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THE RELATIONSHIP OF VERTICAL TURBULENCE AND SPRING DIATOM FLOWERINGS

By

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The causes underlying the initiation of the spring diatom flowering have been a subject of vigorous discussion in recent years. With the gradual accumulation of records it has become quite clear that no one factor controls this peculiar phenomenon. The obvious prerequisite, an abundant supply of nutrient salts in the euphotic zone, is generally satisfied during the autumn and early winter, yet a flowering does not in most cases follow immediately. In a few localities, such as Cape Cod Bay and Ipswich Bay (Bigelow, 1926), the Woods Hole region (Fish, 1925), and Long Island Sound (Riley, 1941), diatom bursts have been recorded in December or January, but in most north temperate waters they do not occur until March or April.

Atkins (1928) maintained that in the English Channel light is the controlling factor. Through a period of several years he correlated the beginning of the spring flowering with the time when the vernal increase in radiation began. Marshall and Orr (1928) found by experimental means that not only was there sufficient light for plankton growth at the surface even in mid-winter, but that on sunny days it might even be strong enough to inhibit growth. They suggested, however, that the length of day might be an important factor particularly at lower levels.

That Atkins' conclusions did not have a universal application was shown by Føyn (1929) who found that the vernal increase on the Norwegian coast began near land and occurred somewhat later in deep water, although the radiation was approximately uniform throughout the entire area. He, and later Gran (1932), thought this was due to liberation of nutrients near shore by the outpouring from the spring thaw. But Bigelow, Lillick, and Sears (1940) showed that similar differences in the time of the spring flowering occurred in the Gulf of Maine in places where the salinities did not show the freshening influence of land drainage until after the beginning of the bloom.

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[1] Contribution number 315.

The latter authors suggested the importance of vertical stability in the initiation of the vernal flowering. They reported that in parts of the Gulf of Maine, particularly the deep basins, diatom bursts did not occur until a density difference of at least 0.1 had been established between the surface and a depth of 30 m. Their data indicated, however, that the establishment of vertical stability did not always initiate a flowering. For example, off Seguin Island, where the water had a high positive stability at every time when analyses were made (in December, January, March, and April) the flowering did not begin until March. These authors therefore concluded that there was a coincident factor, and suggested that it might be grazing.

This concept of the biological role of stability, or the lack of it, largely stems back to the work of Gran and Braarud (1935), who used it to explain the small size of the plankton crop found in the turbid, turbulent, but nutrient-rich waters of the Bay of Fundy. They pointed out that when the plankton population is at equilibrium (from the standpoint of production) its total photosynthetic rate is equal to its respiration rate. Under optimal conditions photosynthesis exceeds respiration; frequently it is about five times as much. Thus, in order to survive, a phytoplankton cell would have to be exposed to light one-fifth of the time. This would limit the phytoplankton crop according to the ratio of the fraction of the crop in the euphotic zone at any one time to the total crop. It follows that the establishment of vertical stability, limiting the region of active vertical turbulence to a narrower stratum, perhaps not much more than the thickness of the euphotic zone, would increase the production rate and perhaps initiate a diatom flowering.

An analogous application of this principle was made by the present author in a study of the plankton of Georges Bank (Riley, 1941a). Here, as in many other places, the spring diatom flowering began in shallow water. There was no evidence that nutrients, transparency, or other such factors were more favorable in the shallows. The rate of production (photosynthesis per unit organism) was approximately uniform all over the bank. There was, however, a seasonal rise in the surface photosynthetic rate, showing a correlation of .894 with radiation, which had produced a slight increase in the population at all stations between January and March. And according to the reasoning of Gran and Braarud, the place where the greatest production occurred should be where the ratio of the plankton in the euphotic zone to the total crop was greatest, namely in shallow water. Synthetic examples were prepared to show that such a mechanism might produce the observed differences in the quantity of plankton in various depths of water. It was concluded, therefore, that the balance between the effects of turbulence and the increasing vernal radiation initiated the spring flowering.

SPRING DIATOM FLOWERING ON GEORGES BANK

Four cruises were made to Georges Bank during the spring of 1941. A comparison of the average quantity of plankton observed on these cruises with the results of the previous year is shown in Figure 24. It appears from the figure that the 1941 spring flowering began and ended slightly later than the one in 1940. By moving all the 1941 averages to a point about a week earlier it would be possible to fit the data for both years to a single smoothed curve, and examination of individual stations gives a further impression of an orderly series of events. In March, 1941, all but two of the stations had a surface crop of 3000 to 10,000 Harvey units per m³. The two shallowest stations, 38 and 44 m. respectively, had concentrations of 15,000 to 20,000 units. During the cruise of March, 1940, four or five shallow stations had blooms equal to or greater than this, but around the edges of the Bank the quantity of plankton was still small. In April, 1941, some of the shallow stations had the highest surface concentrations recorded on any of the cruises, and the flowering was beginning to extend outward in all directions. In April, 1940, the diatom

