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CAUSATIVE ANALYSIS ON A NEARSHORE BLOOM OF *Oscillatoria erythraea* (TRICHODESMIUM) IN THE NORTHERN GULF OF MEXICO

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ABSTRACT: Physical, chemical, and biological characteristics which preceded and caused a bloom of *Oscillatoria erythraea* commonly known as trichodesmium in coastal waters of Mississippi and adjacent waters of the Gulf of Mexico are described. This is the first report of the blue-green alga occurring in high density near the mainland and in a predominantly estuarine area of the northern Gulf of Mexico. Environmental conditions immediately prior to and during the bloom were characterized by low rainfall, calm sea, a homogeneous water column, low nitrate-nitrogen (0-5 NO_3-N μg-atom/l), no measurable nitrite-nitrogen (0 NO_2-N μg-atom/l), high water temperatures (29-30° C), high salinity (27‰), and a basic pH (8.3 to 8.4). Total phosphorus and orthophosphates were also low prior to the bloom (0.1 P μg-atom/l), but increased slightly during the later stages of the bloom (0.7 to 1.5 P μg-atom/l). The alga disappeared with the return of well-mixed sea water, lower salinity, lower temperature and acidic pH, and an increase in combined nitrogen content. *Oscillatoria erythraea* occurred in bundles of 10 to 25 trichomes or as a single filament, ranging from 8 to 15 μm in diameter and about 0.3 mm in length. The alga occurred in patches with the greatest concentration near the surface. Some entrapment of zooplankton in the dense algal mass was observed, but most of the zooplankton was diverse and unharmed. Harmful effects of the algal bloom on larger animals were not observed nor believed to have occurred.

Blooms of the planktonic blue-green alga *Oscillatoria erythraea* (Ehrenberg) Kutzing commonly known as trichodesmium are common in tropical seas around the world. This organism has been reported frequently from the Indian Ocean, especially the Bay of Bengal, the Red and Arabian seas and the tropical Atlantic Ocean including the coastal waters of South America, the Sargasso Sea and the Strait of Florida (Moseley, 1879; Brongersma-Sanders, 1957; Dugdale, *et al.*, 1961; Dugdale *et al.*, 1964; Sieburth and Conover, 1965; Goering, *et al.*, 1966; Qasim, 1970; Yentsch, *et al.*, 1972; Carpenter, 1973). Blooms in the Pacific Ocean have been reported by Wood (1965) and Bowman and Lancaster (1965). There are fewer reports of the alga from temperate seas, indicating that blooms occur less frequently northward and southward from the tropics. Farran (1932) found trichodesmium off the coast of Ireland and Wood (1965) reports it south of New Zealand and even in Antarctic waters.

Experimental evidence indicates that trichodesmium is capable of nitrogen fixation (Dugdale *et al.*, 1961; Dugdale, *et al.*, 1964; Goering *et al.*, 1966; Ramamurthy and Krishnamurthy, 1967; Carpenter, 1973; Taylor, *et al.*, 1973; Carpenter and McCarthy, 1975). Stewart and Bottomly (1976) review the literature and point out that many morphological types of blue-green algae show nitrogenase activity. In some regions trichodesmium blooms become so intense and widespread that they may make a major contribution to the nitrogen budget of the sea (Eppley and Thomas, 1969; Thomas, 1971; Carpenter, 1973; Carpenter and Price, 1976). Trichodesmium may be detrimental to certain plants and animals (Bowman and Lancaster, 1965; Qasim, 1970), while favoring the growth of others (Calef and Grive, 1966). Ramamurthy (1970) reported no fish mortality in dense concentrations of the alga, however the diversity of fishes was decreased, suggesting bloom avoidance by certain species. He also reported that 80 to 90% of the gut content, of fish taken within the bloom, contained trichodesmium.

