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PLANKTON OF THE FLORIDA CURRENT V. ENVIRONMENTAL CONDITIONS, STANDING CROP, SEASONAL AND DIURNAL CHANGES AT A STATION FORTY MILES EAST OF MIAMI[1]

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ABSTRACT

This is a survey of the standing crop of plankton in the Florida Current, its vertical, seasonal and diurnal changes, and of relevant environmental conditions. The top 100 meters is considered to be the euphotic zone. Most of the phytoplankton is nannoplankton and is concentrated in the euphotic zone, where it shows some seasonal change. Zooplankton also show a small seasonal change and a marked diurnal migration in the euphotic zone. Details are given for siphonophores, chaetognaths, copepods, euphausids, pteropods and young fish. There is some seasonal fluctuation in the total phosphorus content of the euphotic zone, and most of the phosphorus is in the form of dissolved organic matter. A smaller fraction comprises live nannoplankton and detritus, and a very small fraction is due to zooplankton. Both the inorganic phosphorus and inorganic nitrogen are extremely deficient at all times in the euphotic zone.

INTRODUCTION

The majority of the quantitative plankton studies along the eastern coast of the United States have been limited to northern waters, that is, from Chesapeake Bay north to Maine. Some scattered data are available for the area off the Florida East Coast where the Gulf Stream makes its closest approach to the American mainland.

Parr (1933, 1937) reported on the hydrographic conditions in the Gulf of Mexico and the Straits of Florida. An excellent summary of these and later investigations on the hydrographic conditions of the Gulf of Mexico and adjacent areas has been prepared by Leipper (1954). Riley (1937) studied phytoplankton production in Gulf of

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Mexico waters, where he considered the influence of the Mississippi River drainage in the northern portion of the Gulf. Analysis for plant pigments showed that phytoplankton productivity was highest in waters richest in phosphates. However, samples obtained from completely fresh river water produced higher values for plant pigment than those obtained elsewhere, but these values are not high for typical fresh water indicating that the high turbidity of the river water interferes with plankton production. Analysis of open Gulf water showed typically low values. Later work by Riley (1938) was done in the Dry Tortugas area at the end of the chain of the Florida Keys where the waters emerging from the Gulf of Mexico join the Florida Current. He found that in the waters of the Tortugas region, the nitrates were more important than the phosphates as limiting factors in phytoplankton production.

Smith, *et al.* (1950) conducted an ecological survey of Biscayne Bay, adjacent to Miami. The results of this survey indicate that a large role is played by land drainage and sewage in the growth of plankton and sedentary organisms and that the year around plankton growth is limited by the rate of phosphate production and a grazing rate limited by phytoplankton formation.

Miller, *et al.* (1950) conducted investigations of the Florida Current at a station 10 miles east of Miami. They found that peak values of the phytoplankton concentrations generally succeeded those of the nutrients, while those of the zooplankton were less clearly related. An extremely high ratio of the filterable nannoplankton to net caught phytoplankton was found to be typical for this area.

In 1953, the Marine Laboratory, University of Miami, commenced a study of productivity in the Florida Current off Miami. The initial phase of this survey was planned to measure the standing crop of the zooplankton and phytoplankton along with the available inorganic and organic nutrients and such environmental factors as temperature, salinity, and illumination. It also was designed to define the vertical distribution and possible seasonal variations of these organisms. If, as proved to be the case, the seasonal variations are small, Riley's method of regression would not be applicable to this phase of the work. The products of this investigation are here reported together with a discussion of various aspects of the biological system. The tables of data are too lengthy to be included in the text and are on deposit at the Marine Laboratory, University of Miami. Some of the data included have been derived from other but related investigations, in-

cluding work of graduate students.

Some hydrographic information has been made available from studies of the area under Office of Naval Research contracts and National Science Foundation grants, and information on plankton under National Science Foundation and National Geographic Society grants. For several plankton groups masterate or doctorate theses are referred to. Some of these results are as yet unpublished and the workers concerned have generously allowed us to include data extracted from their studies. They include D. O'Berry and E. C. Jones (Copepods), R. L. Wormelle and T. Dow (Pteropods), D. C. Roane and H. B. Moore (Siphonophores), H. Owre (Chaetognaths), N. Voss, G. L. Voss, J. Clancy, V. A. Legaspi (Fish Larvae), G. L. Voss (Cephalopods), and J. B. Lewis (Euphausids).

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Many members of the staff of the Marine Laboratory have from time to time contributed assistance and advice. To all of those we wish to express our gratitude. The present paper is published under the name of a single author since joint authorship of all who have participated would have been hardly feasible. He wishes to make it clear that he has acted as compiler of the results and as chemist in the last phases of the work, but that credit is due to many others also.

Physical and Chemical Conditions

Temperature and Salinity

Samples for this study were collected at a routine station approximately four miles west of Gun Cay (25°33′ N. - 79°25′ W.), where the depth of the Florida Current is over 700 meters. During the course of the collection, it was impossible to hold an exact station due to the strong currents encountered. It was necessary to interrupt the collection operation numerous times in order to return to the station. In spite of the above difficulty, the samples were collected in an area a few miles in diameter.

The station was occupied approximately once every month during the initial year. However, due to weather conditions and other factors, it was frequently necessary to delay the cruises for longer intervals. During the following year, the station was occupied less frequently, mainly to check for variations and for collection of miscellaneous data.

Temperature measurements at the station were made with a 900 ft. bathythermograph and reversing thermometers attached to Nansen bottles. Surface temperatures were measured with a bucket thermometer.

Water samples for salinity determinations and other chemical analyses were collected with Nansen bottles placed at 50 meter wire intervals. Salinities were determined by titration according to the Knudsen silver nitrate method.

Figs. 1 and 2 show the extreme range of temperatures encountered in the Florida Current off Miami. As one would expect, the upper

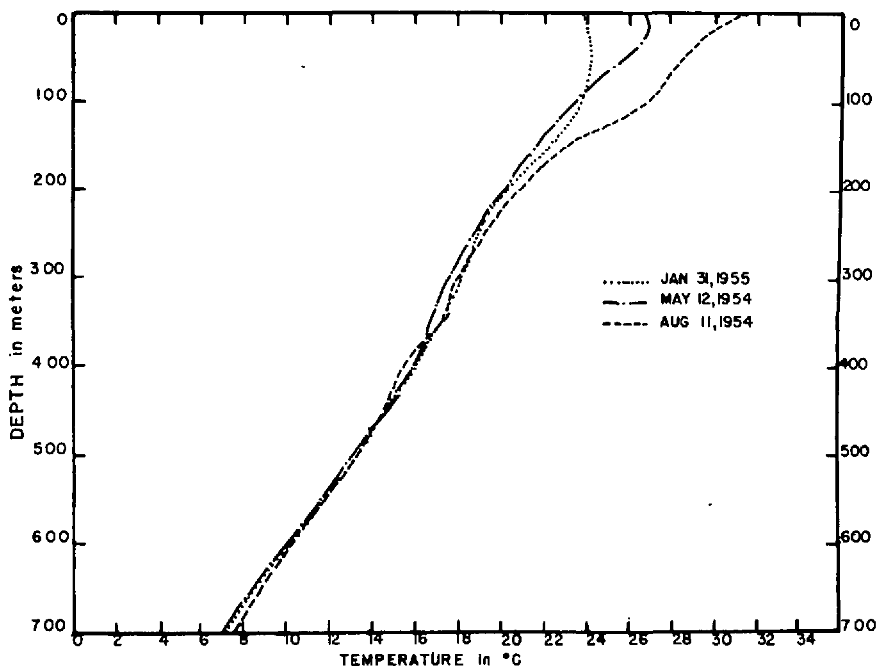

FIGURE 1. Typical vertical distribution of temperature encountered in the Florida Current, showing the extreme fluctuations.

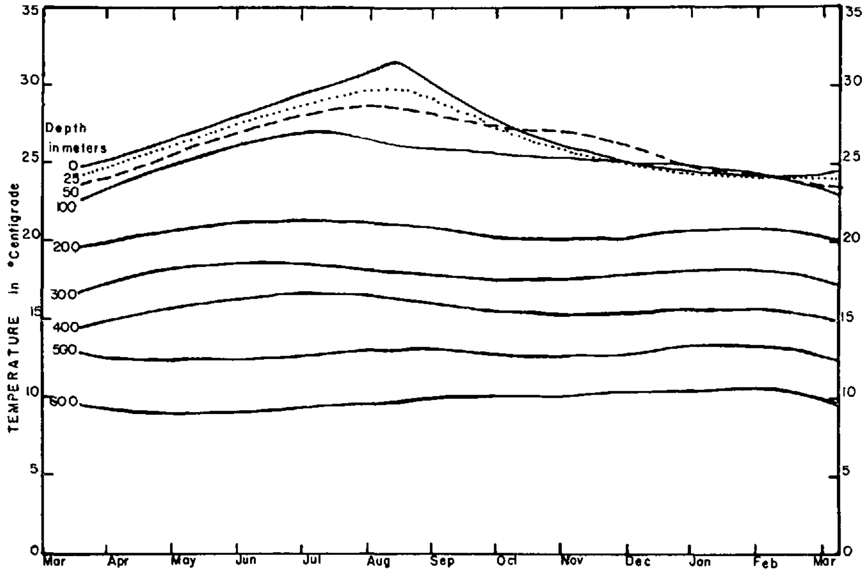

FIGURE 2. Seasonal variation of temperatures at constant depths.

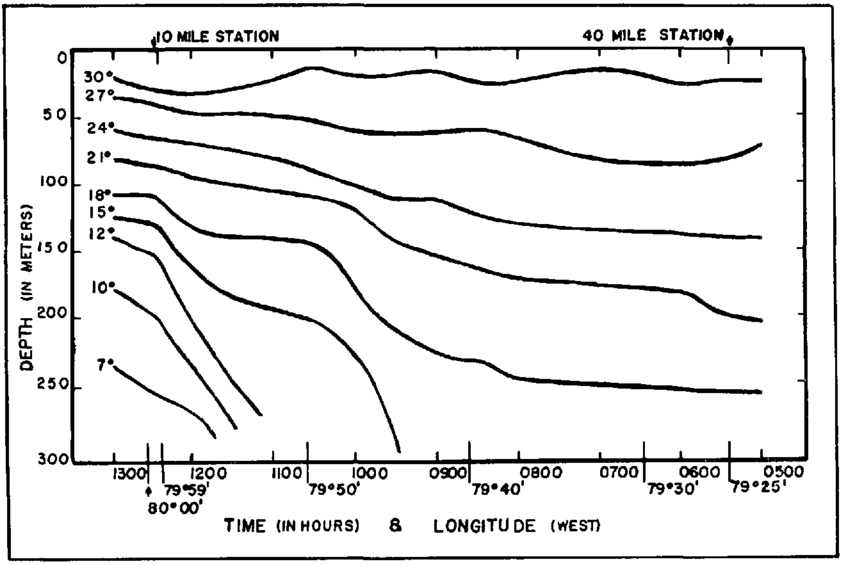

FIGURE 3. Temperature profiles across the Florida Current, at 25°33′ N. Lat., during the summer months.

surface waters show considerable variation during the yearly cycle. At depths below 150 meters, the temperature remains fairly constant. The maximum surface temperature of 31.4°C. was recorded during the August cruise, the lowest, 23.8°C., during the February cruise. This temperature range is in good agreement with that obtained by Miller, *et al.* (1953) for the 10 mile station off Miami. Fig. 3 shows the variation of the isotherms in a typical section across the Florida Current from Miami to Gun Cay. The isotherms on the western side, where the depth is approximately 300 meters, are more closely packed.

The T-S and S-D curves (Figs. 4 and 5) resemble those obtained by Miller (1953) and Lewis (1954). According to the work of Parr (1933), the water mass of the Florida Current is composed of waters from the Gulf of Mexico and the Yucatan Channel. Typical temperature-salinity curves are given for these water masses; however, he has shown that when the Gulf Water is present it is limited to a shallow layer and usually extends only a short distance across from the Miami shore. The temperature-salinity curve obtained at our Forty-Mile Station is typical of that obtained by Parr for the Yucatan Channel. This

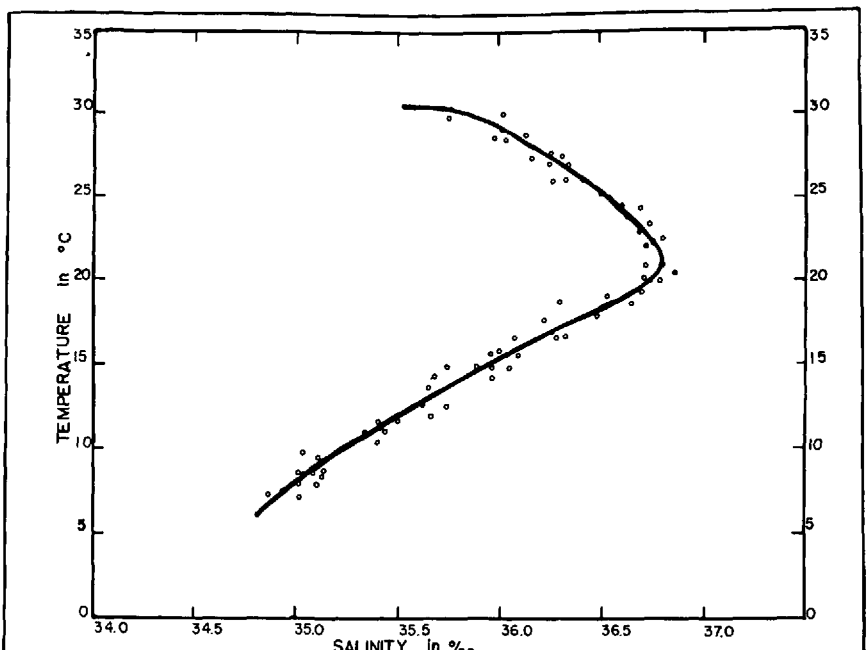

FIGURE 4. Temperature-salinity relationship of the water forming the Florida Current.

water mass remains fairly constant throughout the year as indicated by the slight scattering of the points in both Fig. 4 and 5.

Light

Light transmission in the Florida Current is generally high; the Secchi disc reading is, on the average, around 33 meters. Figure 6 shows the seasonal variation of the extinction coefficient as calculated from the maximum depth of visibility of the Secchi disc. The isolume, which corresponds to 1.0% of sunlight when measured against full sunlight at the surface at noon, is also shown in Fig. 6, and is considered the lower limit of the euphotic zone. This zone appears to oscillate around the 85 meter depth. However, since only a small error will be introduced and since some authors use 0.5% sunlight as an estimate of the compensation depth the euphotic zone throughout this paper has been taken as 100 meters.

Oxygen

Oxygen was determined on several occasions by the Winkler Method. A portion of this data is shown in Fig. 7, as vertical distributions. No special attention or prominence was given to this factor since oxygen concentration never drops low enough to be likely to affect the animals.