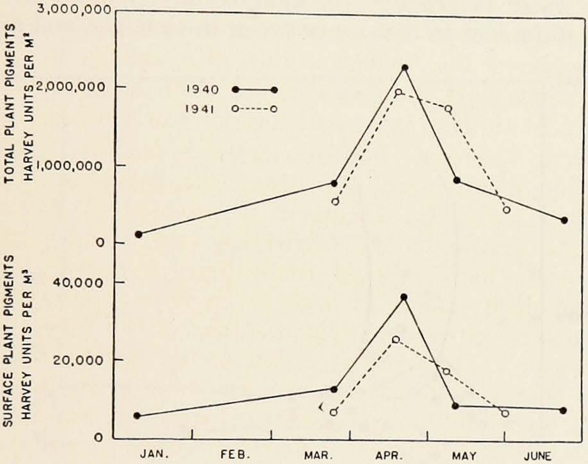

Figure 24. A comparison of the mean quantity of plant pigments found on Georges Bank in 1940 and 1941. The lower figure represents the surface water, the upper one the entire vertical column.

burst had developed to large proportions nearly everywhere, and the quantity was about as great at the deep stations as in shallow water. By the time of the May Cruise in both years the flowering was on the wane, with the greatest decrease in deep water.

THE RELATIONSHIP OF SPRING FLOWERINGS WITH DEPTH AND STABILITY

Figure 25 shows the relationship between depth and stability during the March, 1941 cruise. The concentration of plant pigments in the surface water (average of the analyses at 1 and 10 m.) is plotted against the difference in density between the surface and 50 m. (solid dots), or, at stations where the water was too shallow for a 50 m. observation, the density difference between the surface and 30 m. (circles). It is evident that there is a zero relation between plankton and stability at the deeper stations, although it becomes slightly negative with the inclusion of the two shallow stations where the flowering had started.

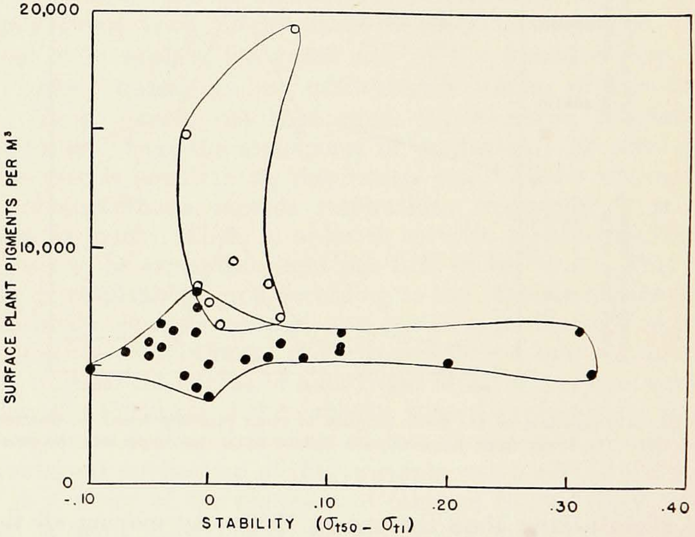

Figure 25. The relation between plant pigments and stability during the March, 1941, cruise. For further explanation see text.

Figure 26 represents the April cruise, plotted in the same way. The highest values again were in shallow water although there were some low records there also. The envelope surrounding the data from the deeper stations shows a slight upward trend suggesting a positive relation between phytoplankton and stability. The correlation is .434, which, with twenty-seven pairs of observations, indicates a probability of about 1:40 that the observed relationship could be due only to chance.

After the peak of the diatom burst the relationship was quite different, as indicated by Figure 27, which shows the relation between phytoplankton and stability during the first May cruise. Large concentrations remained in shallow water and in deeper water that was unstratified. No large quantities of surface phytoplankton were found in highly stable areas, and the coefficient of correlation between stability and plankton for all the observations in the deeper water was —.710. The probability is less than 1:100 that such a result would be due to chance variation.

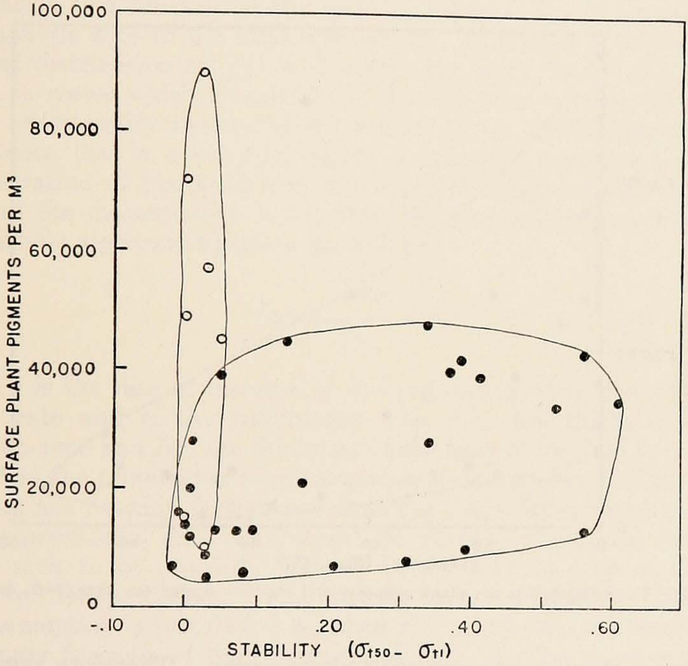

Figure 26. The relation between plant pigments and stability during the April, 1941, cruise.

