.

Research of previous years greatly facilitates our present work, and previously established knowledge is used frequently. Several research projects are now in progress at the Florida Marine Laboratory. In addition, research on the use of G. breve as a bioassay organism is being carried out at Florida State University. Emphasis is on culture techniques and water chemistry. It has become apparent that iron and a chelator provide the most dependable supplements which can be added to water to stimulate growth of the organism.

In past outbreaks of red tide, no blooms were observed along the west coast of Florida north of Clearwater. Recently, however, a bloom in north Florida resulted in a widespread fish kill. Red tide was found as far offshore as 78 miles, and such fishes as sailfish (Istiophorus albicans) were killed by it.

One project, which includes a literature search, deals with seasonal succession of phytoplankton. To approach this problem on a long-term basis, a series of publications called "Leaflets" was started that will result eventually in a handbook on phytoplankton. Taxonomic and ecological aspects of phytoplankton in coastal waters of west Florida are considered in these papers.

The Laboratory's research is designed to discover the properties in water that are unique in this area and related to red tide. The coincidence of red tide and the rich phosphate beds in this area has always been a source of suspicion, although evidence is good that phosphate is not limiting to G. breve blooms along the Florida coast. It has been concluded that dinoflagellates generally grow best in water depleted of nutrients. Since nitrogen is apparently no particular problem, research has turned to some of the other well-known needs of the organism. Iron is one that seems to be mentioned most widely in the worldwide literature on red-tide field and laboratory studies. A literature search revealed that dissolved iron content has been studied in the Peace River in southwest Florida for about 40 years. This river carries tremendous quantities of iron and is acid. Tannic acid, humic acid, and related products are very common in the streams of the area. The quantity of iron delivered to the Gulf from the Peace River increases during floods. It appears that bogs, which are notorious accumulators of iron, are shut off from streams during dry periods, and that heavy concentrations of iron are leached or washed out by rising rivers which flood the bogs.

Two aspects of the recent occurrence of red tide in north Florida were fortunate: the massive outbreak was so far from land that it caused no hysteria, and it enabled us to examine red tide in a different situation and to establish some common denominators.

Over a period of time, it is hoped that nutritional needs can be defined for the most common phytoplankters, so that the presence of chemical constituents can be deduced when a particular organism is found to be very prominent. If these organisms can ever be shown to be precursors of the red-tide bloom, it might be possible to shed some light on the nutritional needs of G. breve.

Another project of our Laboratory concerns the bioassay of vitamin B_{12}. A statistical method has been developed which appears dependable and which may demonstrate that the concentration of B_{12} in the water is being accurately measured.

In our bacteriological studies, plans are to determine whether or not identifiable living precursors of red tide are in the water and, if so, what are they producing that helps develop a bloom. Flavobacterium concentrates in tremendous numbers during red-tide outbreaks, but is not necessarily a factor in red-tide mortalities. The bacterial flora from the southern part of the range during times of low incidence of G. breve has a considerable variety of species.

FIELD AND LABORATORY WORK IN PROGRESS AT THE FLORIDA STATE LABORATORY

By Members of Florida Board of Conservation

St. Petersburg, Fla.

Richard P. Saunders and Karen A. Steidinger presented the following report (abstracted) on current research in Florida.

Regular sampling along the west coast of Florida from Hillsborough to Collier Counties began December 1963. Nine stations were sampled at weekly intervals for phytoplankton and hydrographic data. Samples were collected monthly at 11 other stations in the same general area to record distribution of bacteria and phytoplankton and to determine concentrations of vitamin B_{12}, amino acids, hydrogen sulphide, iron, and carbohydrates. Bioassays were also run with G. breve as the assay organism. Other samples were collected periodically to check for the occurrence of G. breve.

Analysis of regular sampling data, when completed, should provide a picture of the annual phytoplankton cycle in Florida west coast waters. Important diatoms encountered in regular samples were: Skeletonema costatum, Asterionella japonica, Chaetoceros spp., Nitzschia spp., Leptocylindrus spp., Rhizosolenia spp., and Thalassionema nitzschioides.

A red tide in July and August in the offshore water of Apalachee Bay was studied by members of the Marine Laboratory. Counts of diatoms and number of species were low in these samples. Prevalent diatoms were: Rhizosolenia stolterfothii, Lauderia borealis (?), Hemiaulus sp., Chaetoceros spp., and several species of Nitzschia. Trichodesmium, a blue-green alga, was common also in these samples.