There are no detailed reports on blooms of trichodesmium of temperate seas, especially nearshore, estuarine areas. Thomas (1960) and Simmons and Thomas (1962) report trichodesmium from the eastern Mississippi Delta. Gunter *et al.*, 1948; Curl (1959); Humm and Caylor (1957); and Oppenheimer (1970) report it from off the Florida, Mississippi and Texas coasts, respectively. Davis (1954) and Van Baalen and Brown (1969) report it from the Gulf of Mexico. Trichodesmium is known to the present authors to be an ephemeral component of the Mississippi Sound phytoplankton. However, some biological and ecological characteristics of a large bloom of trichodesmium occurring in Mississippi Sound and in the immediately adjacent waters of the Gulf of Mexico during the late summer of 1974 are evaluated and analyzed here to determine the cause of the bloom.

Mississippi Sound is separated from the Gulf of Mexico by a chain of barrier islands, which lie from 12.9 to 19.3 kilometers (8 to 12 miles) off the mainland shore. Four rivers discharge fresh water into Mississippi Sound from the north and sea water enters Mississippi Sound through the island passes; thus the water generally exhibits an increasing salinity gradient from the mainland toward the sea. Additionally, Mississippi Sound is influenced by freshwater discharge from Mobile Bay on the east and occasionally, during flood years, by the Bonnet Carre Spillway of the Mississippi River on the west.

METHODS AND MATERIALS

Field procedure

Surveys by boat and airplane were initiated on 13 August 1974, approximately three days after initial reports of the bloom, to determine its extent and intensity. Clarke-Bumpus samplers fitted with 157 μm mesh nets were used for plankton collections at the surface and bottom. Tows were made at a constant speed for intervals of ten minutes. The tow interval for surface samples taken in the nearshore waters of Ship Island was three minutes, because of the great density of the alga in the water column. Many samples were also taken from the surface and subsurface waters by bucket and subsamples made on a volume basis. Samples were preserved in the field in a 5% solution of formalin buffered with methenamine.

Although hydrological data were taken with each plankton sample, the description of the physical conditions occurring during the bloom is based on unpublished data from a concurrent oceanographic survey of Mississippi Sound described by Eleuterius (1976a,). Conductivity, temperature, pH and dissolved oxygen were measured *in situ* by a Martek water quality analyzer with an accuracy of $\pm$ 0.5° C. Conductivity was later converted to salinity in ppt by an empirical relationship. Transparency was determined by Spectronic 20 Perkin-Elmer Spectrophotometer set at a wavelength of 580 nanometers (nm). Distilled water was used as a standard and the instrument adjusted to 100%. A sample of seawater was read as a percentage of light transmitted. Concentrations of the inorganic nitrogenous compounds, nitrate, nitrite and ammonium, were determined from unfiltered seawater using standard sea water methods (Strickland and Parsons, 1972). Total phosphorus and orthophosphate of unfiltered seawater were determined using methods II.3 and method II.2.1 described by Strickland and Parsons (1972), with no appreciable differences found using filtered and unfiltered seawater samples. Regardless of the presence of phytoplankton or detritus in the samples, for purposes of our analysis it can only be regarded as an estimate or approximation and not an absolute value of the total nutrient budget of the seawater. Sample analyses were carried out consistently and are the only chemical data available which correspond to the development of the bloom. Algal samples were taken near Horn and Ship Islands by Gulf Coast Research Laboratory staff personnel and biologists of the Gulf Islands National Seashore, U.S. Park Service.

Laboratory procedure

Fresh samples were used to determine the concentration of the alga. Preserved plankton samples were stored in seawater formalin (10%) for reference. Algal trichomes were counted in milliliter aliquots using a Sedgwick-Rafter counting chamber. Representative samples of the freshly collected and preserved alga were examined for morphological variation.

RESULTS AND DISCUSSION

Period of occurrence

The senior author first observed the algal trichomes as glittering slivers in the shallow waters near Horn Island on 5 August 1974. On 10 August 1974, reports were received from local fishermen of amber-colored water in Mississippi Sound, especially around the barrier islands. Aerial reconnaissance on 12 August showed that rafts of the alga were forming in the waters north of the barrier islands. Complaints that fishing was poor accompanied these reports in local newspapers and other news media. By 14 August the concentration of the alga had increased to the extent that the water was reddish, brown or gray; a thick (2.8 cm) scum was accumulating on the water surface, and the air was permeated by a strong chlorine or iodine-like odor. Some fishermen discribed the odor as that of freshly-mowed grass or fresh tea. The scum formed great rafts on the water surface and patches of dark brown or reddish water without rafts on the surface were easily delineated by aerial flights on 16 August.