It appears therefore that the relationship between surface phytoplankton and stability is zero in the early spring, becomes a direct relation during the early part of the spring flowering, and shifts to an inverse relation after the diatoms pass their peak. This process of inversion can be noted at certain individual stations. At three stations on the April cruise which showed a high degree of stability it was found that the quantity of plant pigments at the surface was considerably lower than at some intermediate level (one-fifth to one-half). This, combined with the fact that the percentage saturation of oxygen at the surface was high, suggests that the plankton at the surface had been higher at some previous time and had decreased by sinking, grazing, or some such phenomenon. Therefore since part of the plankton had already passed its peak at the time of the April cruise, the early direct relation with stability is best expressed not by a correlation with the surface plankton, which had already suffered diminution, but with the total crop, which had remained more nearly what it had previously been. Thus a higher correlation (.586) is obtained between the total plant pigments and stability during the April cruise. This process was still evident at several stations on the May cruise, so that the inverse relation of stability with the total crop was not quite as marked as with the surface plankton, the correlations being respectively —.671 and —.710.

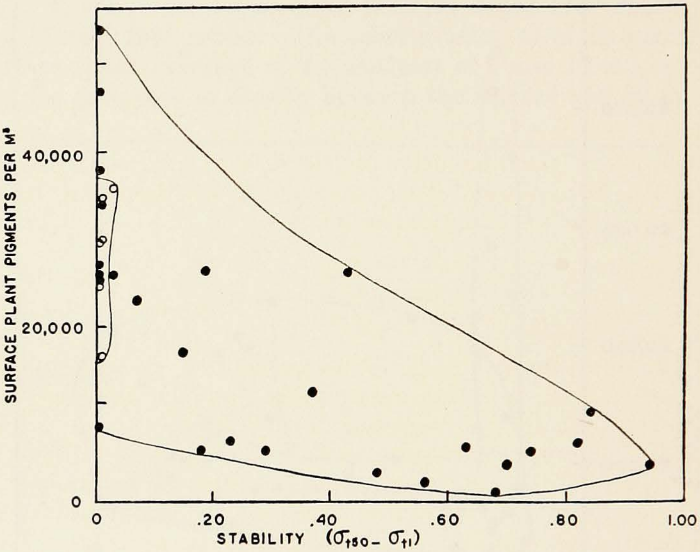

Figure 27. The relation between plant pigments and stability during the May, 1941, cruise.

DISCUSSION

ANALYSIS OF THE APRIL DATA

As pointed out before, the significance of the relationship of the plankton crop with depth and stability depends on the conclusion reached by Gran and Braarud (1935), which may be restated for purposes of the present discussion as follows: The rate of increase in population is a function of the ratio of the quantity of organisms in the euphotic zone to the total population. The latter is limited in its vertical distribution by (a) a discontinuity layer, or (b) the bottom depth in water which is uniform in density from surface to bottom. If we oversimplify the conditions somewhat by postulating complete turbulence, that is, a sufficient degree of mixing to maintain a uniform concentration of plankton from the surface to the bottom, or to the limit of the discontinuity layer, then the proposition may be stated as a simple algebraic equation, as follows:

$$r = r_P \frac{Dr_P}{Dr_c} - r_c \tag{1}$$

where r is the rate of increase of the population, r_P is the photosynthetic rate and r_c the respiratory rate, Dr_P the thickness of the euphotic zone and Dr_c the thickness of the zone of vertical turbulence.

To test the proposition requires certain assumptions: 1. That nutrients are not limiting factors and that the transparency and the rates of photosynthesis and respiration are relatively uniform over the entire area to be studied. This is believed to be true of Georges Bank (cf. Riley, 1941a). It is obvious from the equation that when this assumption is justified, i. e., when r_P, r_c, and Dr_P are constants, r is a linear function of the reciprocal of Dr_c. 2. The water is free of horizontal movements which change the thickness of the turbulent zone. Or, if such movements occur, a decrease in Dr_c increases r and vice versa. Georges Bank is not free of such currents, and certain stations will therefore be in error unless allowance can be made for the changes that have occurred.

The proposition is most easily tested in waters that are homogeneous in respect to density so that the thickness of the turbulent zone is limited by the bottom depth. Eleven stations in the April cruise which had a density difference between the surface and 50 m. of 0.02 or less were chosen for this purpose. If it is assumed that the population has undergone logarithmic growth during the interval between the March and April cruises, then the rate of increase may be determined by the equation

$$r = \frac{\log_{10} Qt - \log_{10} Qo}{.4343t} \qquad (2)$$

where r is the rate of increase, Qo the original population, and Qt is the population at time t.

Qo, obtained by averaging the total quantity of plant pigments at all the stations of the March cruise, is 542,000 Harvey units per m^2 of sea surface. Qt is the total quantity at each station of the April cruise (given in Table I as thousands of plant pigments per m^2). Since most of the stations on the two cruises were taken in the same order, the mean time of 25 days between cruises is a valid figure to use for all the stations. From these values the rate of increase of the population may be calculated for each station. The result is shown in the r column in the first division of Table I.