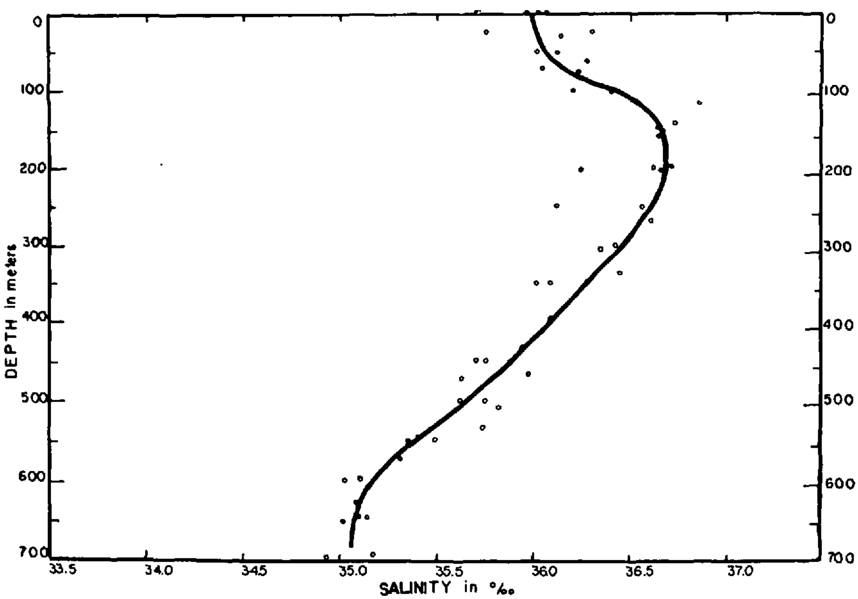

FIGURE 5. Salinity-depth relationship of typical Florida Current water.

Nitrates and Phosphates

Nitrate analyses were carried out in two steps. The initial operation consists of reducing, quantitatively, the nitrate to nitrite using the method of Føyn (1951). The nitrite is then determined by the spectrophotometric method of Bendschneider and Robinson (1952).

Figs. 8 and 9 show the seasonal distribution of the dissolved nitrates occurring in 1955 and 1955. In Fig. 9, it is readily observed that the immediate surface waters remain at very low levels, less than 5 microgram-atoms per liter, throughout the entire year. The large change in the nitrate concentration which occurs for some temperate waters as reported by Riley (1949, 1956) are not present for these subtropical waters. A small build-up of nitrate appears to occur in the early autumn at approximately the 100 meter level. Values of 6 to 10 microgram-atoms per liter form a large band in the intermediate zone that appears to remain constant throughout the year. However, from October to February a large tongue of water of this nitrate concentration

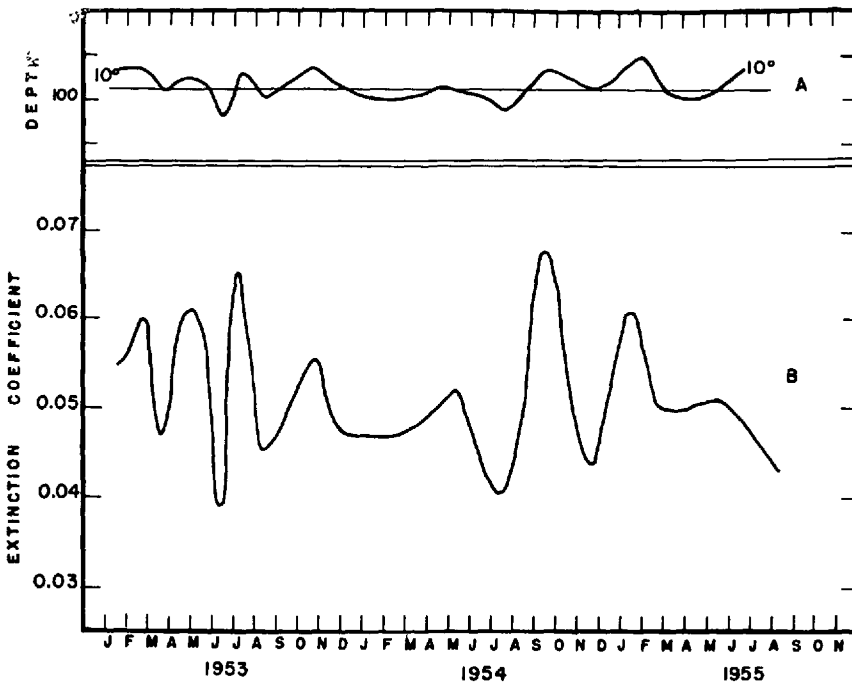

FIGURE 6. (A) Seasonal variation of the isolume corresponding to the limit of the euphotic zone. (B) Seasonal variation of the extinction coefficient of the Florida Current.

extends to the deepest layers. Generally at depths of 300 meters and lower there appears to be no set pattern of variation, the picture becoming rather erratic.

The dissolved inorganic phosphorus analyses were carried out according to the colorimetric method of Greenfield and Kalber (1954). The reagent, containing sulfuric acid, ammonium molybdate, and ascorbic acid stored separately, was mixed just prior to use. The color intensity was measured in a Beckman Quartz Spectrophotometer at a wave length of 820 mμ, using either 10 cm. or 1 cm. cuvettes.

The total phosphorus which includes the inorganic, soluble organic and particulate organic phosphorus was determined by first oxidizing the sample with perchloric acid using the method described by Hansen and Robinson (1952). After digestion, the sample was treated as described for the dissolved inorganic phosphorus.

Figs. 10 and 11 reveal the seasonal, vertical distribution of the dissolved inorganic phosphorus. The concentration of phosphorus in the upper 150 meters is never very high, the value not exceeding 0.2 microgram-atoms per liter. During the summer and fall months, the values drop even lower, to less than 0.1 microgram-atoms per liter. At greater depths, more or less regular ribbons of various concentra-

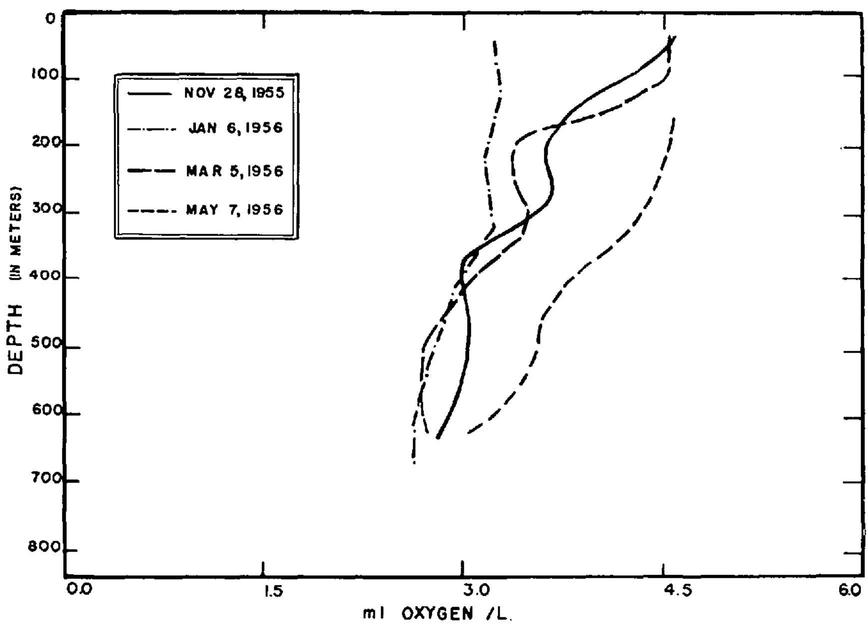

FIGURE 7. Typical vertical distributions of oxygen in the Florida Current.

tions cross the diagram with a steady increase of phosphorus concentration as the depth increases.

The variation of total phosphorus which includes both the bound and unbound phosphorus is shown in Figs. 12 and 13. Here a different picture is presented. The somewhat continuous bands that occur in the dissolved inorganic phosphorus are not observed except in the deeper waters, that is below 400 meters. Above this depth, considerable variation in the total phosphorus concentration occurs throughout the year. During the spring, the total phosphorus concentration is quite low being of the order of 0.5 microgram-atoms per liter or less. As the season progresses into the summer months, a small buildup of phosphorus concentration occurs, the range increasing to 0.5 to 1.0 microgram-atoms. The total phosphorus concentration continues to increase to values ranging from 1.0 to 1.5 microgram-atoms during the autumn months. With the approach of the winter months, the values begin to drop again. Thus the largest concentration appears to occur during the autumn season. It should be noted that during the height of the summer season a pocket appeared in the surface water, reaching a depth of approximately 60 meters, where the total phos-

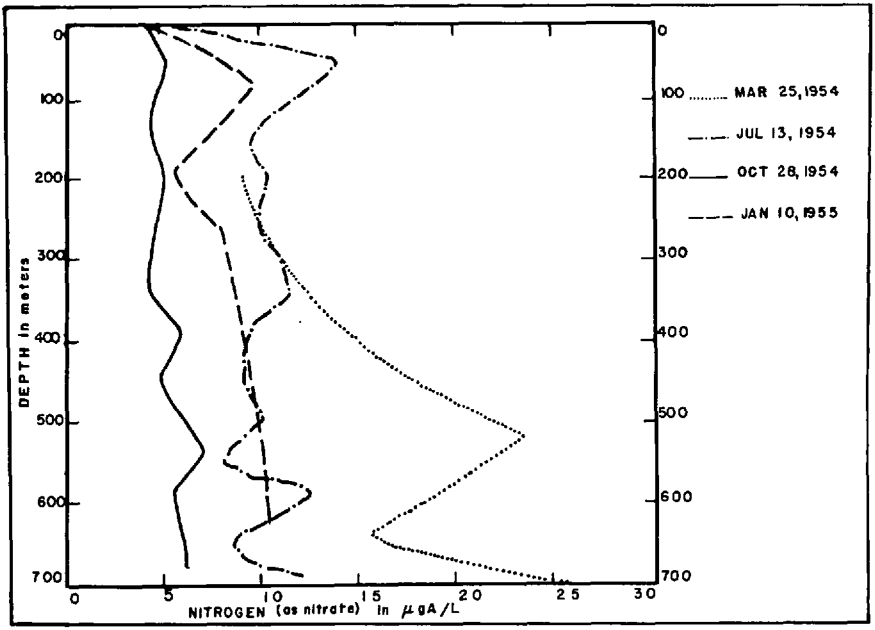

FIGURE 8. Typical vertical distributions of the nitrate-nitrogen in the Florida Current.

phorus concentration increased to a high value of 2.0 microgram-atoms.

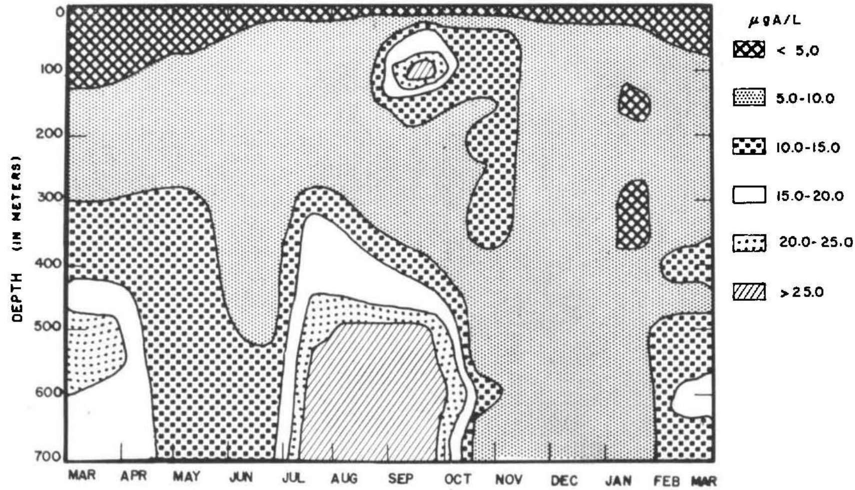

FIGURE 9. Seasonal variation of nitrate-nitrogen in the Florida Current.

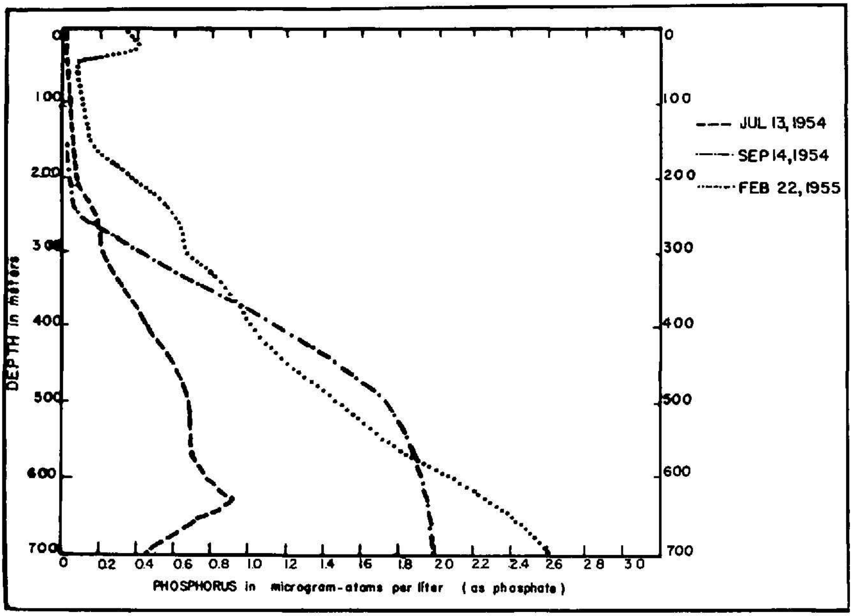

FIGURE 10. Typical vertical distributions of phosphate-phosphorus in the Florida Current.

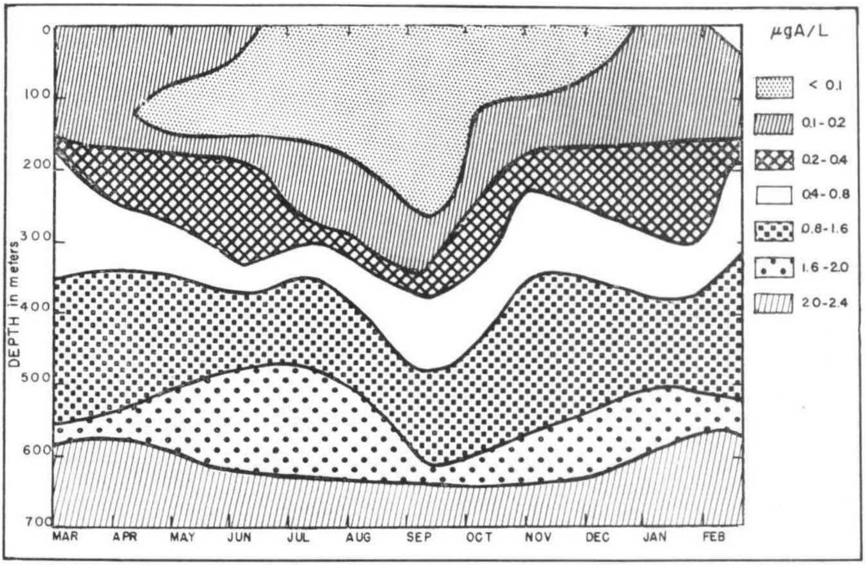

FIGURE 11. Seasonal vertical distribution of phosphate-phosphorus in the Florida Current.