The sea was very calm during the week prior to the bloom, the sunshine brilliant, and a gentle breeze prevailed. These environmental conditions accompanied the bloom for about a week after the onset, the bloom probably reaching peak development on the fourth or fifth day after it was first observed. Heavy rain occurred on 20 August and the alga disappeared for several days, then reappeared in low concentrations near the barrier islands for about another week.

Morphological characteristics of the alga

The alga was found as single trichomes or filaments and in bundles or fascicles just visible to the unaided eye. Algal samples taken during calm sea conditions (early period of the study, 10-14 Aug) were in bundles, while those taken later under rough seas were generally in single filaments. Ramamurthy (1972) reported that the bundles disperse in rough seas. The filaments of the alga were 8 to 15 μm in diameter, and about 0.3 mm in length. Some filaments were much shorter, indicating possible breakage of the filament. Inconspicuous filament sheaths were evident in some samples. The number of trichomes per fascicle ranged from 5 to 60 with an average of 15. Most fascicles contained 10 to 25 trichomes. Sieburth and Conover (1965) reported 12 to 23 with an extreme of 80.

Desikachary (1959) reported three species from the Indian Ocean and McLeod, *et al.* (1962) suggested that two or more species may have been present in their collection at Bermuda, based on taxonomic work by Sournia (1968). We note, however, that the descriptions of the species presented by the authors above were based primarily upon the morphology of the terminal ends of the trichomes which fall within the variability of the specimens observed in our study. Our description and identification of the alga conforms with the revision of the *Oscillatoria* by Drouet (1968). Use of the obsolete generic name as a common name in the present study is based on its frequent use in the past, and the present familiarity associated with the name.

Bloom characteristics and distribution

Trichodesmium occurred in patches from 20-300 meters to over 2 kilometers in diameter. A continuous band of great concentration (over 10^{5-1}), 3 kilometers in width, occurred north of the barrier islands (Figure 1). The algal cells and clumps could be easily seen in the shallow depths as glittering threads as their surfaces reflected light, giving the appearance of numerous small "hairs," commonly known as "sea sawdust." The bloom paralleled the Mississippi coast for about 50 miles and extended less than a mile beyond the barrier islands into the Gulf of Mexico, covering an area of several hundred square miles. Very low concentrations of trichodesmium occurred in the Gulf near the Chandeleur Islands. Housely (1976) stated that the bloom extended into Alabama waters but the entent of distribution was not determined. However, aerial flights indicated that the bloom did not reach as far east as Dauphin Island. The scum was composed of large masses of dead and living trichodesmium trapped in sea foam. Large windrows of scum stained the sandy northern beaches of the barrier island and vast areas of water were virtually covered by the dark sand-colored algal