A more difficult problem is presented by the stations where there was a discontinuity layer. It is obviously impossible to set any exact limits to the depth of vertical turbulence, which varies with the force of the wind. The situation is somewhat simplified, however, by the fact that vernal heating was increasing the stability of the surface waters, for under these conditions the temperature distribution can be used to determine both the maximum thickness of the turbulent layer and the length of time that the water had been stratified. Since vernal heating in perfectly calm water decreases logarithmically with depth in the same way that the effects of visible radiation are manifested, it follows that the normal temperature distribution observed in oceanic waters is due to the combined effect of heating by radiation, which occurs at or near the surface, and the submergence of this warmer water to lower levels by the forces of vertical turbulence. Therefore the maximum limit of turbulence is indicated by the depth at which the submergence of the warmer water ceases. The heat increment during the spring period may be divided into two categories: (a) before the water becomes stratified there is a relatively uniform increment at all levels, and (b) after the establishment of the discontinuity layer there is a further heat increment in the turbulent surface layer.* Consequently over a given period of time when the rate of

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* There are certain minor reservations that limit the exactness with which these categories can be defined. In water that is deep enough to have a discontinuity layer the year around, category (a) obviously does not apply completely. In the region of the thermocline there would be a small amount of heating that would not be uniform. But since the winter thermocline is steep and lies at a relatively deep level, the error is small and is ignored in the present discussion. There is also a small error in category (b) because vertical turbulence does not cease completely at the lower limit of the discontinuity layer, and con-

increment is known and when it remains uniform, or if allowance is made for a change in the rate, the relative proportions of the total heat increment in each of the two categories can be used to determine the length of time that the water has been stratified.

In March on Georges Bank the temperature had been relatively uniform to a depth of 50 m. or more. In April, on the other hand, the surface was frequently warmer, with the temperature at lower levels decreasing steadily to a minimum point at 10, 30, or 50 m. When, as in the majority of these cases, the salinity remained relatively uniform, the sequence of events can be predicted with a fair degree of accuracy. There was at first a period when vertical turbulence was active to a depth of 50 m. or more, and the vernal rise in temperature was uniform at all levels. During this period the rate of plankton growth would be low, as has been shown to be the case when the density difference between the surface and 50 m. is small. The growth rate would increase greatly when, at some point between the March and April cruises, the heating at the surface rose to a point where the total column could no longer be mixed completely. Therefore, according to the theory discussed above, the depth to which the water continued to mix is indicated roughly by the point at which there is no further decrease in temperature with depth. The amount of time that the water had been stratified is determined roughly by integrating the difference between the temperature at each level and the temperature in the lower water which is not being mixed, and dividing this sum by the mean daily increment in heat in the entire water column between the two cruises. The values so obtained for the depth of the turbulent layer and the time it had been established are listed in division 2 of Table I (Dr_c and t).

The calculations made thus far give approximate values for all the terms required in determining the rate of increase except Qo. In division 2, r is derived on the assumption that the growth rate was negligibly small until the time when the density difference was established, in other words that Qo was the same as in March.

The values for r, taken as a whole, show considerable relationship with the estimated depth of the turbulent zone. A large section of the data might even be fitted with a reasonable degree of accuracy by a smoothed curve. There are too many exceptions, however, to permit the acceptance of such a curve without rationalizing the discrepancies.

It is especially important in this respect to examine the data in

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sequently there is a slight heat increment at lower levels even though the temperature is practically uniform.

relation to the current pattern on Georges Bank, since, as was pointed out above, horizontal movements which changed the thickness of the turbulent zone would also be expected to change the growth rate of the diatoms.

The upper part of Figure 28 is a chart of the April cruise. The station positions are marked by circles (division 1) or dots (division 2), and the station numbers are recorded immediately above the positions. The isohalines for the surface water are sketched in. Stations where unusually high or low values were obtained for the rate of population increase (in respect to depth) are indicated by the letters *H* or *L*, respectively.

The aberrant stations clearly fall into two classes: the first a group of five stations in the west central part of the bank which were consistently low, and the second, which includes both high and low stations that have nothing in common except that they all occur at the periphery of the bank.

The lower part of Figure 28 shows the salinities in the central and southern part of the bank plotted on the isopycnic surface of $\sigma_t = 25.84$. With a mass of lighter water south of the bank, and with the isopycnal emerging at the surface in the central part of the bank and sloping downward toward the south, reaching a depth of 30 to 50 m. at the southernmost stations, there is good reason to suppose that water masses were moving on the bank in this western portion and drifting across in a northeasterly direction. In view of this conclusion the plankton results appear reasonable, for the diatoms at any particular station in the drift area had until recently been in water of greater depth and according to the theory would therefore have a lower mean growth rate than if they had been located at that station since March (though actually the growth rate was probably not as low as it appeared to be, for the initial population in March was probably smaller in deep water off the bank). Such a situation would not be expected to exist much past the middle of the bank, however, for gradually deepening water would throw the process into reverse.