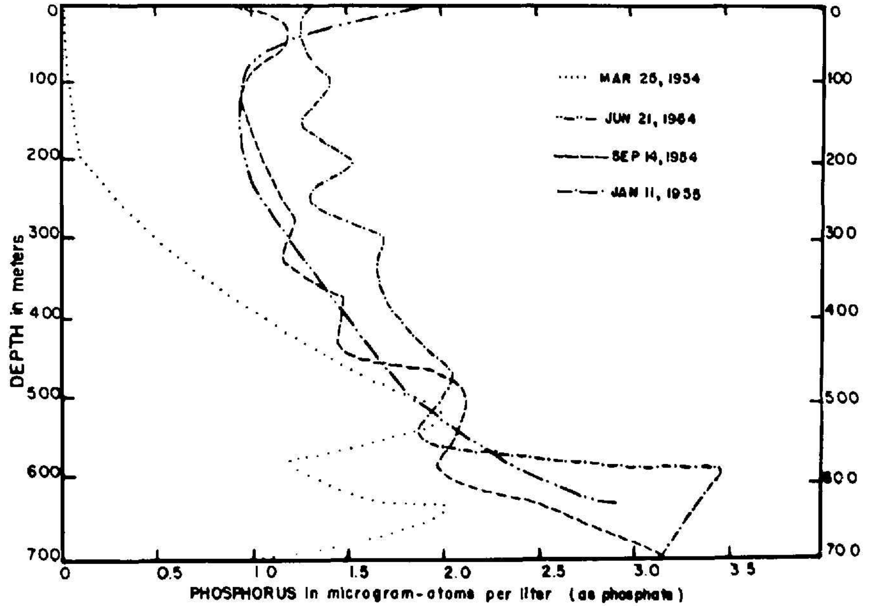

FIGURE 12. Typical vertical distribution of total phosphorus in the Florida Current.

PLANKTON

No attempt was made to study the net phytoplankton in the Florida Current since it has definitely been shown that it is present in very small quantities. Miller and Moore (1953) have shown for this area, that the nannoplankton by weight measurement is consistently about a thousand times as rich as the fraction of phytoplankton which can be collected with a net. Metered Clarke-Bumpus No. 20 net hauls were compared with the results obtained from samples filtered through a No. 54 Whatman filter paper. Therefore, it became clear that the net hauls do not provide an adequate picture of the standing crop of phytoplankton. Hart (1934) demonstrated that the proportion of armored dinoflagellates in the phytoplankton population increase greatly in the lower latitudes as compared to the Antarctic seas. If the nannoplankton are considered to be largely unarmored dinoflagellates, then it would not be unreasonable to suspect that they would constitute a high proportion of the phytoplankton in the warmer waters.

Nannoplankton

The nannoplankton as discussed in this study consist of planktonic forms in the size range of 107 microns or less. No attempt was made at the identification of the species present. Also, no extensive attempts have been made to separate the living material from detritus, which

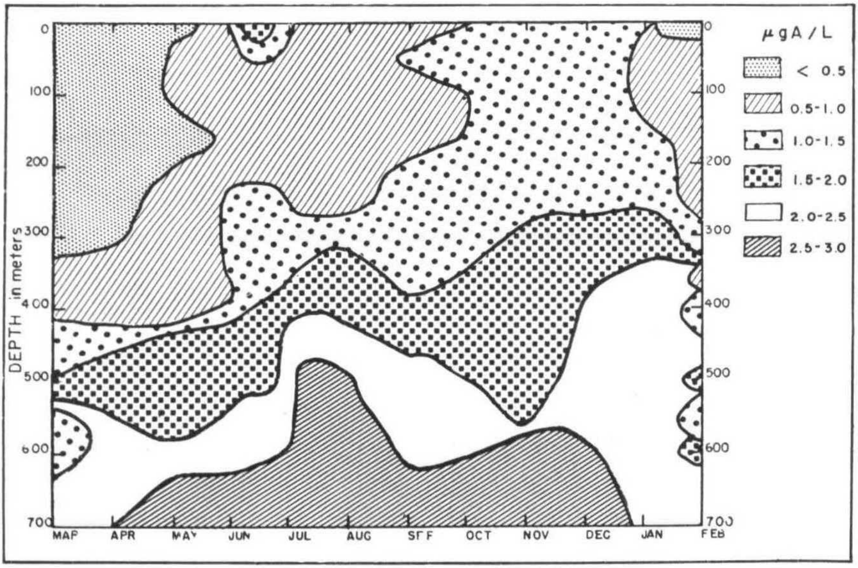

FIGURE 13. Seasonal variation of total phosphorus in the Florida Current.

is believed to be present in only small quantities.

The nannoplankton was obtained by pumping sea water into treated steel drums of 200 liter capacity, after which it was passed through a Sharples Super-Centrifuge running at approximately 23,000 rpm. The macroplankton were eliminated by screening the water through a 107 micron mesh stainless steel screen which was attached at the orifice of the drums. All samples collected in the field in this manner were quick frozen by dipping the container into a dry ice-acetone bath, stored on dry ice and returned to the laboratory for analysis. The use of the centrifugal pump-super centrifuge apparatus was found to be impractical at depths below 600 feet, due to the excessive bulk of the hose and difficulty encountered with the pumping operation.

Dry weights of the nannoplankton were determined by drying the samples by lyophillization and subsequent weighing of the dry material.

The seasonal vertical distribution of the nannoplankton as dry weights are shown in Figs. 14 and 15. It is readily observed in Fig. 15 that a bloom occurs during the summer months, the increase being about seven fold in the upper 35 meters of water at the height of the bloom. The over-all effect of this summer bloom extends slightly beyond the lower limit of the euphotic zone at 100 meters, and extends throughout the autumn months in the upper 40 meters of water.

The general chemical analyses of the nannoplankton samples were

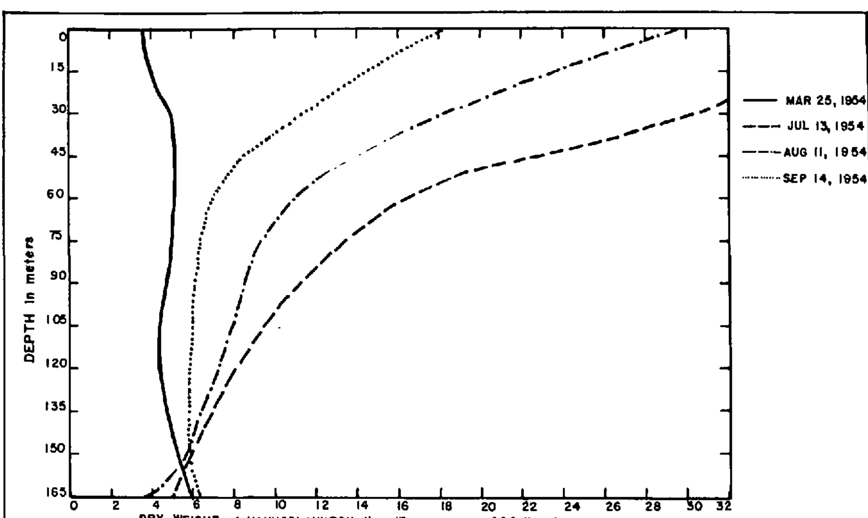

FIGURE 14. Typical vertical distributions of nannoplankton as dry weight.

performed on trichloracetic acid extracts and the remaining solid residue. These analyses included total phosphorus, nitrogen, carbohydrates, fats and pigments. As these biochemical data of the nannoplankton are as yet incomplete, they will not be presented here.

Zooplankton

The plankton nets used for the collection of the zooplankton were of the "Discovery" type (Kemp, Hardy, and Mackintosh, 1929), with a 70 cm. diameter opening. This net as well as the closing mechanism has been adequately described by Miller, *et al.* (1953). The net is lowered to the desired depth open, but is closed before returning to the surface. It has been shown (Moore, 1949) that the amount of plankton caught at the intermediate depths as the net is being lowered does not introduce a serious error.

The net hauls were made at 100 meter intervals from the surface to the near bottom or 700 meters. Generally two nets were towed simultaneously with a depth-distance recorder (Miller, *et al.* 1953) accompanying one of the nets. In the case of the top pair, a third net was usually towed simultaneously at the surface. The nets were towed for one half hour at the required depth and at a speed of about 2 knots. Owing to the variable currents encountered in this area, it is difficult to control the distance towed, so the readings of the depth-distance

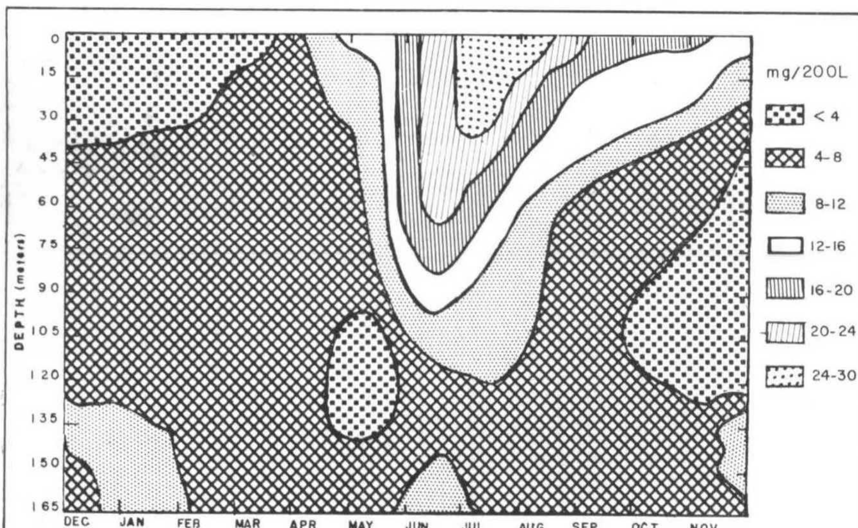

FIGURE 15. Seasonal vertical distribution of nannoplankton as dry weight in the Florida Current.

recorder were applied to the data and all measurements of the catch were corrected to the equivalent of a towing distance of one mile. Upon the completion of each haul the plankton samples were collected in jars and preserved in a 5 percent solution of formalin neutralized with borax.

The basic measurement of zooplankton quantity had to be made as displacement volume. This method is not very satisfactory but is the only rapid method which will allow further examination of the animals. Displacement volumes were determined by straining the plankton sample on a filter composed of No. 20 silk bolting cloth and removing the excess water with absorbent paper. The plankton were then placed into a measured volume of water from which the displacement volume is determined. Examination of the various species of animals present was made by counting.

Seasonal Variation

The first point to establish is the extent of the seasonal variation in the total zooplankton population. Smith, *et al.* (1950) have shown that a small seasonal change occurs at a station on the edge of the reef and also inside Biscayne Bay (Table 1).

TABLE 1

Month	Station 9	Station 5-10
February	0.5	0.9
April	1.0	0.8
June	0.25	0.6
July	0.5	2.0
August	1.0	2.0
October	4.5	3.7
December	2.5	2.6

At the Ten-Mile Station, Miller, *et al.* (1953) have shown the day catches in the top 250 meters were distinctly larger in the February-July period than during the remainder of the year. Unfortunately, there was a gap in the readings for the March-May period and, further, it is possible that some change in the plankton volume may have been associated with the varying proportions of Gulf and Yucatan water masses. The ratio of the mean volume in the February-July period to that of the rest of the year was 1.56 : 1.

The volumes of all the catches at the Forty-Mile Station were first corrected to the equivalent of one mile of towing. Assuming that all the water which passed through the ring of the net was filtered, the plankton content per cubic meter was obtained. By combining the results at different levels, the total plankton content of a column of water under a surface area of one square meter down to a depth of 600 meters, was determined. Actually less water was filtered because of net resistance, and because the lead section of the nets was of large mesh, but tests made with a meter from a Clarke-Bumpus net, placed at different positions indicated that 70 to 80 percent of the theoretical quantity actually passed through the net. There is also an error due to the more active organisms avoiding the net. The extent of this is unknown. It may be assumed to be a serious error for fishes, cephalopods, decapods and the larger euphausids. For the coelenterates, smaller crustacea, chaetognaths, salps, etc., the counts probably represent 60% of the true population. The herbivores, being generally smaller and less active, are probably more correctly estimated than the carnivores.

Fig. 16 shows the seasonal variation in the day plankton volume at the Forty-Mile Station. In 1953 the March-June catches were two to three times those for the rest of the year. For various reasons it was not possible to produce comparable figures for the spring-summer period in other years but the values at other times were in reasonable

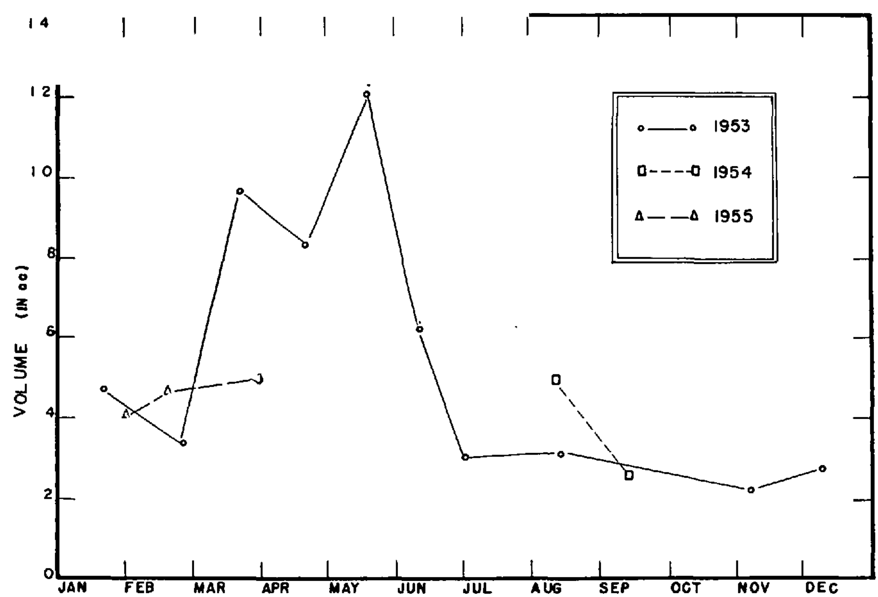

FIGURE 16. Seasonal variation in the day volumes of plankton at the Forty-Mile Station under one square meter to a depth of six hundred meters.

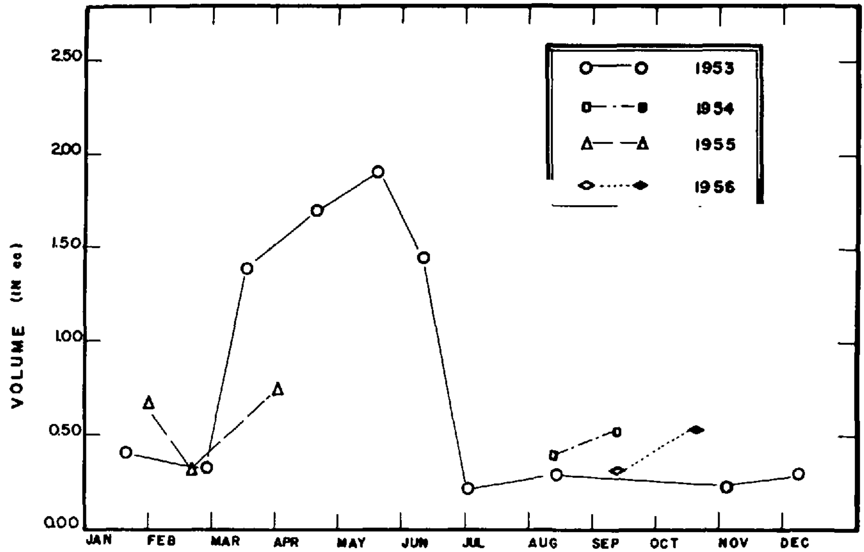

FIGURE 17. Seasonal variation in the day plankton volumes of the euphotic zone at the Forty-Mile Station under one square meter to a depth of one square meter to a depth of one hundred meters.