The Florida Marine Laboratory's Dinoflagellate Project was briefly described.

A morphological variant of G. breve that had been observed during a red-tide outbreak in Apalachee Bay (July and August 1964) was discussed. A report "Observations on Gymnodinium breve Davis and other dinoflagellates," is in press (Fla. Bd. Conserv. Mar. Lab. Prof. Pap. Ser. 7, Part I).

Studies in southwest Florida (November 1963 to November 1964) were mentioned but not discussed in detail. As of March 1965, 25 genera of dinoflagellates had been recorded from the Gulf of Mexico and adjacent waters. The interpretation of these studies is in progress and will be published in Fla. Bd. Conserv. Mar. Lab. Prof. Pap. Ser. 7 as Part II.

CURRENT FIELD STUDIES OF THE BUREAU OF COMMERCIAL FISHERIES

By Alexander Dragovich

Bureau of Commercial Fisheries Biological Laboratory, St. Petersburg Beach, Fla.

Tampa Bay, Charlotte Harbor, and the adjacent Gulf to 20 miles offshore now constitute the study area of the St. Petersburg Station. The area of about 1,500 square miles is the site of many past red-tide outbreaks. Seven major rivers flowing into the Gulf also are included in the area.

We have reviewed past studies, eliminated measurements found to be unrelated to red-tide blooms, and added new observations where applicable. Our past research included several hydrological measurements and counts of G. breve. Of the hydrological determinations, we retained temperature, salinity, and inorganic phosphate phosphorus; dissolved oxygen and iron were added. An intensive qualitative and quantitative study of phytoplankton associated with G. breve, and chlorophyll determinations, also were added to our biological program in February.

The relation of planktonic successions to physical, chemical, and biotic factors was reviewed.

The preliminary examination of samples collected during the first 8 months of this study showed that phytoplankton consisted principally of diatoms, dinoflagellates, tintinnids, and occasionally blue-green algae. Sceletonema costatum was the most numerous organism in the bays. The concentrations of S. costatum decreased seaward from the heads of Tampa Bay and Charlotte Harbor; this alga was uncommon 10 and 20 miles offshore. The most intense blooms were during late winter and early spring. During September S. costatum was usually associated with Asterionella japonica. The spring bloom was a mixture of species of diatoms and dinoflagellates. Gonyaulax diegensis, Ceratium furca, and Polykrikos Hartmanii Zimmermann were responsible for the spring and fall blooms of dinoflagellates. In the areas with the most intense blooms of C. furca (14.29×10^6 cells per liter), the water was discolored blood-red. No mortality of fish or of other organisms was observed in the field. C. furca was not toxic to a few species of resident fish when tested in laboratory experiments. An April increase in populations of diatoms in Tampa Bay was attributable to Melosira nummuloides, Biddulphia sinensis, Rhizosolenia stolterfothii, and a few species of Chaetoceros. G. breve was not found in samples collected during the study.

Phytoplankton collections from the bays suggested seasonal changes in species composition. The dinoflagellates bloomed during spring and fall; blooms of different species of diatoms occurred throughout the period. The appearance and disappearance of certain species may be determined by water temperature. Upon completion of the study we may be able to distinguish "warm-water" and "cold-water" species.

The offshore plankton was dominated by diatoms throughout the period. The diversity of species was greater in the offshore waters than in the bays. The phytoplankton density was greatest in the upper portion of Tampa Bay, however, in an area enriched by river inflow. Extensive surface concentrations of a blue-green alga, Skujaella thiebauti, were present in the offshore waters from February through July. This alga forms a fine, rusty-beige dust or film on the sea surface and is often mistaken by commercial airline pilots for red tide. Dense concentrations of this organism sometimes cover several square miles of the sea; it undoubtedly produces tons of organic matter in the offshore waters. Little is known about the physiology of this organism. Skujaella (Trichodesmium) erythraeum is reported to grow 20 m. below the surface in the Red Sea and dead cells accumulate on the surface.

Concentrations of G. breve varied from 0 to 53,800 cells per liter during the period. Maximum concentrations and widest distribution were in September and February, during periods of reduced salinity. Low incidence and concentrations in the period March to August coincided with extremely high salinities. Because of little rainfall, salinities increased progressively from February to August. During May, 95 percent of all offshore salinities were above 35.50‰. Fifteen to 20 miles offshore, all salinities were above 36.00‰. G. breve was present at all depths, but was most abundant at the surface.