Around the edges of Georges Bank the dynamic picture is so complicated that even with adequate data it would be difficult to reach a reasonable solution, although the consistency with which high values appear at the southern edge of the bank and low ones at the north and east just outside the 32.50 isohaline, is symptomatic of the existence of areas which, with the aid of a broader network of stations might be explained as was the one in the middle of the bank.

In bringing the discussion to a conclusion we return to the fundamental proposition, that the rate of increase in population is a linear

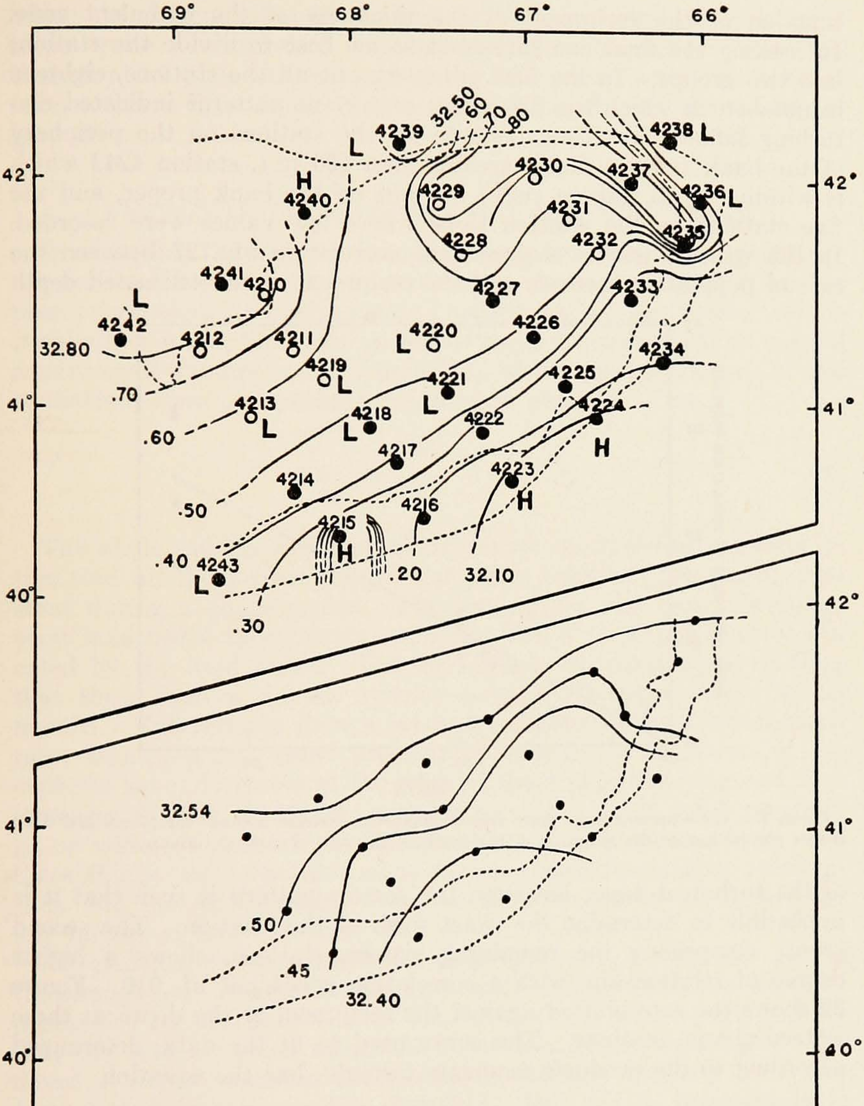

Figure 28. Upper figure: Station numbers and positions during the April, 1941, cruise. Solid lines indicate surface isohalines. For further explanation see text. Lower figure: salinities at the stations on the southern part of the bank plotted on the isopycnal $\sigma t = 25.84$.

function of the reciprocal of the thickness of the turbulent zone. In making the final comparison it seems best to divide the stations into two groups. In the first group we put all the stations, eighteen in number, in which the discussion of current patterns indicated disturbing influences. These include all the stations on the periphery of the bank (with a depth greater than 100 m.), station 4242 which is within the 50 fathom curve but not on the bank proper, and the five stations on the western slope where low values were recorded. In this group there is a significant correlation of .727 between the rate of population increase and the reciprocal of the estimated depth of the turbulent zone; however, the scatter pattern is such that it is impossible to determine the exact form of the relation. The second group, comprising the remaining sixteen stations, shows a higher degree of relationship, with a correlation coefficient of .919. Figure 29 shows the rate plotted against the reciprocal of the depth at these sixteen chosen stations. The curve used to fit the data, determined according to the products moments formula, has the equation

