A POSSIBLE INITIAL CONDITION FOR RED TIDES ON THE COAST OF FLORIDA

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ABSTRACT

It seems likely that the occurrence of a discrete mass of water, with a salinity lower than that of normal Gulf of Mexico surface water, is a necessary prerequisite for the occurrence of red tide off the Florida Coast.

On the basis of certain elementary assumptions, it has been shown by Kierstead and Slobodkin (1953) that there is a minimum critical size for a water mass physiologically suitable for the growth of a phytoplankton population which will permit an increase in the concentration of organisms. If the rate of increase of the phytoplankton is given by

$$\frac{dN}{dt} = KN, \tag{1}$$

where N is the total number of organisms in the water mass, then the size of the critical water mass is given by

$$L_c = \pi \sqrt{\frac{D}{K}} \tag{2}$$

in a linear model, where D is the rate of diffusion and L_c is the length of the water mass. For any length less than L_c, the organisms will not increase in concentration.

In a circular model the relation is given by

$$R_c = 2.4048 \sqrt{\frac{D}{K}}, \tag{3}$$

where R_c is the radius of the water mass. The order of magnitude of the relation remains unchanged by geometric assumptions.

This relationship is not of particular significance if the phytoplankton species in question is tolerant of a wide range of environmental conditions, but it is important if the physiological requirements and tolerance of the species are highly specialized. The dinoflagellates responsible for red tide outbreaks (Gunter, et al., 1948; Galtsoff, 1948; Brongersma-Sanders, 1948) are not generally amenable to normal culture techniques (personal communication from Provasoli), and *Gymnodinium brevis*, the species responsible for the 1947 outbreak on the Florida Coast (Davis, 1947) is not normally found in the marine phytoplankton of the region (personal communication from Graham). It can be assumed, therefore, that the physiological requirements of these organisms are specialized and that water masses suitable for their propagation are not common.

On *a priori* grounds it seems reasonable to consider that, if peculiar chemical properties (as yet undefined) are required for propagation of these organisms, small masses of water with the required properties will be more common than large ones. The value of K in (1) can be considered fixed at a first approximation. L will probably be small. Therefore the possibility of a plankton bloom will depend on the value of D in (2) and (3). The likelihood of a bloom will increase with decreasing values of D. D can be considered to vary as A, the coefficient of eddy diffusivity (Riley, 1951), and the conditions which promote the occurrence of a bloom can be considered as identical with those that lower the value of A.

While the precise theory of diffusivity is still unknown, it is apparent that diffusivity is reduced at the junction of water masses of different density (Ichie and Katsumi, 1949) and that it is roughly proportional to current velocity (Riley, 1951). Therefore, red tides might be expected when density differences are liable to permit the persistence of small water masses. Admixture of nonsaline water with sea water in a local area will produce a mass of low density water which may be expected to show a low mixing rate at its boundaries. Therefore, the red tides may be coastal phenomena associated with heavy land drainage. Examination of the rainfall data of the U. S. Weather Bureau during the period immediately preceding red tides on the Florida Coast confirms this expectation (Table I).

In compiling Table I, weather stations in the region of the first recorded outbreak were examined. The values shown are those of the stations with heaviest rainfall. This involves arbitrary selection of data, but in no case does the distance between the weather station and the point of initial reported outbreak preclude the possibility of a water mass moving from one to the other without losing its integrity.