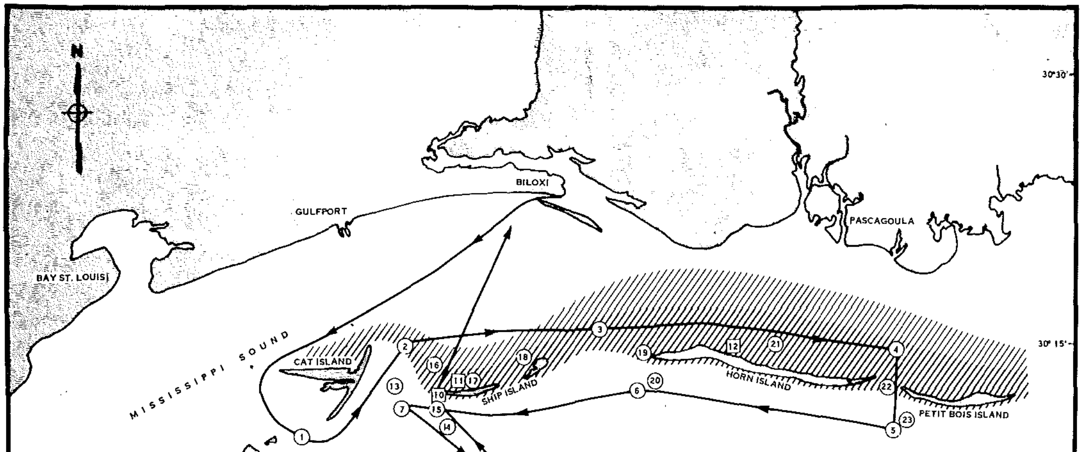

Figure 1. General location of (*Oscillatoria erythraea*) trichodesmium bloom off the coast of Mississippi. The lightly shaded area delineates its location, with the heavily shaded area indicating the greatest concentration. The solid line indicates the track of the research vessel with circled numbers showing locations of stations established to determine the presence or absence of the alga, while numbers in squares show stations where plankton tows were made.

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layer. After a few days, the pigment phycoerythrin (Shimura and Fujita, 1975) released from the dead algal cells, stained a wide swath on the sandy beaches on the north side of the barrier islands an intense purple. There was a distinct absence of algal windrows on the southern beaches of the islands.

Although Wyatt (1975) and Reynolds and Walsby (1975) provide information on possible responses of phytoplankton blooms including patterns of development and movement by vertical and horizontal displacement, all of our observations indicate that the bloom occurred *in situ* in Mississippi Sound including observation of filaments throughout the water column three weeks before the appearance of the surface scum. We have no evidence that the bloom drifted into Mississippi Sound. Furthermore, Perry, *et al.* (1979) recently reported on the apparent *in situ* occurrence of a red tide bloom in Mississippi Sound and Gunter *et al.* (1948) reported on the *in situ* occurrence of red tide blooms along the Florida coast. There is also ample evidence in the literature on eutrophication in estuaries and on associated algal blooms, that indicates typically marine planktonic organisms can and do cause blooms in coastal waters.

Other phytoplankton associated with trichodesmium

Inhibitory interaction between blue-green and other algal species have been suggested by Boyd (1973) and Vance (1965). Bell, *et al.* (1974) have suggested that selective stimulation by extracellular products may account for algal blooms, but nutritive competition has generally been considered the cause (Hulbert, 1970; Thomas, 1970; Carpenter and Guillard, 1971; Lange, 1974).

The surface slick associated with trichodesmium has been previously assigned to the commonly associated diatom, *Coscinodiscus concinnus* (Sieburth and Conover, 1965). Although this diatom was very abundant in our samples, the contribution to the surface slick is unclear since *C. concinnus* is known, from related work by two of the junior authors, to be common and abundant in Mississippi Sound throughout the year. Furthermore, the pattern of phytoplankton productivity in Mississippi Sound ascertained to date, generally follows that described by Russell-Hunter (1970) and Williams (1972) for estuarine waters. The most abundant phytoplankton genera associated with the trichodesmium bloom studied here were the diatoms *Coscinodiscus, Chaetoceros, Biddulphia, Nitzschia* and *Thalassiothrix*, and the dinoflagellate *Ceratium.* Comparison of our data with those of Thomas (1960), Simmons and Thomas (1962), and Housley (1976) indicate that the phytoplankters listed above, other than trichodesmium, form a major component of phytoplankton under non-bloom conditions. We surmise that trichodesmium had little effect on other phytoplankters.

Animals associated with trichodesmium

Zooplankton species (32) comprised primarily of common larval forms, appeared to be unaffected by the occurrence of the bloom; however, some mortality occurred through entrapment by the dense mass of filaments near the surface of the water. The overall effect of entrapment on zooplankton populations was probably negligible.

Animals found entrapped were motile, indicating that no toxic, lethal effect of trichodesmium occurred. Zooplankton diversity was typical of summer communities in Mississippi Sound (Perry and Christmas, 1972). This contrasts with a previous report where Qasim (1970) found a sparse community of zooplankton associated with a bloom of trichodesmium in the Indian Ocean. In addition, we found no associated organism which appeared to be favored by the algal bloom such as that reported for the copepod, *Macrosetella gracilis*, by Calef and Grice (1966), and no evidence that the bloom caused any mortality of larger animals.