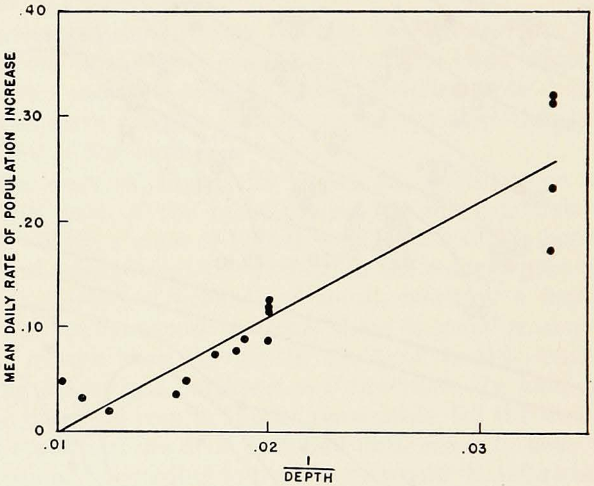

Figure 29. The estimated mean daily rate of population increase between the March and April cruises plotted against the reciprocal of the depth of the zone of vertical turbulence.

$$Y = 11.03X - 0.111 \qquad (3)$$

where Y is the rate of increase in the population, and X is the reciprocal of the estimated depth of the turbulent zone. The equation is almost a true fit. The slight curvature exhibited by the data between 50 and 100 m. is hardly more than might be expected in a system in which the prerequisite of complete, continuous vertical turbulence is never quite accomplished (as indicated by the vertical distribution of plant pigments and oxygen). It is near enough to a linear form to leave little doubt of the essential correctness of the original proposition.

SEASONAL CHANGE IN THE RELATIONSHIP

In discussing the seasonal change in the relationship between plankton and stability we return once more to equation (1). But since it presupposes that the phytoplankton constitutes a closed system, which it definitely is not, the equation can be applied more readily to natural conditions if another factor is added, r_s, which denotes the rate of loss of diatoms from the system by sinking or grazing. Thus,

$$r = (r_P \frac{Dr_P}{Dr_c} - r_c) - r_s \tag{4}$$

The whole validity of the previous section was based on the assumption that all the factors except r and Dr_c remained reasonably constant during a single cruise. The assumption was based on somewhat inadequate experimental evidence, but it appeared to be vindicated by the final result. The evidence is of about equal validity that these factors do not remain constant throughout the spring months. Experiments show a gradual increase in the photosynthetic rate; transparency, which presumably affects the thickness of the euphotic zone, decreases at the peak of the spring flowering and then increases slightly theerafter; respiratory and grazing rates generally go up with temperature; and the number of animals increases. All these things can affect the slope of the plankton-stability relationship, and the real problem therefore is to determine which are the key factors at any one time.

All evidence points toward the photosynthetic rate as the key to the change between the March and April cruises. Positive evidence is supplied by the experimental data from the previous year showing that the rate increased about 20% between March and April. Indirect evidence supports the conclusion because most of the other factors tend in the opposite direction. The rise in temperature is to be regarded as an adverse influence through its effect on respiration and grazing. Although there is undoubtedly much truth in the suggestion made by Bigelow, Lillick, and Sears (1940) that grazing is an important factor, it could hardly have any influence here, for generally the number as well as the activity of the zooplankton increases between March and April, thus retarding rather than accelerating the flowering. It is doubtful, however, whether any of these factors had much influence as retarding agents, for the change in temperature, and probably in the quantity of animals, was relatively slight. The sinking rate is an unknown factor. It may or may not have changed between the two cruises. But if it did change in a positive direction, it was due to physiological factors rather than the physical environment and so may be considered a function of the production rate. Thus, by a process of elimination, we again reach the conclusion presented before, that the balance between the effects of vertical turbulence and the increasing vernal radiation determines the beginning of the spring diatom flowering. This is the only explanation that satisfies both the observed local differences and correlations of the type presented by Atkins (1928). It does not, however, exclude the possibility that nutrients derived from the land may be important in some localities.

The inverse relationship between plankton and stability that occurs after the peak of the spring diatom flowering has been recognized for many years. The classical explanation, based on reduction of the vertical transport of nutrients by increasing stability followed by depletion in the euphotic zone and hence a decrease in the production rate, probably cannot be applied to Georges Bank because in both 1940 and 1941 the decrease in plankton occurred before there was any marked depletion of phosphate or nitrate, although it is possible that some other nutrient was a limiting factor. Moreover, since the surface photosynthetic rate had continued to increase (about 30% according to 1940 experimental values), and since the transparency had increased slightly, it is obvious that the explanation of the reversal of the relationship must depend on a great increase in the effectiveness of one or more of the adverse factors. The vertical distribution of plant pigments immediately suggests that the sinking rate is the key factor, but unfortunately we know very little about the quantitative aspects of this phenomenon. Grazing might also account for the observed results, and this seems a reasonable explanation because there appears to be a great increase in the quantity of zooplankton between April and May. However, this factor would not produce the observed change in vertical distribution unless the greater part of the feeding occurred in the surface waters.

The preceding discussion shows that the changes observed in the relationship between plankton and vertical stability are not wholly unreasonable on the basis of what we know about the factors which might affect the relationship. The real solution of the problem, the quantitative evaluation of key factors, requires more knowledge than we have at present about the grazing phenomenon and the physiological properties of the diatoms during the spring flowering. It is intended, therefore, to devote subsequent papers to a study of these matters.