On June 2, 1952 red discoloration of the sea at approximately 84° 30′ W Long. and 28° 30′ N Lat. was found by the U. S. Fish and Wildlife vessel ALASKA. This discoloration was caused by a dense population of a red ciliate, probably *Mesodinium pulex* Noland or a closely related form (Kudo, 1947). The surface salinity at a hydro-

TABLE I(a). DATE AND LOCATION OF RED TIDE OFF THE FLORIDA COAST, AND ASSOCIATED RAINFALL

Year	*Date of Initial Report*	*Location of Red Tide*	*Rainfall (inches), Month; Weather Station*
1844	Unknown (Ingersoll, 1882)	Tampa Bay	15.79, August; Tampa
1854	Unknown (Ingersoll, 1882)	Tampa Bay	15.5, July; Tampa
1878	September (Jefferson, *et al.*, 1878)	Florida Bay	9.40, August; 25.10, September; Miami
1880	August (Ingersoll, 1882)	Tampa Bay	6.40, July; 14.00, August; Tampa
1882	July 20 (Anonymous, 1882)	Mouth of Tampa Bay	5.28, June; 10.44, July; Tampa
1883	Reported by Brongersma-Sanders (1948) from Walker (1884). Reference to Walker's original paper shows that these authors refer to the same 1880 outbreak. Walker's paper was submitted for publication under date of December 21, 1880.		
1885	October (Glennan, 1886)	Egmont Key to Charlotte Harbor	10.64, September; 1.95, October; Tampa 13.68, September; Manatee
1908	Reported by Taylor (1917) as killing sponges, without any mention of dead fish. This is probably an outbreak of sponge blight rather than red tide (Smith, 1941).		
1916	October 3 (Taylor, 1917)	Boca Grande to San Carlos Bay	12.56, July; 8.22, August; 5.34, September; Fort Myers
1946*	November 20 (Gunter, *et al.*, 1948)	Naples	9.23, September; 2.03, October; 9.69, November; Naples
	In October 1946, Fort Meyers, Punta Gorda and the Everglades, Florida were flooded by unusual tides in the wake of a hurricane on October 7–8. Charlotte Harbor and part of the Everglades can be considered as having been thoroughly mixed with sea water, which drained into the Gulf of Mexico in considerable volume. November was warmer by 6.1° than any previous November on record (71.2° mean for Florida). October was 1.1° above normal and warmer than any October in five years for the state as a whole.		
1947*	March (Gunter, *et al.*, 1948)	Florida Bay	10.37, March; Captiva 8.94, March; Fort Meyers Greatest March rainfall on record for state with exception of 1930
1947*†	June 20 (Gunter, *et al.*, 1948)	Bonita Beach (South of Fort Myers)	6.47, May; 12.84, June; Fort Myers (2.69 inches fell after June 20) 3.34, May; 13.33, June; Punta Gorda (.04 inches fell after June 20)
1947*†	July 18 (Gunter, *et al.*, 1948)	Venice to Sarasota	13.06, June; 11.44, July; Sarasota (7.64 inches after July 18) 18.25, July; Punta Gorda (12.72 after July 18) Floods in Okeechobee region during June and July
1952	October 25	Boca Grande and Southwest of Sanibel	12.35, September; 8.34, October; Fort Myers (none after October 25)

* All outbreaks marked with an asterisk are considered by Gunter, *et al.* (1948) as representing a single occurrence. Since discoloration and fish mortality disappeared between each of the listed dates, they are here considered as separate.

† The interval with no fish kills separating these two outbreaks is of the order of two weeks and may or may not indicate separate dinoflagellate populations.

TABLE I(b). MEAN RAINFALL (inches) BY MONTHS AT FIVE FLORIDA WEATHER STATIONS

	J	*F*	*M*	*A*	*M*	*J*	*J*	*A*	*S*	*O*	*N*	*D*	*Years*
Belle Glade	1.68	1.48	2.70	2.33	3.60	9.01	6.90	8.06	7.41	4.84	2.90	1.32	1924–1951
Fort Myers	1.76	2.02	1.89	1.89	4.13	8.91	8.16	8.82	7.45	4.48	1.33	1.56	1851–1951
Miami	2.27	2.03	2.63	3.41	7.15	7.07	5.60	5.88	8.65	7.74	3.26	1.98	1855–1951
Punta Gorda	2.24	1.83	2.21	2.20	3.61	7.48	7.54	8.05	8.22	3.97	1.56	1.85	1914–1951
Tampa	2.69	2.56	2.33	2.01	2.99	7.25	7.95	8.18	6.42	3.19	1.72	2.07	1840–1951

graphic station in the discolored water (33.4‰) was lower than that at surrounding stations (34.99, 35.47, 36.17). This would seem to confirm the theory in so far as protista in general are concerned, since the discolored water was approximately 90 miles from the nearest coast.