A preliminary examination was made of preserved plankton collections taken in January, February, and March 1963 (Collection and examination of living plankton began in April). The principal phytoplankton components before, during, and after the April red-tide outbreak in Tampa Bay were diatoms, dinoflagellates (including G. breve), and Tintinnidae. Cyanophytes and silicoflagellates were of minor importance. Phytoplankton was much denser in the upper portions of Tampa Bay than in the lower part of the estuary. A preliminary analysis of phytoplankton counts and associated hydrologic data indicated that blooms of G. breve during April were coincidental with (1) blooms of Ceratium furca, Prorocentrum micans, Gonyaulax diegensis, Rhizosolenia stolterfothii, and Tintinnidae; and (2) the intrusion of offshore waters into Tampa Bay during a period of exceptionally low rainfall. The offshore waters contained G. breve. The change in planktonic successions cannot be accounted for by any of the observed hydrological factors alone. The reduction in plankton populations prior to the blooms is evidence, however, that the phytoplankton was kept at low levels by physiological limitations and physical dispersal.

AN APPROACH TO THE RED-TIDE PROBLEM

By Albert W. Collier

Oceanographic Institute of Florida State University, Tallahassee, Fla.

Red-tide research can be approached in three steps: (1) explaining how outbreaks are caused and why they occur when they do; (2) deriving from this approach a method for predicting outbreaks; (3) with the knowledge gained from explanation and prediction, attempting to develop control measures. These steps require experimentation, intensive field study, and finally, by a combination of these, the development of control techniques.

Much more detailed and thorough research on G. breve itself is an outstanding need. It is a highly sensitive organism that is difficult to work with--if it were not so sensitive, we would have red tides with us constantly. Comprehensive and detailed work on the fundamental cytology of this organism will be required before we are able to isolate the critical factors in the environment.

THE PUBLIC HEALTH SIGNIFICANCE OF GYMNODINIUM BREVE

By Sammy M. Ray

Marine Laboratory, Agricultural and Mechanical College, Texas, Galveston, Tex.

By way of investigating the public health significance of G. breve, mussels and oysters that had been held in cultures of this organism were fed to chicks to determine whether toxic symptoms would be produced. Preliminary results indicate a relation between the number of G. breve cells ingested by the mollusks and the severity of the symptoms in chicks to which the mollusks had been fed. Symptoms ranged from partial loss of equilibrium to death. Similar tests are planned with cats as the experimental animals.

Of interest is the fact that the annelid Polydora quickly emerged from oysters subjected to cultures of G. breve. Research will continue on the toxic effects to polychaetes.

The possibility appears to be good that G. breve is of significance in shellfish poisoning. Only a few authenticated cases of such poisoning have been reported in the Gulf of Mexico, probably in part because mollusks normally are not produced commercially in areas where red tides occur.

Work will continue also in culturing, and in comparing the toxicity of Gonyaulax catenella with G. monilata and G. breve.

COMMENTS ON ETIOLOGY OF RED TIDE

By Gordon Gunter

Gulf Coast Research Laboratory
Ocean Springs, Miss.

In spite of the meticulous manner in which scientists collect samples, our methods still appear to be somewhat crude. This shortcoming may not be critical, however, in the study of red tide. Except in years of extremely heavy blooms, few people concern themselves with this phenomenon because no damage is done. Observations of the past agree with recent statistical analyses in showing that outbreaks of red tide generally follow long periods of no wind.

When considering the detection of G. breve through use of cameras, aircraft, and instruments, it should be remembered that the red-tide organism is not the only one that discolors coastal waters. Numerous Trichodesmium are often present, for instance, but can often be recognized with the naked eye because many of the organisms float on the surface. Whenever plankton (including zooplankton) is dense, conditions are usually excellent for a red-tide bloom. In other words, G. breve cannot be studied without reference to other organisms. This fact has been stated before but needs to be re-emphasized.

A DESIGN FOR FURTHER RED-TIDE RESEARCH

By Luigi Provasoli

Haskins Laboratories, New York, N.Y.

The need for a continued program of research is stressed. Red tides, though very obnoxious, are simply sporadic algal blooms. They cannot be understood if we do not consider them in the larger context of the regular succession of phytoplankton species of the Florida Gulf.

It is inadvisable to institute crash programs when red tides appear and dismantle them when the outbreaks subside. This very costly and wasteful procedure cannot be justified, even for political expediency. Since red tides will continue to reappear, we should support a modest, well-planned research program which will end only when we know the reasons for the outbreaks--the prerequisite for finding a way to control them.