ACKNOWLEDGMENTS

I am indebted to Dr. Columbus O'D. Iselin for data on salinities, and to Mr. T. S. Austin for assistance on one of the cruises. Some generalizations about the zooplankton of Georges Bank are derived from data that were kindly provided me by Dr. George L. Clarke and Mr. Dean F. Bumpus. I also thank Mr. G. Evelyn Hutchinson and Mr. Albert E. Parr for reading and criticizing the manuscript, and Mr. Parr for information about physical oceanography.

SUMMARY

1. Cruises to Georges Bank in the spring of **1941** showed that the relationship between plankton and stability was zero in March, positive in April, and negative in May.

2. Theoretical considerations suggest that when the thickness of the euphotic zone and the rates of photosynthesis and respiration are constant, the rate of increase in the plankton population is a linear function of the reciprocal of the thickness of the zone of vertical turbulence. Data from the April cruise fit the theory.

3. A discussion is presented of the reasons for the seasonal change in the relationship of plankton and stability.

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TABLE I—DATA DERIVED FROM THE APRIL, 1941 CRUISE

For explanation of symbols see text

Station Number	*Total Plant Pigments in Thousands*	*Depth*	$\sigma t50-\sigma t_1$	t	Dr_c	r
DIVISION 1. UNSTRATIFIED STATIONS						
4210	1,195	89	.00	25	89	.032
4211	3,449	57	—	25	57	.074
4212	1,862	97	−.01	25	97	.049
4213	491	60	−.02	25	60	−.004
4219	2,415	44	—	25	44	.060
4220	530	36	—	25	36	−.001
4228	5,070	53	—	25	53	.090
4229	3,865	54	—	25	54	.079
4230	1,845	62	.01	25	62	.049
4231	1,328	64	.01	25	64	.036
4232	900	80	.01	25	80	.020
DIVISION 2. STRATIFIED STATIONS						
4214	2,424	90	.38	12	50	.125
4215	3,312	430	.41	4	30	.455
4216	3,483	157	.34	3	10	.621
4217	645	69	.03	2	50	.087
4218	481	48	—*	4	30	−.030
4221	1,764	60	.16	4	10	.296
4222	3,571	84	.34	16	50	.118
4223	3,476	172	.61	2	10	.931
4224	1,788	133	.56	6	50	.199
4225	2,689	75	.56	5	30	.321
4226	2,597	68	.05	5	30	.314
4227	861	57	.04	4	50	.116
4233	1,740	95	.52	5	30	.233
4234	4,356	932	.37	22	50	.095
4235	1,070	105	.09	3	30	.227
4236	512	94	.39	5	30	.011
4237	905	84	.07	3	30	.173
4238	593	189	.08	8	50	.011
4239	687	230	.21	20	50	.012
4240	2,755	58	—*	3	30	.544
4241	3,049	171	.14	43	100	.041
4242	325	69	.03	4	50	−.128
4243	2,487	136	.31	41	50	.037

* Density difference between the surface and 30 m. of .03 or greater.

TABLE II—ANALYSES ON THE APRIL CRUISE

Station Number Date Position	*Depth*	*Temperature*	*Density*	*Plant Pigments*	*Oxygen % Saturation*
4210 4/15/41	1	4.09	26.08	15100	97
41–33	10	4.10	26.08	12800	98
68–30	30	4.10	26.08	13300	98
	50	4.12	26.08	13500	98
4211 4/15/41	1	3.84	25.92	54100	106
41–21	10	3.78	25.92	60200	106
68–19	30	3.79	25.95	61500	105
4212 4/15/41	1	4.18	26.01	13600	99
41–13	10	4.18	26.01	18300	100
68–52	30	4.14	26.01	18600	100
	50	4.08	26.00	20100	98
4213 4/15/41	1	3.75	25.87	6600	97
40–53½	10	3.73	25.85	7600	97
68–37	30	3.75	—	8800	97
	50	3.75	25.85	8400	96
4214 4/16/41	1	4.18	25.76	40500	120
40–34	10	4.24	25.75	43000	119
68–22	30	4.03	25.87	31000	101
	50	3.57	26.14	19100	94
4215 4/16/41	1	5.08	25.92	38400	121
40–19	10	5.08	25.92	39800	119
68–09	30	4.75	26.03	49900	107
	50	5.51	26.33	22500	94
	100	7.76	26.82	5900	80
4216 4/16/41	1	3.42	25.62	25800	122
40–30	10	2.46	25.63	30700	119
67–38	30	2.54	25.90	33300	108
	50	2.71	25.96	32700	100
	100	5.25	26.46	13200	86
4217 4/16/41	1	3.78	25.76	8100	100
40–44	10	3.49	25.79	10200	99
67–46	30	3.44	25.80	8900	100
	50	3.43	25.79	9400	99
4218 4/17/41	1	3.79	25.80	10000	100
40–56	10	3.81	25.80	11000	99
67–58	30	3.44	25.83	9500	100
4219 4/17/41	1	4.02	25.86	48100	108
41–09	10	4.01	25.86	50100	108
68–08	30	4.02	25.86	59300	107
4220 4/17/41	1	4.05	25.85	14500	101
41–17	10	4.06	25.84	15400	100
67–37	30	4.01	25.85	14100	100

TABLE II (Continued)