Local reports by fishermen indicated that fish apparently avoided the bloom and no dead fish or other animals were seen during the bloom, either in the Gulf, estuary, or on adjacent beaches. Statistical comparison of fisheries data (Perry, *et al.*, 1974) taken during the bloom with that of prior and subsequent sampling periods, showed that no differences in fish diversity and abundance could be assigned to trichodesmium. However, observations by the senior author corroborate reports that larger fishes avoided the bloom, perhaps, because of the algal organism, or physical and chemical conditions associated with the bloom. No large fish were seen in the bloom area or taken by net, but large schools of small menhaden and very small mullet were observed on two occasions in the bloom near Petit Bois Island and near the east end of Horn Island . Few crabs were observed in the shallow water north of the islands during the bloom, although in other years "egg" crabs are generally very abundant there during August.

Environmental conditions

Physical and chemical parameters for ten stations within Mississippi Sound including the island passes of Dog Keys, Horn and Ship islands (see Figure 1) were combined and plotted as monthly averages as shown in Figure 2. River discharge, also shown in Figure 2, is indicative of the rainfall pattern for the Mississippi coastal plain during the study period. Comparison of the river discharge pattern with salinity, temperature, oxygen, transparency, pH and nitrate-N, however, clearly shows that during the July-August 1974 bloom period relatively little fresh water was discharged into Mississippi Sound, accounting in part for the high salinity of the near-shore sea water.

Phorphorus as orthophosphate and total phosphorus, although not shown in Figure 2, followed the same general pattern as that of nitrogen. Ketchum (1967) and Abbott (1957) indicated that phosphorus and nitrogen sources are important factors affecting nutrient availability and phytoplankton concentrations in sea water. The pattern of nutrient flux determined for Mississippi Sound follows that general pattern described for temperate estuaries by Pomeroy, *et al.*, (1972) and Williams (1972) except for the environmental conditions surrounding the bloom. In the present study bright sunlight and transparent water were important factors that initiated and sustained the bloom. The reduced amount of suspended organic matter resulting from the low river discharge, calm seas, and high salinity water contributed to water transparency. Jerlov (1955) described similar factors affecting the transparency of waters in the Baltic Sea. Furthermore, Packard and Blasco (1973) found that nitrogen was light dependent and Grant and Turner (1969) also showed that bright sunlight stimulated nitrate assimilation in several species of algae. Vaccaro and Ryther (1960) also observed a relationship between phytoplankton and the distribution of nitrite in the sea, and Bates (1976) in a related study showed that light and ammonia affected the nitrate uptake of two estuarine phytoplankton species. These reports taken collectively, in view of our findings, indicate the phytoplankton composition and concentration are also related in a complex manner to nutrient availability, interference, bright light and transparent water. In the present study relatively high pH and moderate concentrations of dissolved oxygen were recorded. Water temperatures also reached their annual peak (30°C) in August and there was no wind. Water transparency increased during July and also reached the summer maximum during August. Sournia (1968), Gessner (1970) and Carpenter and Price (1976) found that blooms of trichodesmium occurred during calm and impoverished conditions of tropical seas during periods of bright sunlight.

CONCLUSIONS

In the present study a reduction of detritus was related to the reduced discharge of fresh water from the adjacent river systems. Freshwater discharge is often loaded with suspended solids. Consequently the intrusion of highly saline water into Mississippi Sound probably caused flocculation of suspended materials. These conditions, coupled with calm seas, were probably the primary factors responsible for the highly transparent sea water (Jerlov 1955, Jones and Willis 1956). Kiefer and Austin (1974) also found that great concentrations of algae affected light transmission in the open sea, thus at great concentration, trichodesmium may have affected its own ability to reproduce, which probably contributed to the demise of the bloom.