Such a program should aim at the discovery of the mechanisms governing the succession of phytoplankton species. The red tides are only one of the blooms in this succession. The phenomena underlying the succession of species are the key to our understanding of phytoplankton production, which in turn governs the entire productivity of all the organisms feeding directly or indirectly on algae, i.e., oysters, shrimp, and fish. The program therefore should be of special interest to the Fish and Wildlife Service.

The research program could be modeled after the ecological study of the Sargasso Sea by a taxonomist, a chemist, and two plant physiologists from Woods Hole Oceanographic Institution. A hydrological study will also be necessary, but this work could be done more efficiently by an outside oceanographic institution.

In the Woods Hole approach, the general chemical and biological features of the ecological situation were assessed by the taxonomist and the chemist, who made a 2-year study of the qualitative and quantitative composition of the phytoplankton and the fluctuations in nutrients. The Sargasso Sea proved to be very poor in nutrients: nitrogen and phosphorus vary little, and iron does not show any seasonal peak. The flora is equally poor--essentially a yearly diatom bloom in the spring. A coccolithophorid, Coccolithus huxleyi, is present the year-round as an almost steady, but sparse population.

This picture posed a main question: since nitrogen, phosphorus, and iron varied, but not widely, other factors must have been responsible for the endemicity of C. huxleyi, and for the spring bloom of diatoms. This was especially true because temperature varies little during the year. The main species of spring diatoms and C. huxleyi were cultured bacteria-free, and their nutrition was studied by the plant physiologists.

The main results were: all diatoms needed vitamin B_{12}, but C. huxleyi required only thiamine. This finding seemed to offer a fitting explanation, but necessitated field confirmation. A vitamin B_{12} bioassay was perfected, employing one of the Sargasso diatoms, Cyclotella nana, that requires B_{12}, and the yearly cycle of B_{12} in the waters was determined. Vitamin B_{12} varied from an undetectable to scarce level from May to October. It rose steadily and slowly during the winter and reached a maximum before the spring diatom bloom exhausted the vitamin.

Vitamins in this situation govern species composition; the quantity of B_{12} determines diatom growth, and C. huxleyi is independent of the vitamin.

The importance of the other nutrients was assessed by using depleted Sargasso water (i.e., at the end of the diatom bloom) that contained its natural algal populations. The water was then enriched with various nutrients, singly and in various combinations. It was found that iron is the most limiting factor--no diatom growth occurred without its addition. Iron alone, however, induces only a short burst of growth. Sustained growth is achieved only by the addition of iron, nitrogen, and phosphorus, indicating that nitrogen and phosphorus are also limiting. Laboratory data on C. huxleyi show that it can be grown for several transfers without added iron.

The validity of the findings seems assured since all the laboratory and field data are in agreement. Further study will be needed to find the causes that underlie the succession of species during the diatom bloom.

This highly successful research was done by four talented scientists and their research assistants. If a similar group is formed for the study of the blooms of the Gulf (including red tides), it should be similarly small and competent; number does not substitute for competence, and talent is rare and expensive.

If the operation is to be successful, there are other requisites which are often disregarded, i.e., freedom from administration, a high degree of initiative and competence, and wide cooperation with researchers here and abroad. It is highly advisable that a great deal of the hydrological work be contracted to other laboratories, as mentioned before. The laboratory work on bacteria-free cultures--an area where there are few competent workers--can be done anywhere (be it in the United States, Canada, England, Germany). Specialists can be induced to cooperate.

The essential work to be done in situ is hydrography, chemistry, taxonomy, and the collection of samples. It is also necessary and easier to establish raw and clonal cultures of the various dominant organisms of the Gulf in situ. Bacteria-free cultures can be achieved anywhere, but the physiological work should be done exclusively on the strains isolated in the Gulf, even if the same species are already in bacteria-free culture elsewhere. We know that strains of the same species from different localities have widely different nutritional requirements.

The existing body of knowledge on red tides should be extended widely, as has been mentioned by other participants in this Symposium. We need to know far more about the hydrology of the region and the physical and chemical influence of the rivers. These rivers, rich in tannic and humic acids (both metal-chelators), are sure to enrich the coastal waters with metals. The cycle of iron is being investigated but is still poorly known. The cycle of other trace metals--zinc, copper, cobalt, molybdenum, manganese, titanium, zirconium, and others--which may be necessary, stimulatory, or poisonous to algae is completely unknown. A study of the concentrations of trace metals, vitamins, and other nutrients in the water is essential; so is the study of their role in the nutrition of the different species of algae of the Gulf, including G. breve, which is already in bacteria-free culture.