On the basis of this evidence it can be stated tentatively that red tides require a discrete mass of water of relatively low salinity, but this does not imply that salinity difference is the sole requirement for red tides. The water mass must also satisfy the other physiological requirements of dinoflagellates. It does seem likely, however, that in any newly isolated mass of sea water the nutrient and other requirements of at least one of the algal or protozoan species in the mass will be met and will result in a temporary bloom.

The possible connection between heavy rainfall and fish mortality has been noted by Aggasiz (1890) and by Webb (1886) in their studies of fish mortality on the Florida Coast. Braarud (1951) has found that *Prorocentrum micans*, *Peridinium trochoideum* and *Amphidinium* sp. show maximal reproductive rate at 15–20 ‰ salinity. The salinity optimum for *Exuviaella baltica* is 10 ‰. In July 1952, Riley found a salinity of 24.9–22.7 ‰ in a bloom of *Gonyaulax* sp. in Long Island Sound off New Haven, Connecticut (personal communication from Riley). Ketchum and Keen (1948) have reported a salinity of 33‰ in the 1947 Gulf of Mexico outbreak, which is well below the salinity of normal Gulf of Mexico water (36 ‰).

These reports indicate that the salinity requirements of at least some dinoflagellates are such that a mass of water in the Gulf of Mexico stabilized by low salinity will be physiologically suitable for growth and reproduction. There is some indication that amino acids and vitamins are part of the nutritional requirements of dinoflagellates (personal communication from Provasoli). The possible presence of these compounds in fresh water is indicated by the work of Hutchinson and Setlow (1946).

The excessively high values of total phosphate found in the 1947 outbreak on the Florida Coast can be adequately explained on the hypothesis of Ketchum and Keen (1948), who stated that the excess phosphate "may be the result of terrigenous contamination . . . or may be the result of active swarming of organisms." Both of these