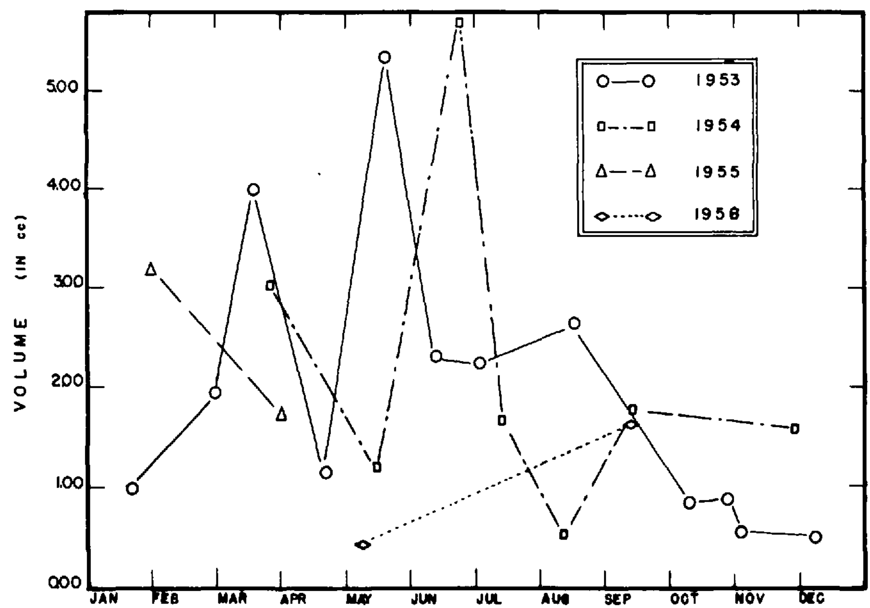

FIGURE 18. Seasonal variation in night volumes of plankton in the euphotic zone at the Forty-Mile Station under one square meter to a depth of one hundred meters.

agreement though perhaps suggesting some yearly differences in the time of the peak.

For the euphotic zone, the top 100 meters, there is a similar increase in plankton volume for the April-June period, the increase being about four fold. The data of 1954 or 1955 are in reasonable agreement with those of the more complete 1953 series as shown in Fig. 17. A better comparison of the two years may be obtained when the night hauls from the euphotic zone are considered since this is a more complete series (Fig. 18). Both years show an early summer increase but this is complicated by shorter periods of fluctuation which are likely to be associated with the effect of varying illumination on the extent of night migrations into the euphotic zone. The system of peaks is rather similar except for a time displacement in the two years. A correlation between peaks and moonlight is doubtful.

Since plankton volumes may give an erroneous impression on account of the varying proportions of such gelatinous forms as medusae, salps, etc., a check on the seasonal cycle was obtained from copepod counts. The data were supplied by D. L. O'Berry from a study of the

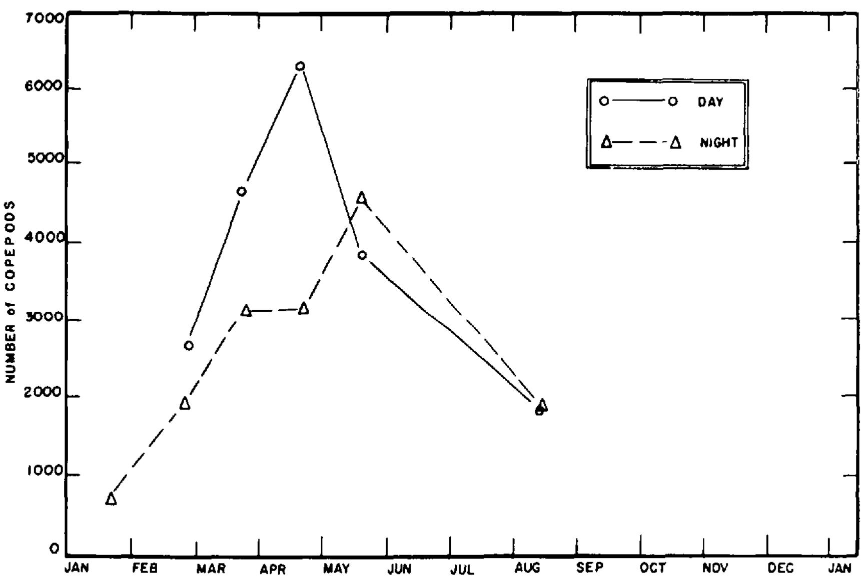

FIGURE 19. Seasonal variation in the number of copepods at the Forty-Mile Station. Day values are the numbers under one square meter to a depth of six hundred meters. Night values are the numbers under one square meter to a depth of five hundred meters.

factors controlling diurnal migration. They were treated in the same way as the volume data and in this case, there is no significant error due to escape (Fig. 19). Although they do not cover the entire year, the results confirm the position of the peak in the spring with a value of two to three times of that later in the year.

It is interesting to note that in Bermuda (Moore, 1949) the total volume of zooplankton showed a maximum in May-June and a minimum in October, with the maximum being about twice the value of the minimum. This fluctuation was attributed to a seasonal change in the current system, later confirmed by Hela and Moore (1953). However, if a part of this change represents a true seasonal variation, its cycle would be in agreement with that found in the present work.

Confirmation of the spring peak can be obtained from the total night plankton down to 600 m. although it is to be expected that they will show some fluctuations in relation to the varying conditions of moonlight (Fig. 20). Similarly, Fig. 19 shows the night values for copepods; these also confirm the seasonal peak shown in the day hauls. It should be noted that owing to the inadequacy of the deepest hauls in the night series, copepod counts have been made to 500 meters only. The day hauls were taken to 600 meters. An appropriate allowance

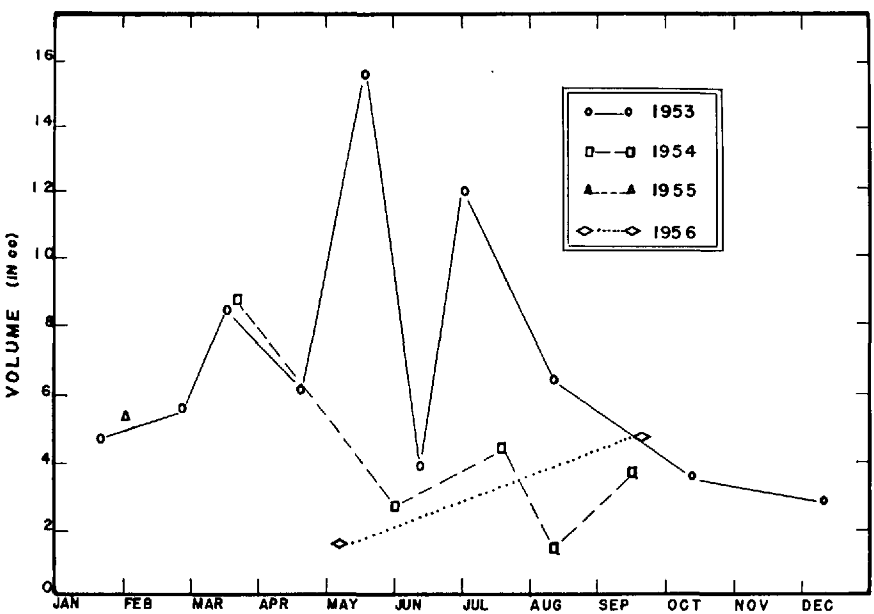

FIGURE 20. Seasonal variation of night (20-04 hr.) plankton volumes at the Forty-Mile Station under one square meter to a depth of five hundred meters.

must therefore be made if the day and night results are to be compared quantitatively.

Diurnal Migration

A considerable proportion of the zooplankton descends below the euphotic zone during the day. For a study of productivity, it is therefore essential to know the diurnal variation in the herbivore population in this zone. By grouping together the data from all stations, we obtain the results shown in Fig. 21. This represents the volume per mile towed, which is equivalent with the assumption referred to earlier to 600 m^3 of water filtered.

Although the figure is somewhat patchy, it is clear that there is a very marked diurnal migration of the plankton as a whole, affecting the entire water column sampled. Further, the assymetry indicates a time lag in the upward movement in the evening so that, although there is indication of the ascent as early as 15 hours below 600 meters, the surface concentrations are from 2100 hours to as late as 0900 hours.

In Fig. 22 we have grouped together as night values all readings between 1800 and 0600 hours. It will be seen that below about 100 meters the night values are approximately one third greater than the day values down to around 350 meters; between 350 and 500 meters

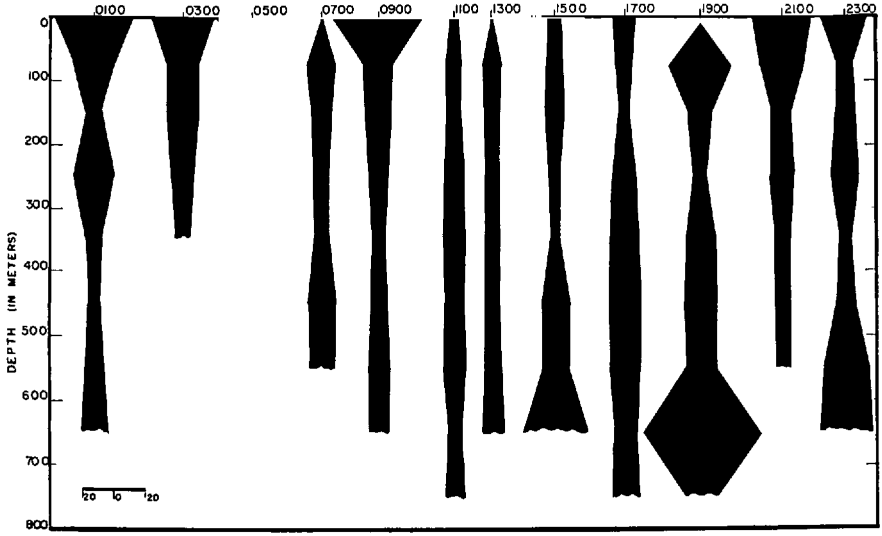

FIGURE 21. Vertical distribution of plankton volumes at the Forty-Mile Station, showing the diurnal migration.

the values are nearly equal, and from 500 to 700 meters the night values are again about one third greater than the day values. In the

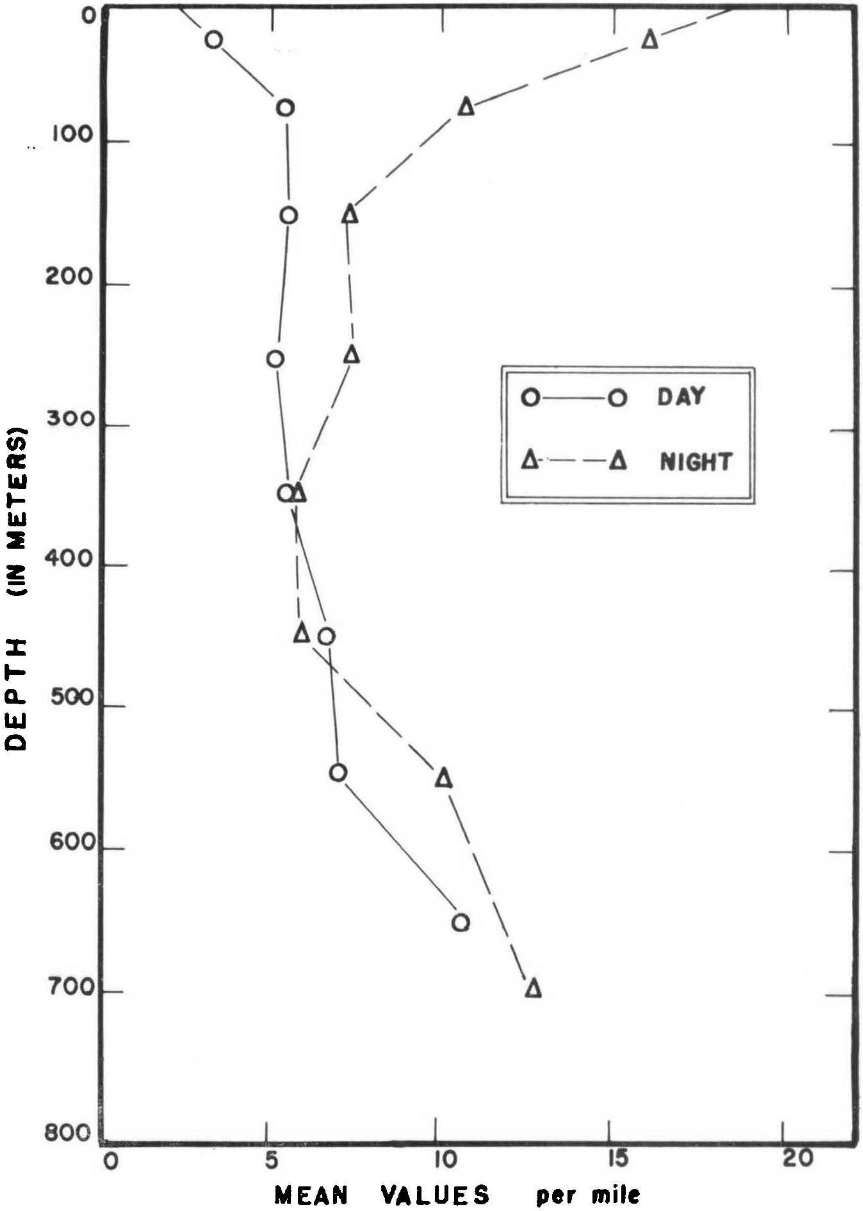

FIGURE 22. Vertical distributions of plankton volumes in cubic centimeters per mile tow at the Forty-Mile Station. Day (10-16 hr.), Night (18-06 hr.).

top hundred meters, which we are considering as the euphotic zone, the increase is about two fold.