Plant hormones and unknowns should not be excluded. We have found that normal morphology of two green seaweeds, lost when they are grown aseptically, can be restored by adding filtrates of two marine bacteria, or by supernatants of aseptic cultures of red or brown seaweeds. The active principle of the supernatant of brown seaweeds, extracted by charcoal and eluted by ethanol, is a tannin. Higher plant tannins, and the waters of the Florida rivers investigated, have no effect on the two green seaweeds, but they may contain some active substances for the local phytoplankton or G. breve. Similarly, the chemicals produced by a preceding bloom during life or after decay, can determine by their inhibitory or beneficial action which one of the many species is to grow to bloom proportions next. A host of exciting mysteries awaits the anxious hand of the researcher who will persist until he uncovers them.

Last but not least, after the first broad analysis of the environment it would be wasteful to continue working throughout a region as vast as the one in which the red tides occur. The concerted Woods Hole approach, which is a work in depth where every detail counts, should be accomplished at a small number of stations carefully selected to be representative of the environment being studied. As one environmental niche becomes well known, the next niche should be taken up and analyzed.

SCREENING OF CHEMICALS FOR THE CONTROL OF GYMNODINIUM BREVE

By Kenneth T. Marvin

Bureau of Commercial Fisheries Biological Laboratory, Galveston, Tex.

The Bureau of Commercial Fisheries has been investigating the chemical control of red tide for about 12 years. Most of the initial investigation centered around the use of copper. The conclusion from field testing was that copper sulphate gave some temporary relief in localized areas, but that effects were not durable enough to be considered economically feasible for a large-scale application.

Since March 1959, some 4,700 primarily organic compounds have been screened systematically as possible control chemicals. A material was considered acutely toxic to G. breve if it produced 100 percent mortality within a 24-hour period at a concentration level of 0.04 p.p.m. Culture media were based on water taken several miles offshore at St. Petersburg Beach, Fla. G. breve used in the tests had been maintained under laboratory conditions about 6 years. Of the compounds tested, 191 were acutely toxic. The second phase consisted of determining the minimum toxic levels of the compounds in artificial media and then running tests to determine how many, if any, were selective enough to be considered as controls for G. breve. Four compounds were toxic at 0.0004 p.p.m., 5 at 0.001 p.p.m., 20 at 0.004 p.p.m., 32 at 0.01 p.p.m., and 120 at 0.04 p.p.m.

At this point, it was decided that a potential control must produce 100 percent mortality to G. breve within 24 hours at a level of 0.01 p.p.m. This standard left 32 compounds with which to conduct selectivity tests. Estimates of the specificity of the "0.01 compounds" were obtained by testing them against commercially important indicator organisms, such as post-larval shrimp, small fish and crabs, and other forms of marine animal life from the Galveston, Tex., area. The selectivity requirement arbitrarily assigned to a potential control was that it must not kill more than 50 percent of any of the indicator organisms at a concentration of 0.1 p.p.m. All but 8 of the 32 compounds were rejected. The supply of two of the most toxic compounds was exhausted during the tests. A supplier for one of them has not been located, and a new supply of the second, which we were able to obtain for $100 per gram, was not toxic to G. breve at any level tested (maximum 0.01 p.p.m.). This difference suggests variation in toxicity of the chemical in different lots or from different manufacturers.

Comparative tests of toxicants on G. breve cultured in an artificial medium and in sea water from Florida suggested that the Florida water medium contained an inhibitor which reduced the effectiveness of the toxicants. Further comparative tests with the two types of medium are underway.

OCEAN CURRENTS AND GYMNODINIUM BREVE

By Saul Broida

Institute of Marine Science, University of Miami, Miami, Fla.

Streaks and ripples often occur in a fairly calm sea, and these phenomena have a close relationship with internal waves. Surface slicks could be caused by oils associated with some form of sea life--in the present instance, possibly G. breve. Changes may occur in the film of oil which floats on a shallow surface layer over the trough of an internal wave. The effect on surface tension can be such that light wind will cause ripples and slicks alternately. The high surface tension of the water will allow the wind to generate ripples, whereas the oil-covered surface with its relatively low surface tension will remain undisturbed. The progress of the associated internal wave can be measured by the movement of the alternating streaks.