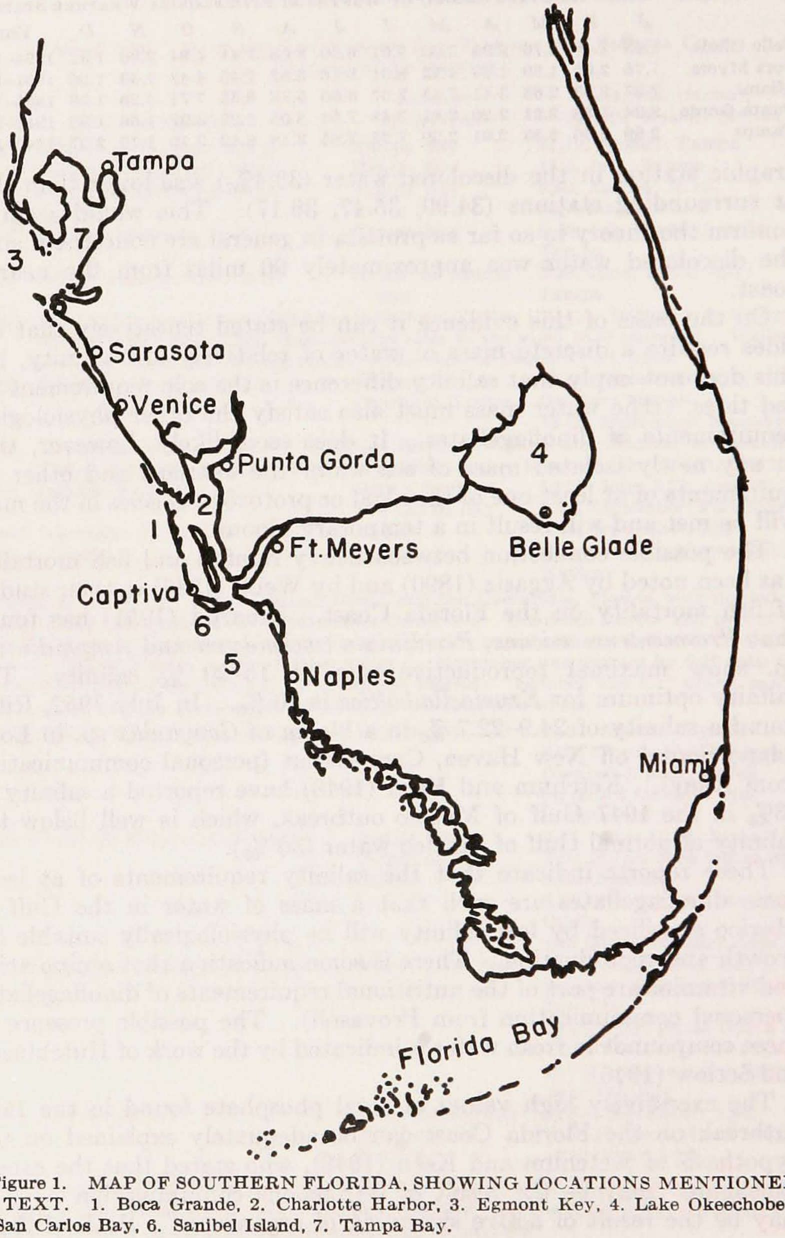

Figure 1. MAP OF SOUTHERN FLORIDA, SHOWING LOCATIONS MENTIONED IN TEXT. 1. Boca Grande, 2. Charlotte Harbor, 3. Egmont Key, 4. Lake Okeechobee, 5. San Carlos Bay, 6. Sanibel Island, 7. Tampa Bay.

TABLE II. Vertical Distribution of *Gonyaulax monilata* During a Red Tide on the East Coast of Florida. Stations *d* and *e* Were not Red but Were in the Same Water Mass as Stations *a*, *b* and *c*.

	Depth (feet)	Millions of *G. monilata*/liter
Red Water Stations		
a	0.5	3.60
	1.5	2.15
	2.6	.90
b	0.7	4.60
	1.2	1.00
c	0	8.20
	1	5.70
	1.5	1.45
	8	.45
Non-red Stations		
d	0.5	.80
	2.0	.17
	5.0	1.19
	8	.94
	9.5	.73
e	0.5	.57
	1.5	.46
	3.3	.07

alternatives are almost certainly true. Samples taken during an outbreak of *Gonyaulax monilata* (Howell, 1953) at Melbourne, Florida in August 1951 showed striking vertical stratification in shallow water (Table II). This outbreak occurred in the inland water way (Indian and Banana rivers). The stations indicated as "not red" were located as close as possible to the edge of discolored areas. It is apparent that a vertical concentration of 10 times in total P by diurnal migration of the organisms is possible.

Conclusions—It is considered likely that red tide outbreaks are initiated by the occurrence of discrete masses of water which differ in salinity and chemical characteristics from the normal water of the Florida Coast. The abnormal nutrient concentrations found in 1947 can be explained on the basis of vertical stratification of the organisms. Upwelling or other purely marine phenomena are superfluous assumptions. Once the nutritional requirements of the dinoflagellates are satisfied, the limiting condition for a bloom is the rate of diffusion of the physiologically suitable water mass. Prediction of red tides will depend on intimate knowledge of coastal drainage and hydrography. Prevention of most red tides may be possible by altering the drainage pattern of the Charlotte Harbor—Calloosahatchee estuary region.

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