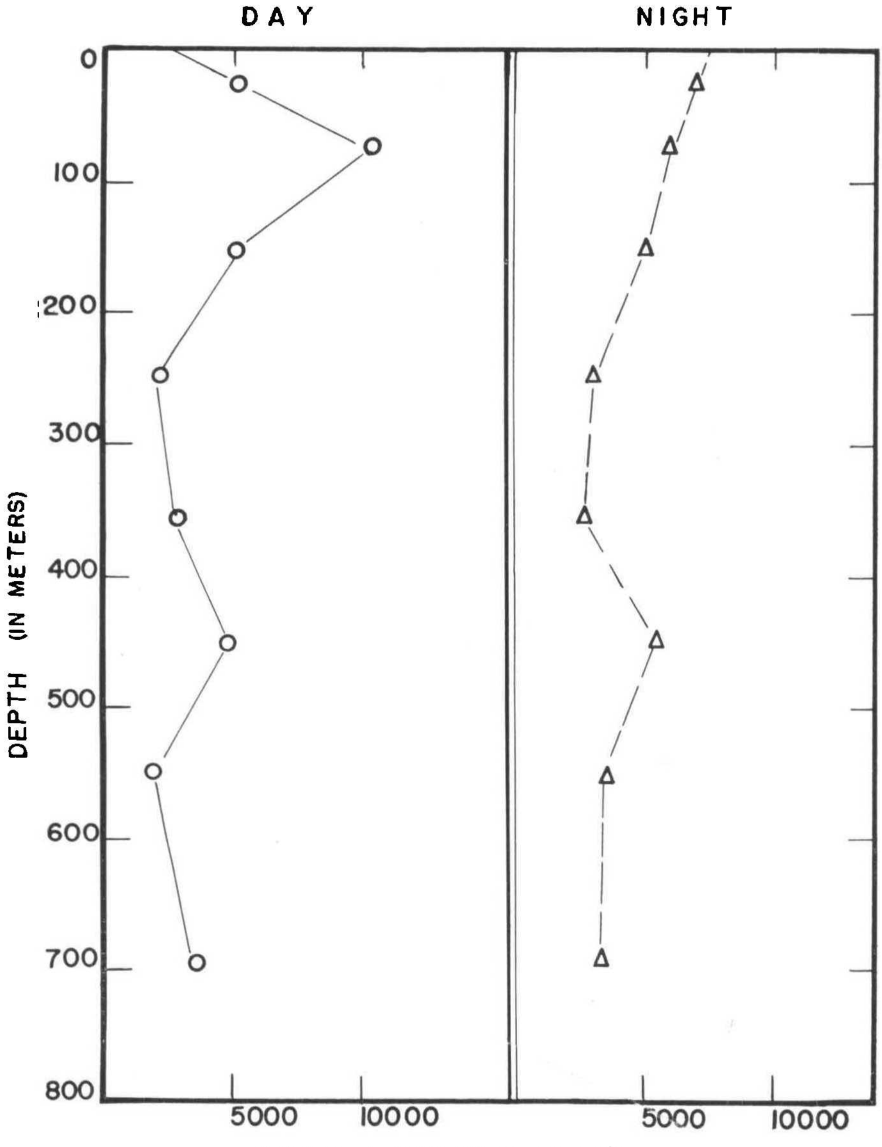

FIGURE 23. Vertical distribution of copepods as numbers per mile tow at the Forty-Mile Station. Day (10-16 hr.), Night (18-06 hr.).

The extent of the diurnal migration varies considerably in the different groups of animals. As a result, there may be a considerable diurnal variation not only in the quantity of plankton at a given level, but also in its constitution. For the various groups studied, we have therefore presented first the diurnal change in vertical distribution and then the day and night graphs showing the number of individuals of each group per cubic centimeter of plankton sample at the different levels.

Copepods

Bermuda data (Moore, 1949) showed a definite diurnal migration of copepods as a whole but unfortunately lacked hauls in the midday period. The present data on copepods are based on counts by D. L. O'Berry. Fig. 23 shows that at the Forty-Mile Station there is no significant diurnal change in number below 150 meters, although we know that some individual species migrate farther than this. Within the euphotic zone there is no significant diurnal change in total number, but a shift in level so that the copepods are predominantly in the lower part during the day, and the upper part at night.

Because the copepods execute less diurnal migration than the rest of the zooplankton (Fig. 22) they become relatively more important in the euphotic zone in the daytime and in the deepest layers at night (Fig. 24). In the euphotic zone, there are twice as many copepods per cubic centimeter of total plankton during the day as there are at night. Below 100 meters there is a slight increase at night.

Although copepod numbers stay relatively constant in the euphotic zone, there is, as described later, a change in weight. This is associated with the fact that some of the smaller species move downward at night and are replaced by larger species moving upwards.

Pteropods

Most of the information on pteropods is based on counts made by T. Dow on material from the Ten-Mile Station. These were published in part by Moore, *et al.* (1953). One Forty-Mile Station has been examined by Mrs. R. Wormelle and is unpublished. At the Ten-Mile day station (Fig. 25) and at both the day and night Forty-Mile Station (Fig. 27) the pteropods are most abundant near the surface with a marked drop just below the euphotic zone and a gradual increase in numbers downward below that level. Owing to hydrographic differences already referred to, the vertical pattern is compacted into a smaller range than at the Forty-Mile Station. Practically all the pteropods caught were Thecosomata. Of these, the species of *Limacina* are so much smaller than all the others that it seemed advisable to consider

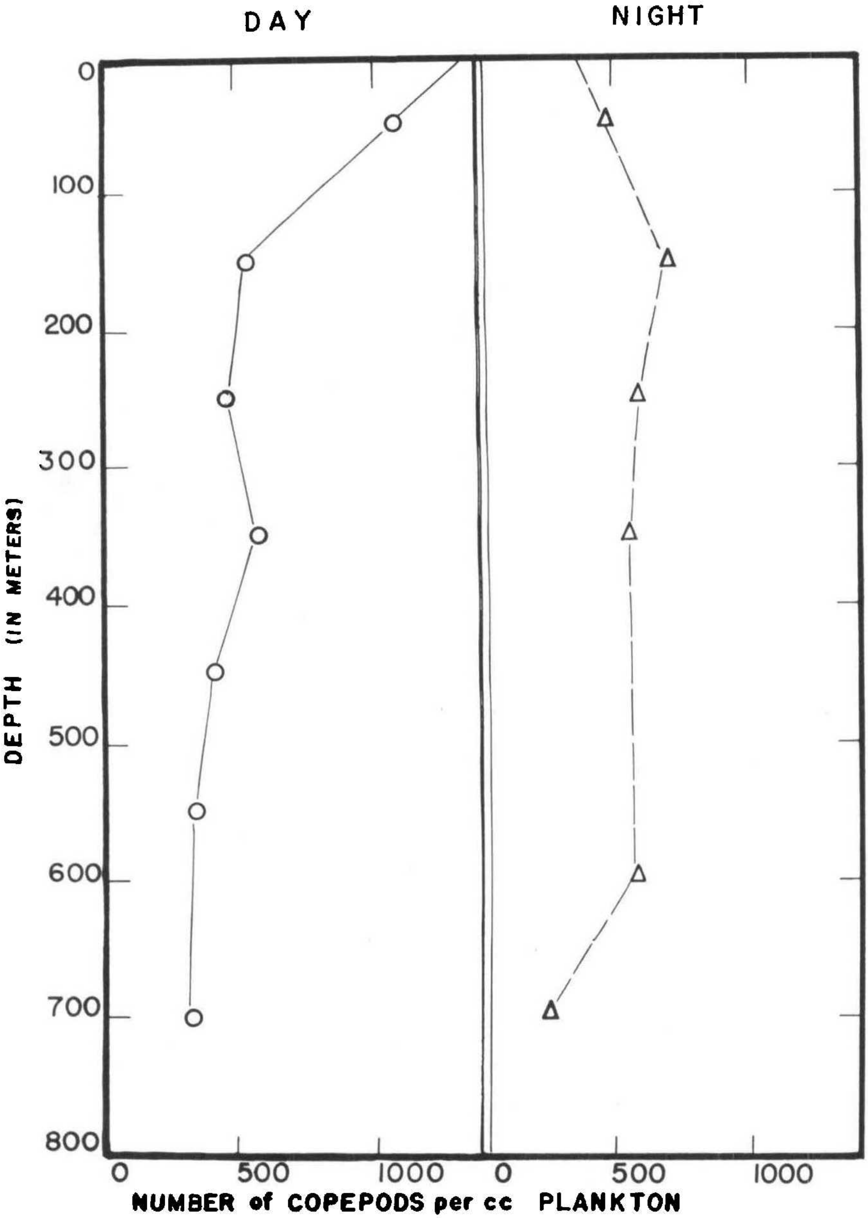

FIGURE 24. Vertical distribution of the number of copepods per cubic centimeter of plankton, showing the diurnal change in the constitution of plankton at the Forty-Mile Station. Day (10-16 hr.), Night (18-06 hr.).

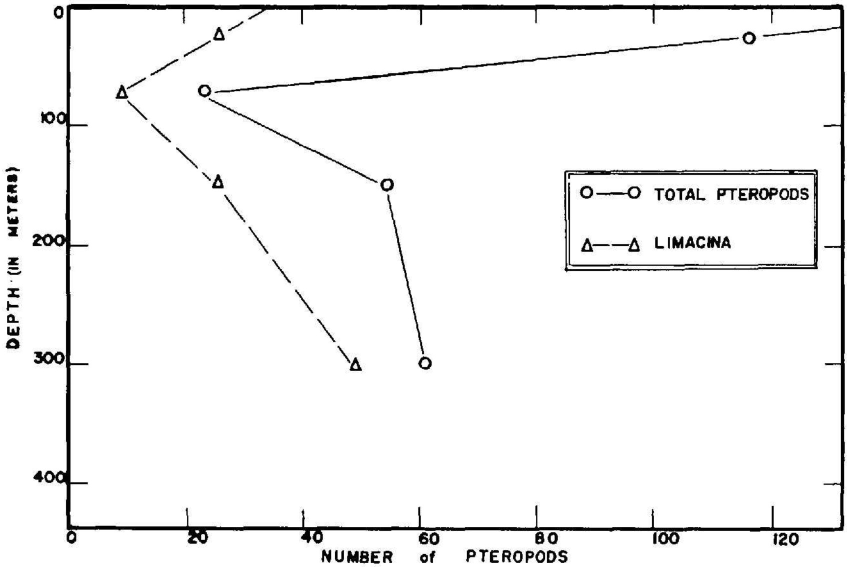

FIGURE 25. Day vertical distribution of pteropods as numbers per mile tow at the Ten-Mile Station.

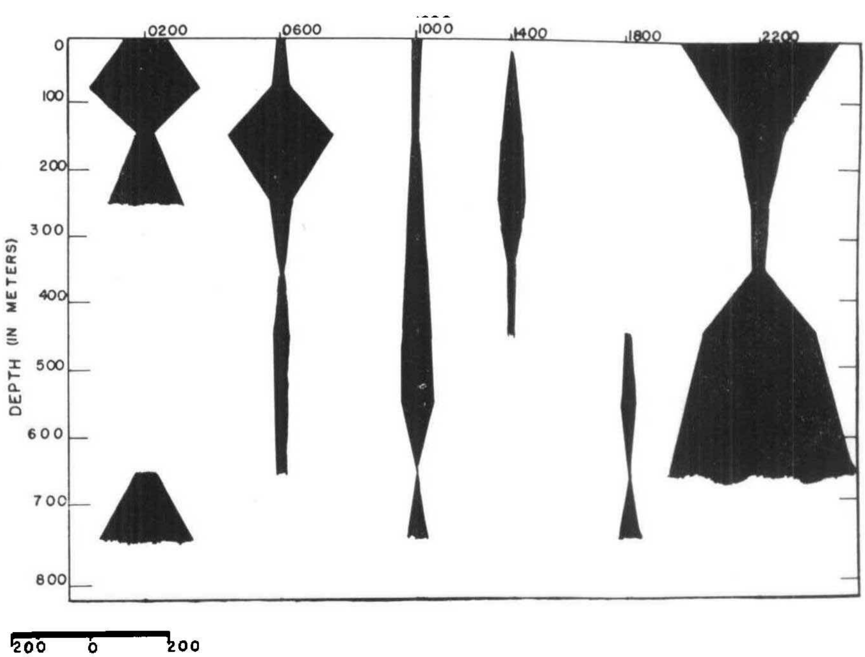

FIGURE 26. Vertical distribution of total pteropods at one Forty-Mile Station, showing diurnal migration.

them separately. *Limacina* constitute about half of the total pteropods, numerically, at the Ten-Mile Station and rather more at the single Forty-Mile Station. By weight they are almost negligible fractions.

A diurnal migration has been shown for two species of pteropods in Bermuda (Moore, 1949). The results for the single Forty-Mile Station show a very pronounced diurnal migration of both total pteropods and *Limacina* species (Figs. 26 and 27).

The night increase in total pteropods is about nineteen fold in the top 100 meters and about four fold for each increment of depth of the total water column down to 650 meters. Thus the euphotic zone receives a very great increment of the pteropods and a large fraction of those pteropods which ascend from below 800 meters do not approach the actual surface layer. It must be remembered that these deductions are made from the results of one twenty-four hour station only and might need some modification if more data were available.

Fig. 28 shows the number of pteropods per cubic centimeter of plankton. If we may judge from the single Forty-Mile Station examined, they constitute relatively less of the plankton there than at the Ten-Mile Station. They also constitute more of the plankton at night than in the daytime, almost five times in the euphotic zone and three times in the whole column down to 650 meters.

Chaetognaths

H. Owre has studied the chaetognaths at the Ten-Mile-Station. Fig. 29 shows the very strong diurnal migration and Fig. 30, the day and night vertical distribution. The night population is nearly five times the day population in the euphotic zone and about twice in the column down to 350 meters and approximately equal throughout the deeper layers. The day vertical distribution at the Ten-Mile Station (Fig. 31) is similar to that at the Forty-Mile Station but vertically compacted and with larger numbers. The double peaks, one in and one below the euphotic zone, appear at both stations. The number per cubic centimeter of plankton (Figs. 31 and 32) show a double peaking with the day values of the same order at the two stations. At night at the Forty-Mile Station, there was a considerable drop in number per cubic centimeter (the night value being about half of the day value in both the euphotic zone and in the entire column down to 650 meters). A distinction was made (Fig. 32) between the large species, *Sagitta hexaptera, S. lyra,* and *S. enflata,* and the remaining smaller species, but the behavior of the two groups appeared similar.