The question arises as to the ability of the organisms to move. Is their inherent ability to move sufficient to be effective in the ocean? In my opinion, it is not. An analogy can be made by considering molecular diffusion, which is negligible in oceanic mixing or even in a teacup. Eddy diffusion really mixes the water masses. Probably, then, the ability of G. breve to propel itself is far overshadowed by the turbulent motion of the water itself. Therefore, the understanding of red tide might be advanced by the study of eddy diffusion in areas where red tide occurs.

It is my understanding that red-tide outbreaks start in or near the passes between offshore islands. Why not then induce turbulence in one of these narrower passes and observe the results? It could be done economically by laying a perforated plastic hose across the pass. An air pump attached to the hose could bubble air through the holes, thus inducing some vertical turbulence in the water. I feel that the experiment is worth trying.

It might be well also to survey the oceanographic conditions in the area on a regular monthly or semimonthly basis to identify seasonal current patterns. Vessels of the U.S. Coast and Geodetic Survey operating out of ports on Florida's west coast might be asked to cooperate in such a survey.

GYMNODINIUM BREVE IN RELATION TO PRIMARY PRODUCTION STUDIES

By David V. Aldrich

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It seems appropriate to consider the study of the red-tide organism in its broader context--in relation to other research on primary producers. The Bureau of Commercial Fisheries is investigating several aspects of productivity: field estimates of primary productivity; laboratory culturing of primary producers for larval shrimp food; and studies of G. breve, a toxic primary producer. As George Rounsefell has pointed out, however, it is very difficult to "distinguish the poison ivy from the alfalfa," by the methods which are available to us for studying primary productivity. It is suggested that this important problem (as well as the more specific ones posed by toxic phytoplankton blooms) might be approached profitably by the inclusion of red-tide studies in a broad research program on the various aspects of productivity.

LABORATORY CULTURE STUDIES AND THEIR RELATION TO GYMNODINIUM BREVE

By Theodore R. Rice

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At present it cannot be predicted accurately when and where outbreaks of red tide will occur, what specific conditions are most favorable for their occurrence, and how blooms of red-tide organisms can be most effectively dispersed or destroyed. Three causes for red-tide outbreaks may be hypothesized, however: (1) some change in water quality precipitates rapid cell division; (2) some reduction in the normal rate of predation on the red-tide organisms permits the normal rate of division to produce a large population rapidly; and (3) physical factors (or a combination of such factors and the motility of the cells) bring together large concentrations of cells. It is possible that a combination of two or all the factors is required, or that one set of factors is required to initiate a red tide and another set to maintain it.

The classical technique of growing cultures in confined volumes of medium has been used, but little confidence can be placed in relating nutritional requirements observed under these confined conditions to those present in a bloom in the ocean. A continuous culture system, however, permits algae to be grown in the laboratory under conditions more nearly simulating conditions in nature. This system makes it possible to maintain an almost constant population of cells and a desired level of nutrients in the water, and to assay the capacity of sea water collected simultaneously in different geographical locations and at different times in the same location to support red-tide organisms. Populations obtained in "natural water" collected at different times and in different locations can be compared to determine when and where water conditions are most favorable for the growth of G. breve. Also, the concentration of individual nutrients can be varied to determine optimum concentrations, and river water or other natural waters can be mixed in any desired proportions. Organic compounds, vitamins, and water conditioned by growing certain organisms in it can be compared with untreated water. Finally, the effects of predators, competitors, and poisons (such as copper) on population growth of G. breve can be tested.

Additional nutritional data can be obtained by chemical analysis of G. breve grown in different media. By relating concentrations in the cells with concentrations of the same nutrient in the water, a better understanding can be obtained of conditions in natural water prior to a bloom. These data could be obtained in the field only by very frequent sampling, or luck in the timing of sampling.

Since grazing affects the abundance of phytoplankton, the specific organisms which feed on G. breve should be sought out and identified to determine if a reduction in grazers is the mechanism which touches off a red tide. Here, laboratory research should precede field work since zooplankton shows some discrimination in feeding, and there is no reason to suppose that the total quantity of zooplankton is in any way related to the abundance of G. breve.

Physical factors apparently form one mechanism which initiates or maintains a red tide by bringing together G. breve at convergences between water masses. From laboratory research it can be determined if the motility of G. breve meets the requirements of the theory, and from field work it can be determined if the distribution of red-tide corresponds to the distribution of areas of convergence in the sea.

Red tides should be established to test the various theories of red-tide formation. This experimentation should be restricted to enclosed bodies of water.

CALIFORNIA RED TIDE

By John G. Carlisle, Jr.