We found no single factor which could be shown to be the cause of the bloom. For example during the following year (1975) there was no appreciable difference in oxygen concentration or pattern. Dissolved oxygen is generally low in Mississippi Sound during most summers (June-September). Oxygen concentration was only slightly higher at the outset of the bloom when compared to that near the end. Although salinity was higher in October than during the bloom, the average temperature for October was much lower and other

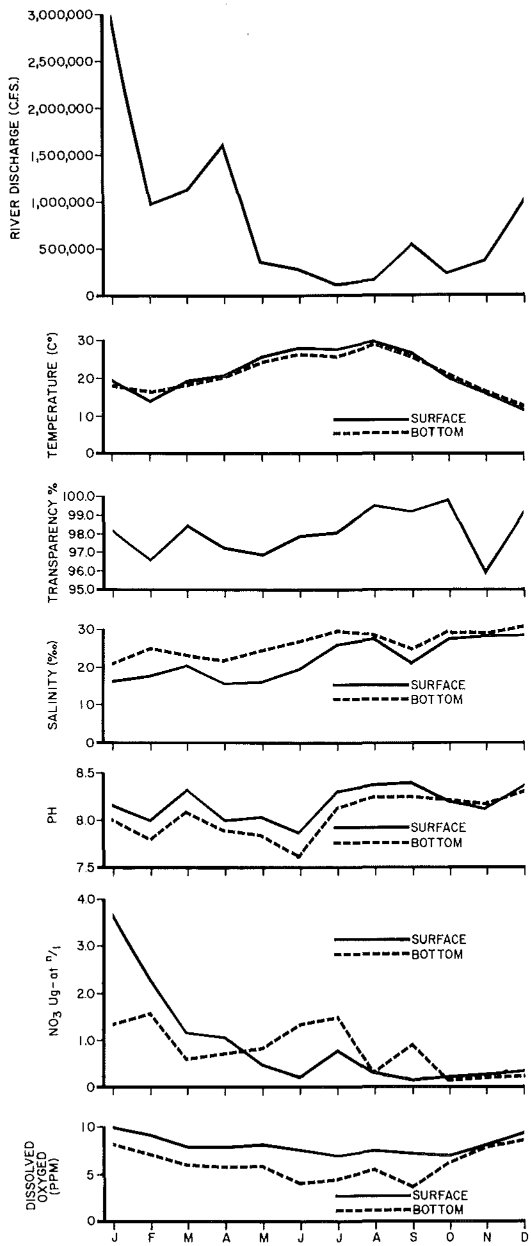

Figure 2. Environmental parameters for 1974. Water salinity, temperature, pH, nitrate, nitrogen and dissolved oxygen are shown for comparison before, during and after the occurrence of the trichodesmium bloom. All plots represent monthly averages for ten stations (see Figure 1). River discharge data (Water Resources for Mississippi Water Years 1974, 1975. U.S. Geological Survey) are not absolute values, but are indicative of the rainfall pattern for the Mississippi coastal plain.

environmental events were obviously different in comparison with those during the summer bloom (Figure 2). The average concentration of nitrogen was also slightly lower during the fall than during the bloom. The bloom appears to be caused by a combination of specific conditions: high temperature, very high salinity, very transparent water, a slightly alkaline pH, low nutrient concentrations, moderate oxygen concentrations, calm seas (no wind) and brilliant sunlight. This combination of physicial and chemical conditions may be of frequent occurrence locally because we have observed trichodesmium blooms in Mississippi Sound of relatively short duration (2-3 weeks) in 1976, 1978 and 1980.

Our findings agree with some environmental parameters as outlined by Sournia (1968), Gessner (1970) and Carpenter and Price (1976) and the morphological features described by Drouet (1968). Very low concentrations of trichodesmium are probably present in Mississippi Sound at all times, and a certain sequence of environmental events probably favor the rapid growth of trichodesmium over other phytoplankton species. Therefore, we conclude that the trichodesmium bloom occurred *in situ* within Mississippi Sound and such blooms occur under a special combination of environmental conditions, whether in the ocean or a typically estuarine area. And the trichodesmium bloom appeared benign in its effect on other marine organisms.

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