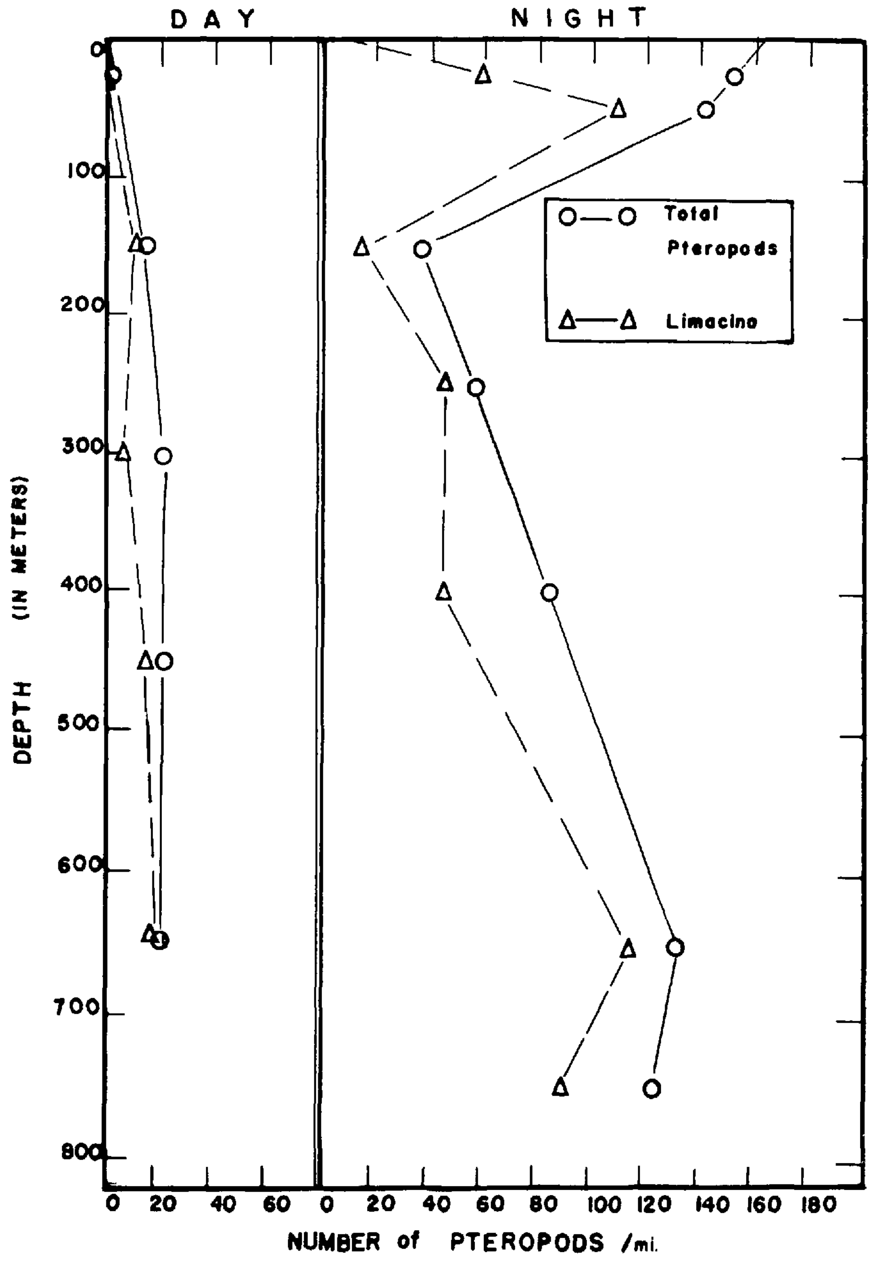

FIGURE 27. Vertical distribution of pteropods at one Forty-Mile Station. Day (08-16 hr.), Night (20-04 hr.).

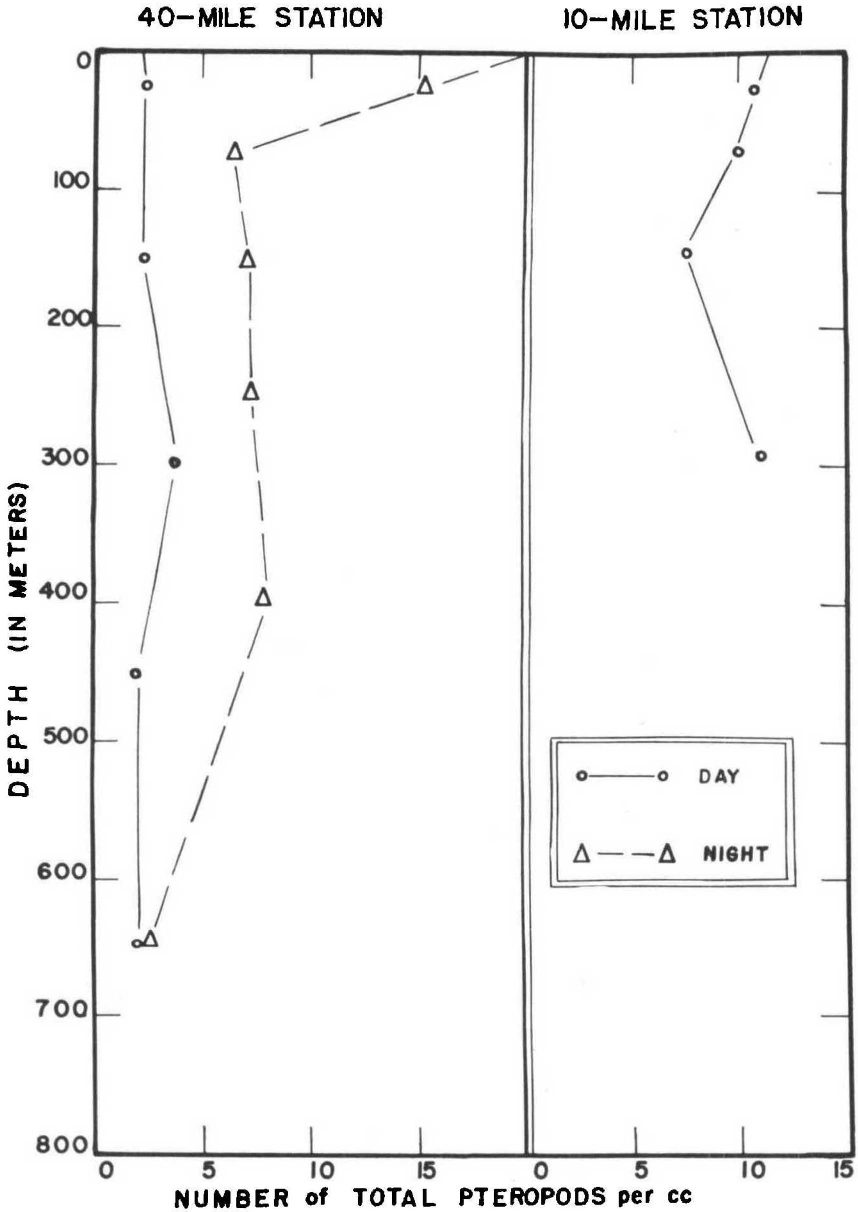

FIGURE 28. (A) Vertical distribution of total pteropods per cubic centimeter of plankton at one Forty-Mile Station. Day (08-16 hr.), Night (20-04 hr.). (B) Vertical distribution of total pteropods per cubic centimeter of plankton at the Ten-Mile Station.

Euphausids

Lewis (1954) has published an account of the euphausids at the Forty-Mile Station. The escape factor is undoubtedly serious in this group, so quantities given can only be considered minimal. Some members of the genus *Stylcheiron* differ from the rest of the euphausids in being very shallow-living and having rather doubtful diurnal migration. *S. carinatum* is by far the commonest species of *Stylocheiron* at the Forty-Mile Station. It is a smaller species than most of the others. Therefore the counts of *Stylocheiron* have been treated separately from those of the remaining euphausids.

There is a marked diurnal migration in both *Stylocheiron* and the other euphausids (Fig. 33). In the former, there is a day concentration just below the euphotic zone, while the day descent is greater in other genera. Fig. 34 shows the day and night vertical distribution of the two groups. The euphotic zone shows about a six fold, night increase in *Stylocheiron* and about an eight fold increase for the other genera. The entire column down to 650 meters shows about a two fold increase in each case (Fig. 35).

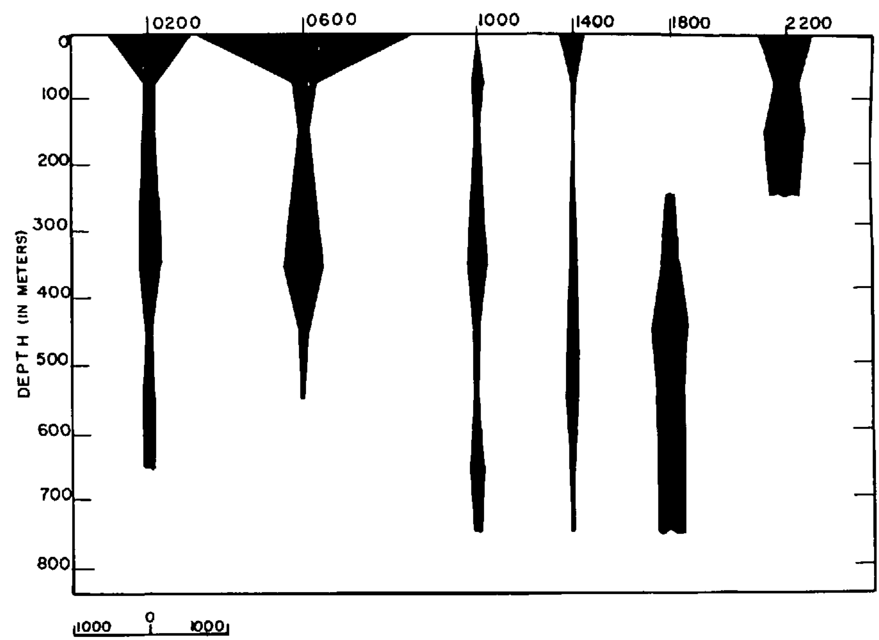

FIGURE 29. Vertical distribution of total chaetognaths at one Forty-Mile Station, showing diurnal migration.

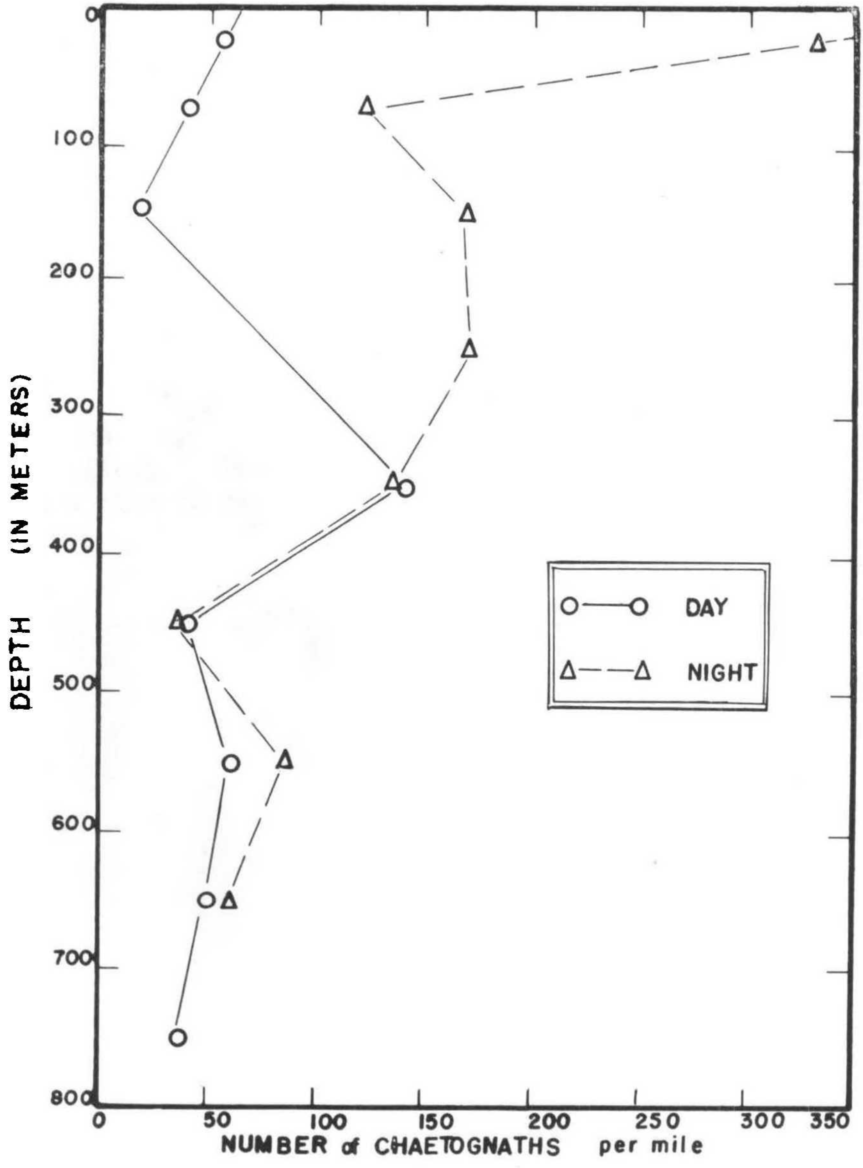

FIGURE 30. Vertical distribution of chaetognaths per mile tow at the Forty-Mile Station. Day (10-14 hr.), Night (22-02 hr.).

Siphonophores

Data on this group are based on the work of Roane (1953) and Moore (1953). At the Forty-Mile Station, the figures quoted as total siphonophores actually include only the eight commonest species. However, on a check of over three thousand siphonophores at the Ten-Mile Station, where the fauna is very similar, these eight species comprised over ninety-two per cent of all the siphonophores, so the figures may be taken as representative.

Diurnal migration is definite, although the range in general is not great (Fig. 36). The siphonophore population of the column down to 700 meters shows no diurnal change but a displacement of the concentration (Fig. 37) toward the surface, above 50 meters, occurs during the night.

The day number of siphonophores per cubic centimeter of plankton indicate a fairly steady decrease in importance from the euphotic zone downwards. This is shown in Fig. 38. At night, the relatively more extensive migration of the other groups leaves them with more or less uniform importance at all depths.

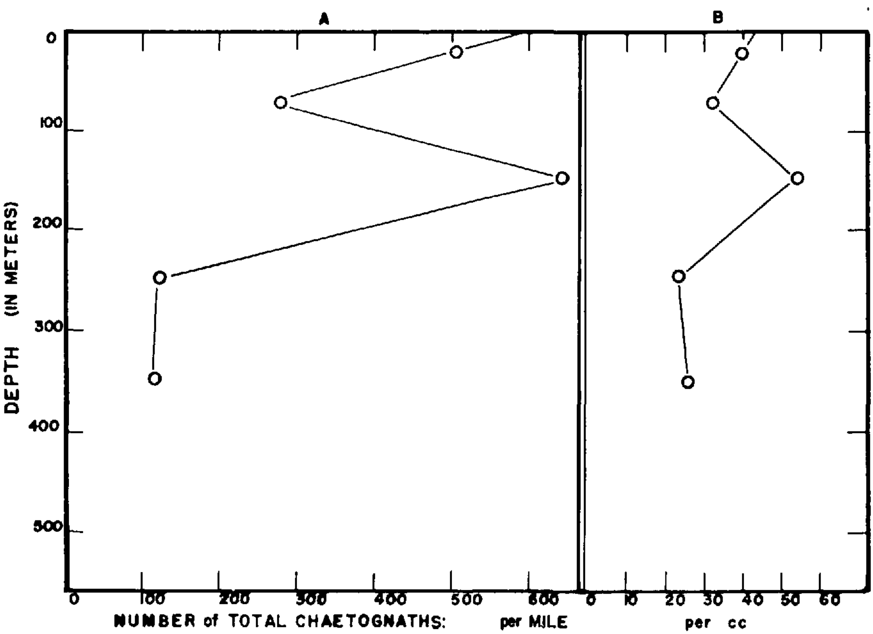

FIGURE 31. (A) Day vertical distribution of total chaetognaths per mile tow at the Ten-Mile Station. (B) Day vertical distribution of total chaetognaths per cubic centimeter of plankton at the Ten-Mile Station.