California Department of Fish and Game
Terminal Island, Calif.

The species mainly involved in California red tide in recent years is Gonyaulax polyedra. It is a larger dinoflagellate than G. breve, is not toxic, and does not cause paralytic shellfish poisoning as does Gonyaulax catenella. Many species discolor water, and when they are concentrated (usually 1 to 1-1/2 million cells per liter) the result is called red tide. Several species of Ceratium also occur in California outbreaks. Gonyaulax causes the chief problems and occurs over a wide area--not always in streaks and patches--along the southern California coast. Fish kills are not as often associated with blooms as they are along the Florida coast of the Gulf of Mexico. Principal fish kills are of the northern anchovy (Engraulis mordax), which is susceptible at low dissolved-oxygen levels. During outbreaks of California red tide kills usually occur in confined harbors. Mussels and barnacles also die along groins and harbor rocks, and here again, death is usually attributed to oxygen depletion in association with blooms.

RED TIDES IN SOUTHERN CALIFORNIA

By Rimmon C. Fay

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Dense blooms of dinoflagellates appear periodically as red tides along the coasts of southern California and Baja California. These blooms are governed by an annual cycle of events, and therefore may be expected when suitable natural conditions exist. Since 1950, an unanticipated increase in the frequency and intensity of these blooms appears to have occurred. Coincidentally, certain other changes have also occurred at specific locations along the coast of southern California which may have created conditions more favorable to red tide.

In sequence, the major physical factors in the annual cycle of the inshore phytoplankton in southern California[1] include a winter

[1] Superscript numbers 1 to 8 refer to literature citations which can be obtained from author.

period of cooling which results in a surface mass of water of uniform density to a depth of 100-200 m. Since vertical stability is minimal, the surface waters become thoroughly mixed. Upwelling occurs in late winter and early spring as deep water from below the euphotic zone rises to replace surface waters that are displaced horizontally by westerly winds of 45-55 knots which blow for periods of about 40 hours. Upwelling provides nutrients to the euphotic zone (Of these nutrients, it is the abundance of nitrates which probably limits primary production in the inshore area of southern California). Spring passes into summer, and as solar radiation increases to maximal annual intensity, vertical stability develops in the water column; a shallow thermocline forms at about the 10-m. isobath. During the afternoon, onshore summer breezes push the surface layers of water toward the beaches and into the lee of sheltered locations. Near the end of summer, the direction of the flow of the inshore current system changes, as slightly less saline water arrives indirectly from the north Pacific(2). This introduction of "northern water"(3) continues until the cooling cycle begins in late fall, when vertical mixing again appears to become more important than horizontal transport in determining the course of biological events in the inshore area.

Biological cycles parallel the sequence and intensity of the physical processes. Concentrations of phytoplankton are low during the winter, minimal during the upwelling period, and maximal in the late spring and summer. Usually an inferior secondary peak of plankton production appears in the early fall(4). Diatoms are the first major group of phytoplankton observed after the enrichment that results from upwelling. During the late spring and early summer, available nutrients have declined to approximately 10 percent or less of the concentrations present at the peak of upwelling; the water column is approaching maximum (i.e., vertical mixing is at a minimum). It is then that the dinoflagellates become the dominant phytoplankton. The dinoflagellates are restricted to water above the thermocline. During daylight in late spring and summer, these phototactic, motile organisms concentrate at the surface. The surface layers of water, crowded and streaked with red dinoflagellates, are blown inshore by the afternoon winds, into the lee of headlands or artificial structures such as breakwaters and harbors, where the organisms accumulate. Cell densities of 10-40 million cells per liter are formed as a result of this concentration(5). These massive standing crops of Gonyaulax polyedra block light penetration, and therefore photosynthesis, at depths below 1 m. The dinoflagellate respiration continues until all available oxygen is consumed. Massive numbers of benthic plants and animals suffocate in this anaerobic environment. Anaerobic digestion of the dead organisms begins to produce hydrogen sulfide from the reduction of sulphate produced by the decomposition.

During the climax of the bloom, the red tide amounts to an extraordinary excess of primary production unlimited by a proportionate increase in zooplankton. The red-tide organisms annihilate the zooplankton, the benthic filter feeders, and themselves when oxygen becomes depleted in the opaque reddish-brown water. Local blooms appear to subside only when the inshore water mass is replaced by "northern water."