Station Number Date Position	*Depth*	*Temperature*	*Density*	*Plant Pigments*	*Oxygen % Saturation*
4221 4/17/41	1	5.21	25.68	21100	108
41–06	10	3.65	25.84	21500	103
67–25	30	3.65	25.84	35000	104
	50	3.66	25.84	31800	102
4222 4/17/41	1	4.97	25.51	26200	127
40–54	10	3.84	25.64	70000	124
67–14	30	3.09	25.79	58700	107
	50	2.92	25.85	27600	100
4223 4/17/41	1	3.17	25.56	24500	120
40–41	10	2.58	25.62	44600	120
67–03	30	2.95	25.76	50700	106
	50	3.24	26.17	31100	91
	100	4.87	26.55	6000	82
4224 4/18/41	1	2.64	25.62	9900	115
40–56	10	2.63	25.62	15100	117
66–35	30	—	—	45900	—
	50	2.27	26.18	12000	89
	100	4.73	26.41	3000	82
4225 4/18/41	1	3.55	25.68	39600	119
41–05	10	3.38	25.69	45400	119
66–46	30	2.99	25.94	29200	98
	50	3.01	26.24	35000	98
4226 4/18/41	1	3.89	25.78	36400	108
41–19	10	3.75	25.80	40600	109
66–57	30	3.31	25.83	34700	104
	50	3.32	25.83	39700	103
4227 4/18/41	1	4.23	25.83	12300	101
41–31	10	4.20	25.83	13500	102
67–08	30	3.89	25.86	16500	101
	50	3.88	25.87	15700	100
4228 4/18/41	1	4.55	25.92	87000	113
41–44	10	4.57	25.94	93000	115
67–19	30	4.55	25.94	98000	113
4229 4/18/41	1	4.61	26.00	69000	111
41–54	10	4.64	25.99	74000	111
67–29	30	4.62	26.00	71000	109
4230 4/19/41	1	4.04	25.93	25500	99
42–02	10	4.05	25.93	30500	101
66–56	30	4.06	25.94	31000	102
	50	4.10	25.94	29100	103
4231 4/19/41	1	3.89	25.88	18800	102
41–50	10	3.88	25.88	22000	101
66–45	30	3.89	25.89	21800	101
	50	3.89	25.89	19500	102

TABLE II (Continued)

Station Number Date Position	*Depth*	*Temper- ature*	*Density*	*Plant Pigments*	*Oxygen % Saturation*
4232 4/19/41	1	3.80	25.84	12500	99
41–39	10	3.78	25.84	10900	100
66–35	30	3.71	25.86	11700	100
	50	3.69	25.85	11000	101
4233 4/19/41	1	4.35	25.56	32700	125
41–25	10	4.13	25.77	34400	108
66–22	30	3.73	26.06	16700	94
	50	3.73	26.08	13200	95
4234 4/19/41	1	4.38	25.57	35200	129
41–12	10	4.33	25.59	43900	126
66–11	30	3.42	25.86	67500	107
	50	2.91	25.94	37400	99
	100	5.35	26.54	9100	86
	200	—	—	3600	—
4235 4/20/41	1	4.41	26.02	12900	100
41–44	10	4.36	26.03	12500	99
66–05	30	4.15	26.07	11000	95
	50	4.20	26.11	9200	94
4236 4/20/41	1	4.31	25.81	8300	102
41–56	10	4.20	25.82	11300	100
65–59	30	3.82	26.05	5300	94
	50	4.07	26.20	3600	93
4237 4/21/41	1	4.44	26.02	12000	99
42–00	10	4.46	26.02	13600	98
66–24	30	4.22	26.09	10500	96
	50	4.23	26.09	9800	96
4238 4/21/41	1	4.43	25.72	5900	101
42–17	10	4.43	25.72	6700	102
66–10	30	4.23	25.77	5900	101
	50	4.00	25.80	5700	100
	100	4.46	26.33	800	82
	200	—	—	1700	—
4239 4/22/41	1	4.30	25.75	6700	99
42–13	10	4.31	25.74	6700	100
67–47	30	4.07	25.79	5600	99
	50	3.31	25.96	3300	94
	100	4.50	26.35	2600	82
	200	—	—	2600	—
4240 4/22/41	1	4.80	25.86	46500	112
41–44	10	4.83	25.87	44500	112
68–16	30	4.54	25.91	48800	110
4241 4/22/41	1	5.66	25.90	41900	117
41–45	10	5.70	25.91	48400	119
68–43	30	5.41	25.91	52000	114
	50	4.53	26.04	20000	101
	100	3.95	26.15	3900	95

TABLE II (Concluded)

Station Number *Date* *Position*	*Depth*	*Temperature*	*Density*	*Plant Pigments*	*Oxygen % Saturation*
4242 4/23/41	1	4.34	26.09	4900	101
41–16	10	4.30	26.10	4600	98
69–17	30	4.02	26.17	5000	96
	50	4.00	26.16	4500	96
4243 4/23/41	1	5.28	25.58	7400	121
40–11	10	4.93	25.64	9200	121
68–50	30	4.12	25.70	16200	121
	50	2.77	25.89	39000	104
	100	5.21	26.45	10200	85