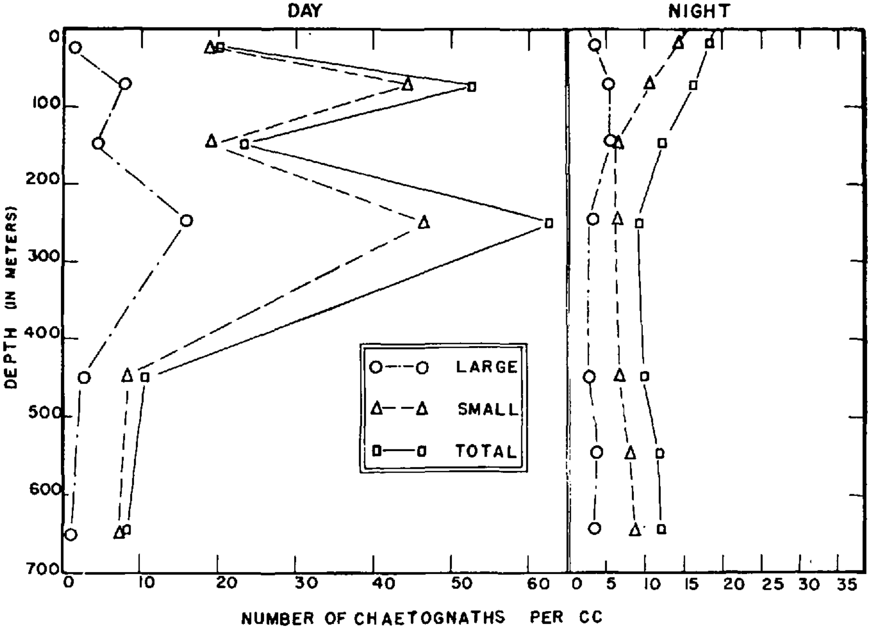

FIGURE 32. Vertical distribution of the number of chaetognaths, divided into large and small, per cubic centimeter of plankton at one Forty-Mile Station. Large includes *Sagitta hexaptera, S. lyra,* and *S. enflata.* Small include the remaining species. Day (10-14 hr.), Night (22-02 hr.).

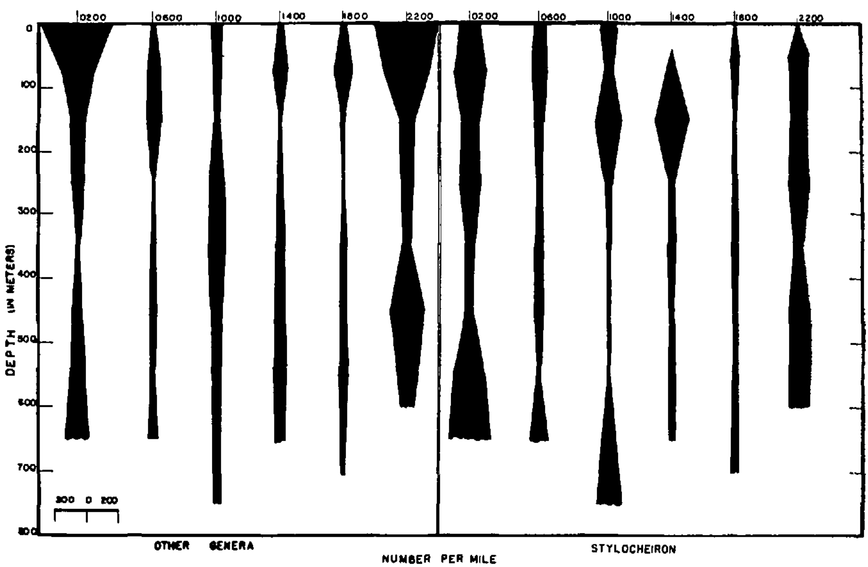

FIGURE 33. Vertical distribution of *Stylocheiron* spp. and of other genera at the Forty-Mile Station.

Fishes

In the course of life history studies, all fish, regardless of stage of development, have been separated from the hauls and counted. Several studies of particular groups have been published (N. Voss, 1954, J. Clancey, 1955, V. A. Legaspi, 1956, and G. L. Voss, 1953). From the total counts at the Forty-Mile Station (Fig. 39) it is clear that there is a very extensive diurnal migration among the fish. Since larval fish typically exhibit very little diurnal migration, the later stages of development must be involved. On the other hand, most of the more active fish are well able to escape capture, so these figures represent only a minimal estimate of the fish population. The increase in numbers in the euphotic zone at night is marked, the increase being about four to five fold, while for the whole column down to 650 meters it is over two fold (Fig. 40).

With this strong diurnal migration, the importance of fish in the

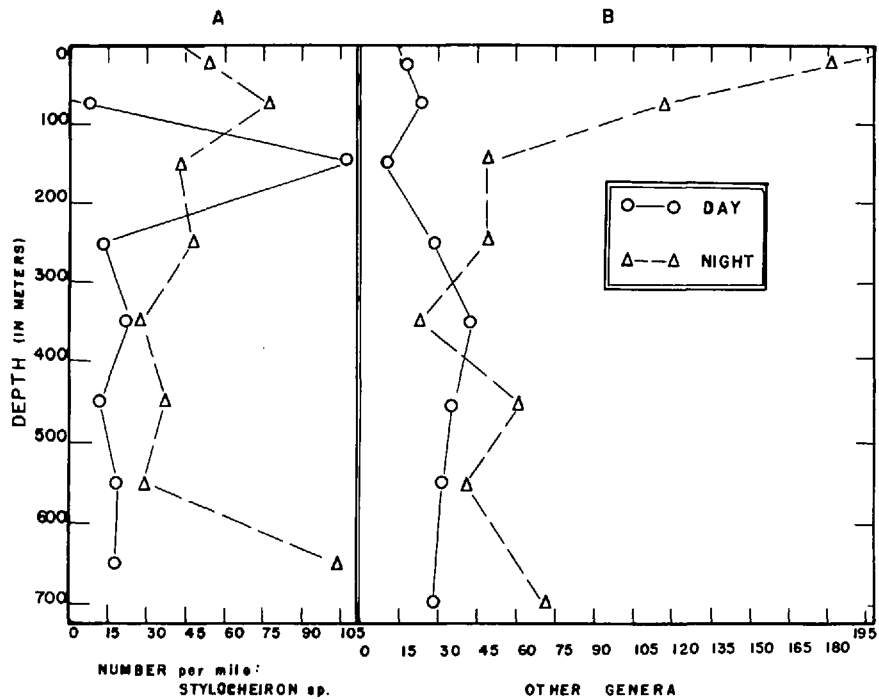

FIGURE 34. (A) Vertical distribution of *Stylocheiron* spp. per mile tow at the Forty-Mile Station. Day (12-16 hr.), Night (20-18 hr.). (B) Vertical distribution of other genera per mile tow at the Forty-Mile Station. Day (08-16 hr.), Night (20-04 hr.).

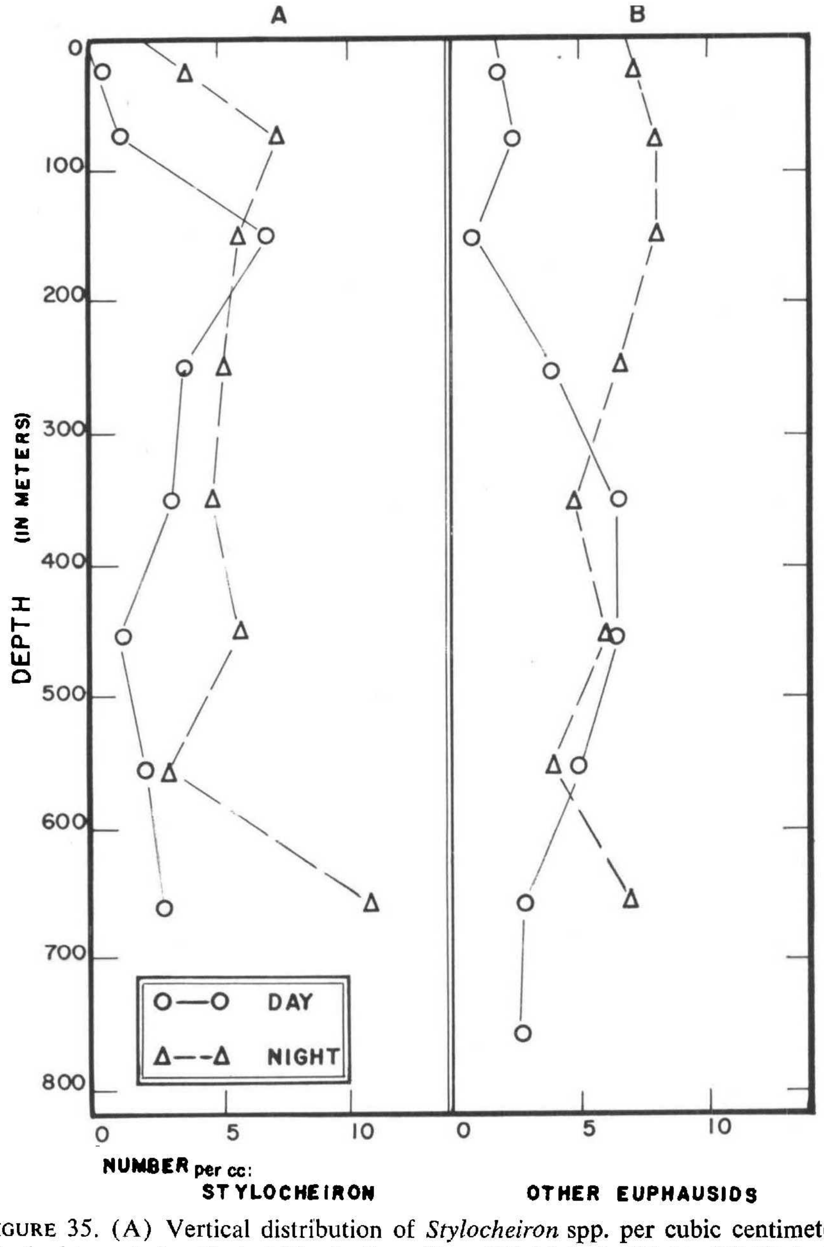

FIGURE 35. (A) Vertical distribution of *Stylocheiron* spp. per cubic centimeter of plankton at the Forty-Mile Station. Day (12-16 hr.), Night (20-08 hr.). (B) Vertical distribution of other genera of euphausids per cubic centimeter of plankton at the Forty-Mile Station. Day (08-16 hr.), Night (20-04 hr.).

plankton population is greater at night at all depths except in the top 50 meters (Fig. 41) where it drops at night.

Cephalopods

These presumably are too active to be taken in the net hauls, except as larvae and even then in small numbers only. They were taken at the Forty-Mile Station on only one occasion in the day hauls (1200-1600 hours). At night they averaged about one for every two miles and were fairly uniformly distributed down to 700 meters. A considerable diurnal migration seems therefore to be indicated. These cephalopods have been separated by G. L. Voss and partially reported upon (Voss, 1955, 1956).

Dry Weight and Volume Relation

An attempt has been made to correlate the zooplankton displacement volumes with their respective dry weights. An exact correlation cannot be obtained due to the variation in both number and size of the animals that comprise the different hauls. However, a rough esti-

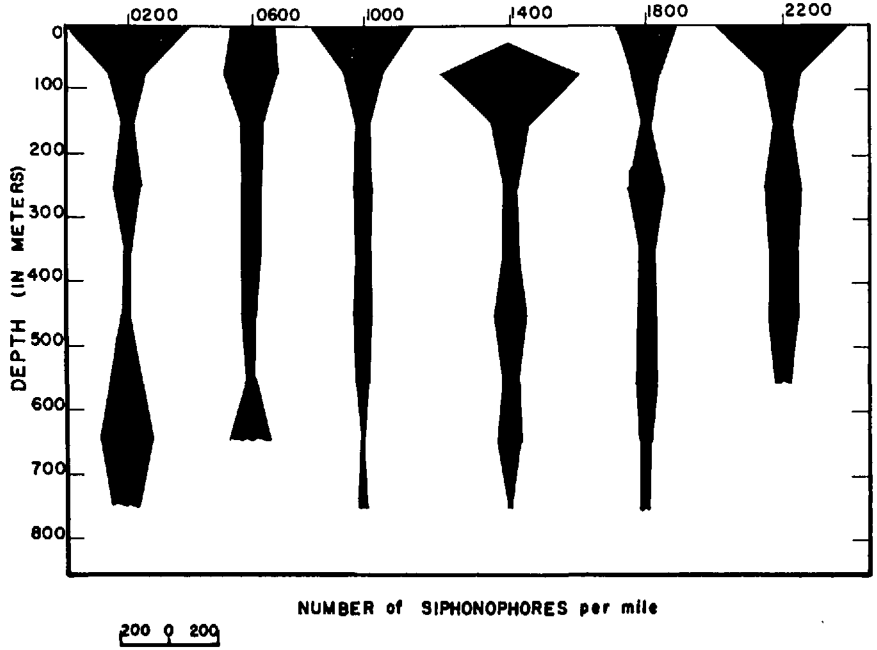

Figure 36. Vertical distribution of siphonophores at the Forty-Mile Station, showing diurnal migration.

mate of the dry weight of a typical plankton sample from this area of the Florida Current may be obtained using the curve of Figure 42. This curve was obtained by measuring the plankton displacement

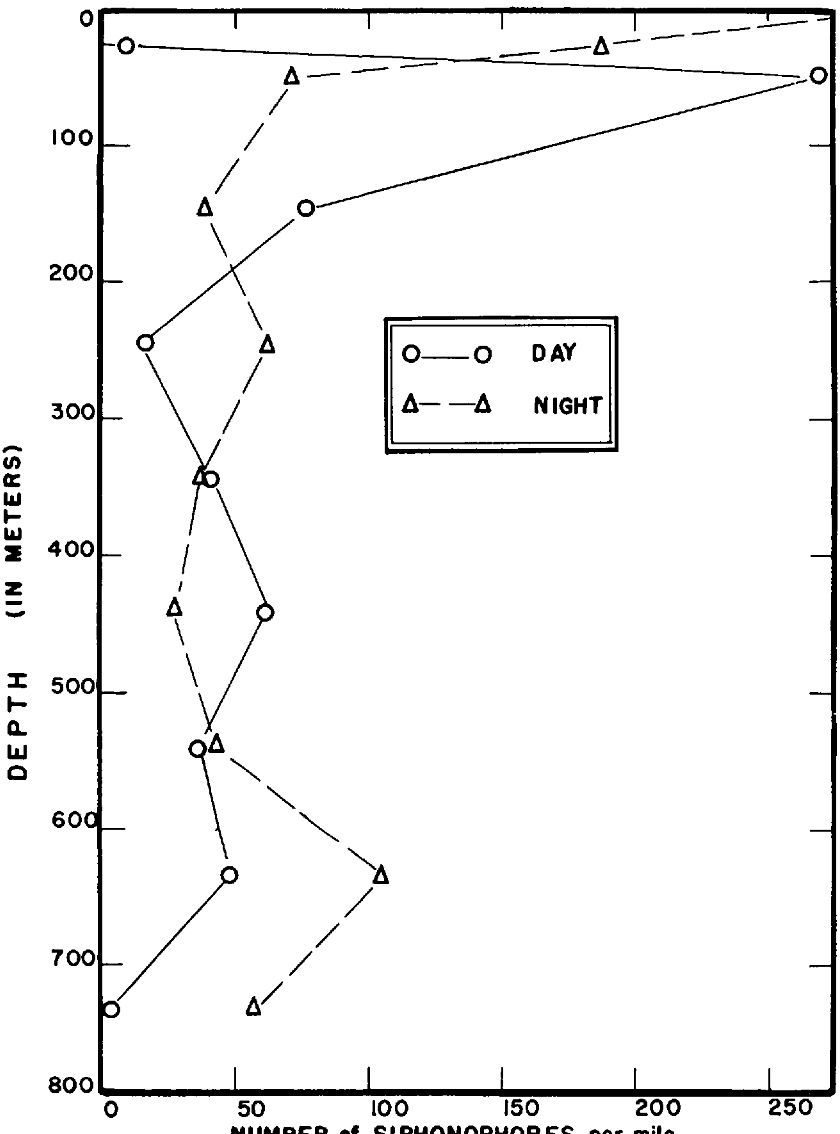

FIGURE 37. Vertical distribution of siphonophores per mile tow at the Forty-Mile Station. Day (12-16 hr.), Night (20-04 hr.).