Economic results of this calamity include severe damage to the inshore fisheries, the bait industry, shoreside recreational facilities, and the resort and restaurant business (an intense red tide may be detected by its odor 6 to 8 miles inland); paint peels from boat hulls, and shoreside and marine structures as a result of H_2S in the air and water. Moreover, annual recurrences of red tide destroy the normal well-developed, highly diversified climax community of perennial benthic organisms(6) of the intertidal and sublittoral zones.

To what extent the following three factors are involved with the problem of the red tides remains to be established: (a) Fish kills occur primarily in artificial harbors and embayments, as already discussed by John Carlisle earlier in this Symposium. If this relationship is obligate, then the construction of additional harbors can only result in increased red tides. It would appear that the same physical situation that causes these natural harbors to act as sediment traps(7) also favors the accumulation of dinoflagellates. Changes in harbor design may help solve problems of excessive accumulation of sediment and plankton. (b) Another possible factor is the disposal of increasing quantities of domestic and industrial wastes into the inshore area. This currently amounts to about 750 million gallons per day, and prospects are for this volume to double within the next 25 years. In theory, this sewage would supply a nutrient enrichment useful to the phytoplankton, but its significance for the inshore area needs to be thoroughly established. (c) A third factor of possibly critical importance is the elimination of massive standing crops of benthic algae along the shores of southern California(8). Benthic algae compete with phytoplankton for nutrients and, presumably, the standing crops of kelps are also limited by nutrient abundance. In the permanent sections of the kelp beds, standing crops of phytoplankton could be expected to be larger, as indeed they appear to be.

Thus the major questions to be answered are: What can be measured that will permit the prediction of the occurrence of a bloom of red tide in advance of its actual appearance? Has the balance of primary production between benthic and planktonic algae been upset or destroyed through the virtual elimination of the benthic algae coincident with the increasing disposal of wastes into the marine environment? What is the biological role of the formation of artificial sedimentation basins (also used in harbors) which appear to favor the accumulation of red-tide organisms? How and why are conditions becoming more suitable for a specific group of phytoplankton, the dinoflagellates, at the expense of the normally highly diversified biota of the inshore area? Can red tides be expected to become more frequent, of longer duration, and greater intensity in the inshore waters of southern California?

CONCLUSIONS

After the presentations and discussions, Symposium participants submitted independent views on the manner in which red-tide research should be pursued in the future. Their ideas are combined in the following list:

1. Studies of the growth requirements of Gymnodinium breve and related plankters under controlled conditions.
   a. Trace metals and growth factors (vitamins and tannic and humic acid).
   b. Physical factors--temperature and light.
   c. Unique metabolic pathways.
   d. Evaluation of biological potential of water.
2. Development of new techniques for identification and estimation of abundance of plankters by water coloration, etc.
   a. Characterization of the specific absorption spectrum in the field and laboratory.
   b. Toxin levels.
   c. Pigmentation.
3. Studies of plankton succession under field and laboratory conditions and the role of predation, competitors, and metabolites.
   a. Qualitative composition of plankton over long periods.
   b. Quantitative composition of plankton over long periods.
   c. Relation of (a) and (b) to productivity of the sea.
4. Standardization of sampling and reporting methods.
   a. Communication of methods and exchange of information.
   b. Fixation methods.
5. Definitive life history studies of the organism.
   a. Morphological variability--seasonal and geographic.

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   b. Encystment and conjugation.
6. Motility of G. breve and its relation to water movements.
   a. Diurnal migration (vertical and lateral).
   b. Rates of movement.
   c. Aggregation and distribution (geographic).
7. Characterization of toxin of G. breve, toxicity to biota, and public health aspects.
8. Study of water movements and meteorological conditions in the eastern Gulf of Mexico.
9. Biological and physical influence of river water and its constituents on growth of plankters.
10. Evaluation of potential control methods in pilot studies.
11. Biochemistry (pigments and metabolites) of G. breve.

The Bureau of Commercial Fisheries, the Florida Board of Conservation, and their institutional contractors are now conducting some of the proposed research. It is recognized, nevertheless, that much is left to be accomplished in field and laboratory studies before red tides can be understood fully. These studies can best be accomplished by common effort of specialists in ecology, taxonomy, physiology, hydrography, and biochemistry. Exchange of information among the specialists should be active and uninhibited. Above all, the continuity and quality of research should not be affected by pressures generated when red tides occur. Research programs should be adequately financed and not conducted only sporadically during crises. The problems are deep and complex, comparable to medical mysteries which appear almost insoluble but which are often overcome by careful investigation.

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