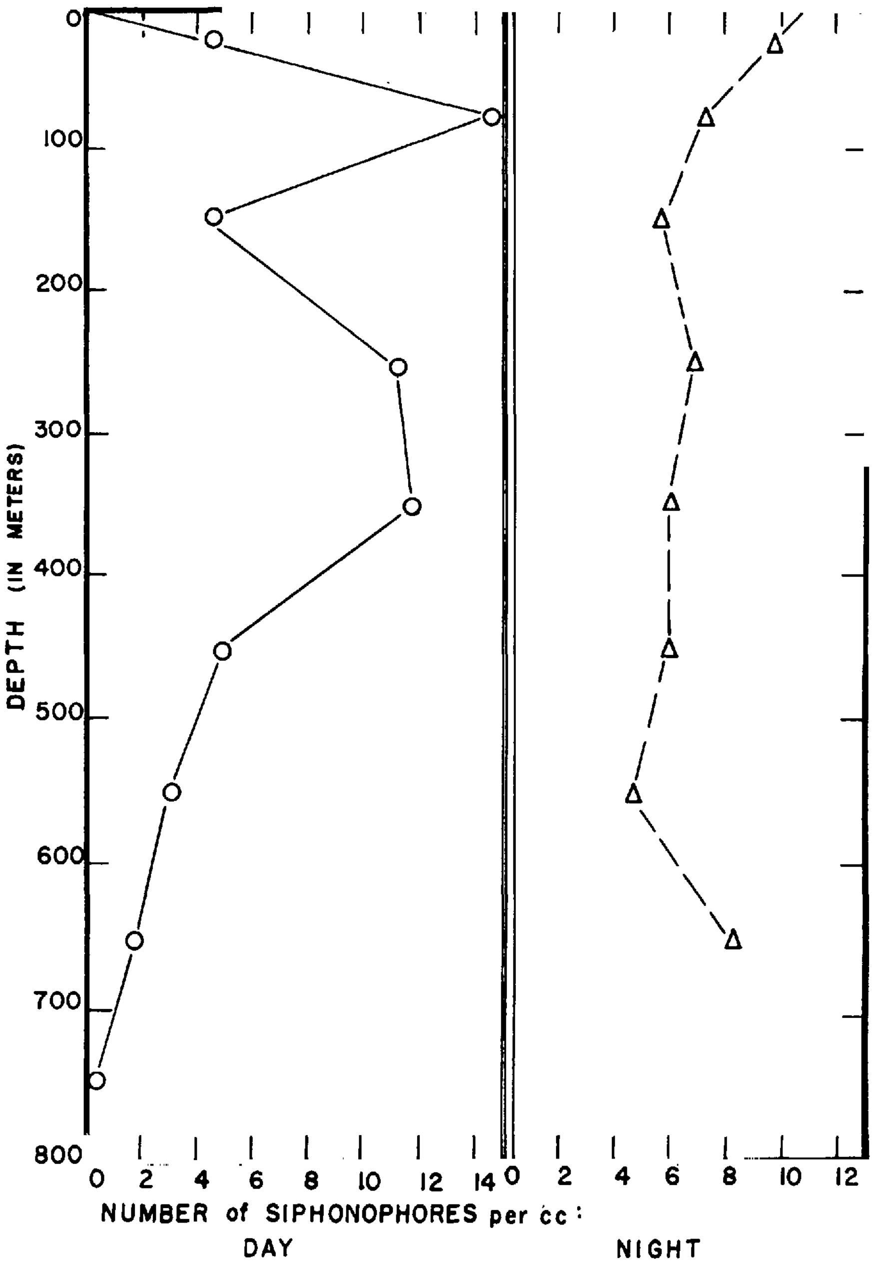

FIGURE 38. Vertical distribution of the number of siphonophores per cubic centimeter at the Forty-Mile Station. Day (12-16 hr.), Night (20-04 hr.).

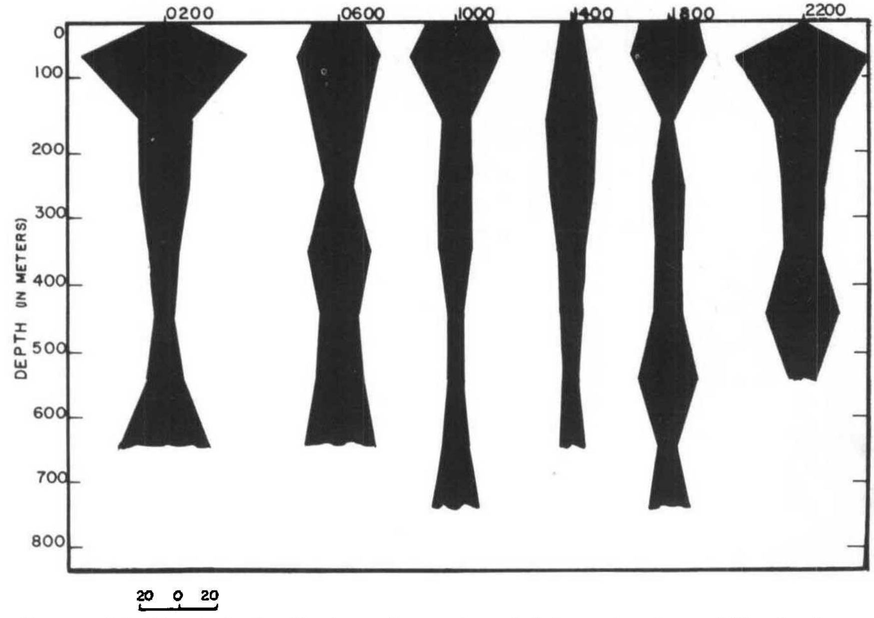

FIGURE 39. Vertical distribution of post-larval fish at the Forty-Mile Station.

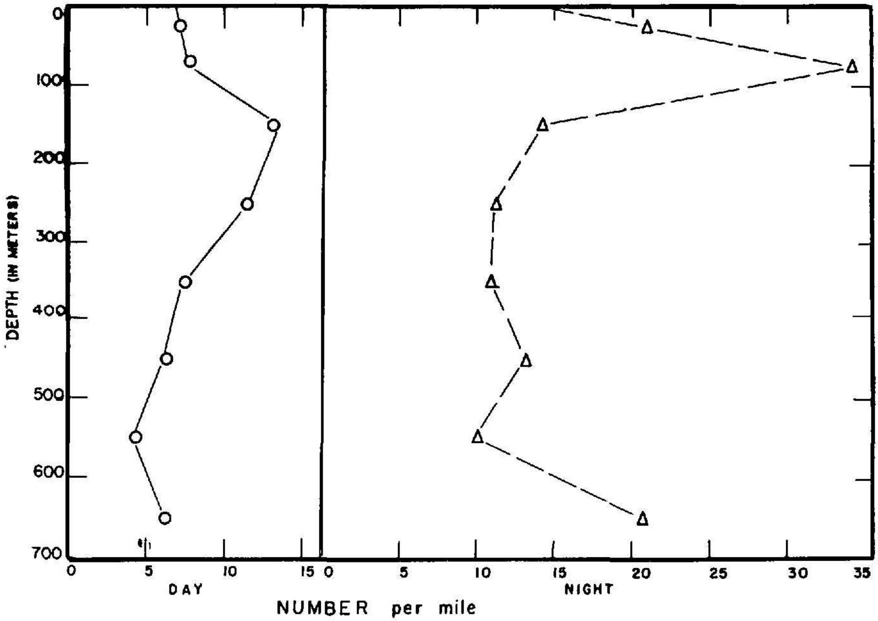

FIGURE 40. Vertical distribution of post-larval fish per mile tow at the Forty-Mile Station. Day (12-16 hr.), Night (20-08 hr.).

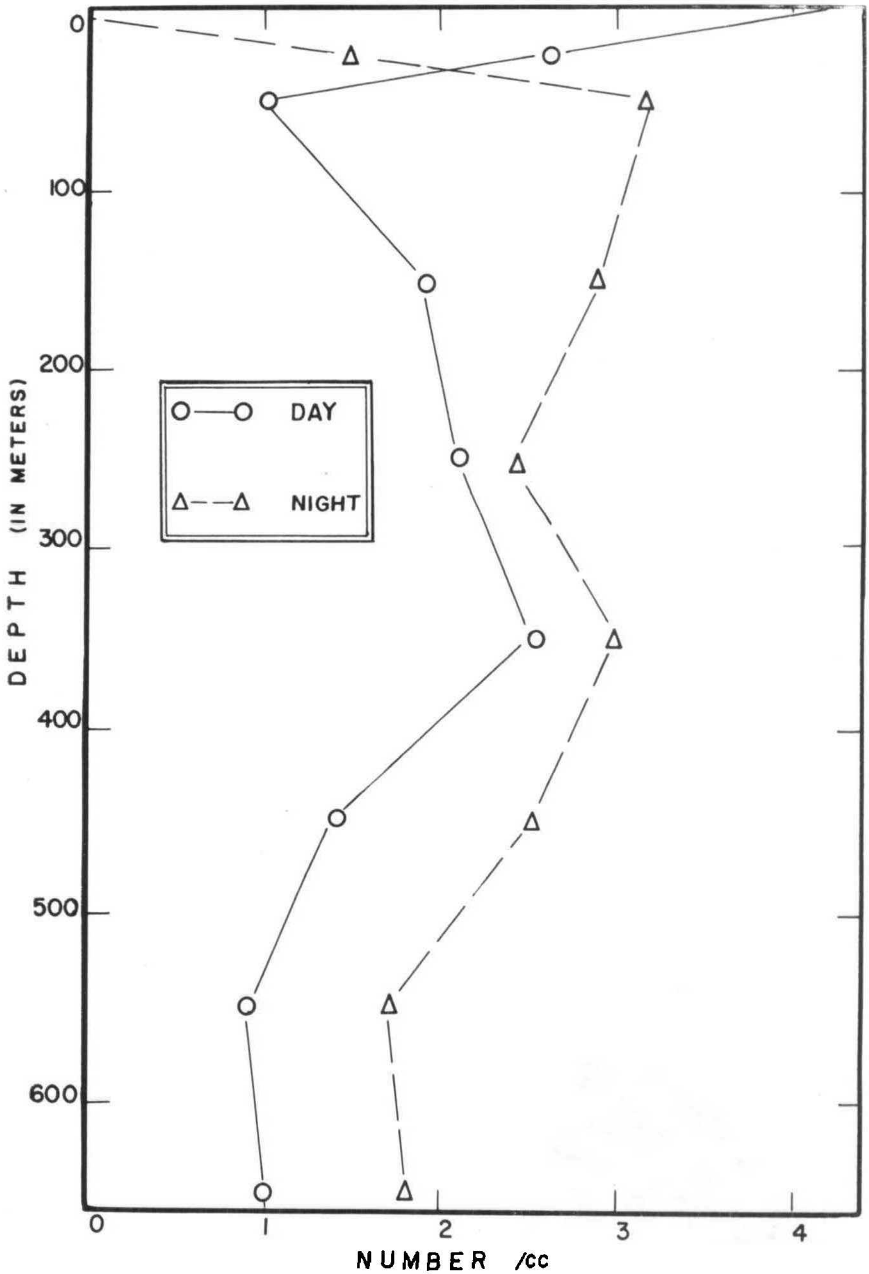

FIGURE 41. Vertical distribution of post-larval fish per cubic centimeter of plankton at the Forty-Mile Station. Day (12-16 hr.), Night (20-04 hr.).

volumes and dry weight for a series of typical bulk plankton samples. These samples were selected at random from both day and night hauls, as well as shallow and deep catches. A more accurate curve could be obtained by drying a great many more samples; however, at this stage of the investigation, it was not advisable since the plankton sample is completely destroyed for taxonomic studies by drying. The dry weight measurements do not include fish larvae or eggs as they were removed before drying the sample. The error introduced by this procedure is assumed to be negligible for dry weights, nevertheless they constitute a much larger fraction of the total volume and cannot be omitted from this measurement. Representative average volumes and dry weights were also determined for a series of copepods, euphausids, chaetognaths, and siphonophores.

Figure 43 shows the accumulative total of the dry weights of these organisms for a day catch in relation to the total weight of the bulk plankton sample as determined by volume measurements. Figure 44 illustrates the accumulative total weights of the above species for night hauls. In both the day and night hauls, it is readily seen that the above mentioned groups comprise, on the average, 50 per cent or more of the total weight of a bulk plankton sample throughout the water column.

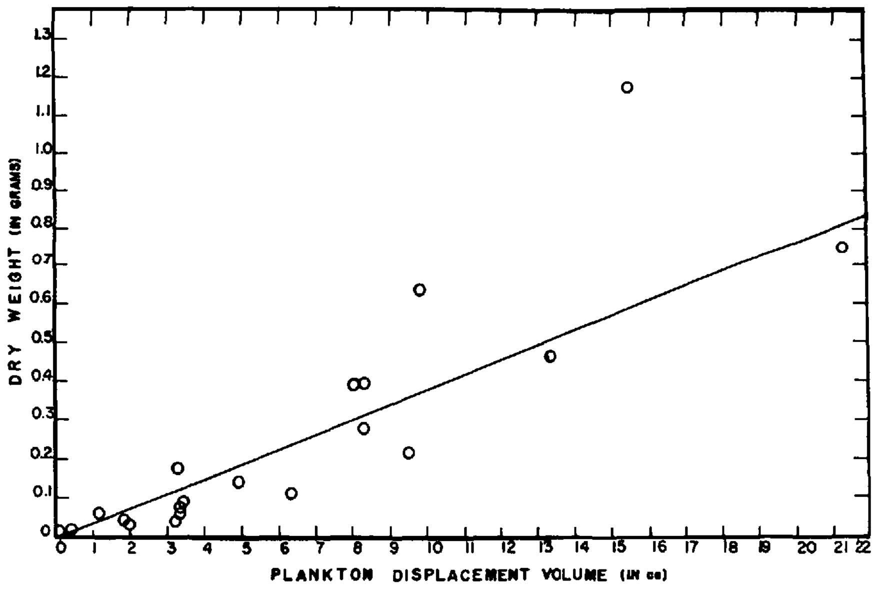

FIGURE 42. Dry weight of mixed plankton in relation to wet volume.

For day samples, the correlation drops off at a depth of approximately 500 meters. For night hauls the best correlation is obtained at depths below the euphotic zone or 100 meter level.

The above discrepancy in the correlations may be explained by the large variation in species that occurs in these two regions at the noted times. Table 2 shows the average dry weight and volumes for the individual groups considered. The average value for chaetognaths was determined on a basis of a number ratio between the large and small

TABLE 2

ZOOPLANKTON DRY WEIGHTS AND WET VOLUMES

Animal	Dry Wt. per Animal	Wet Vol. per Animal	Wt. per Unit Vol.
Euphausids	1.753 mg.	27.2 μl	0.0645
Chaetognaths	0.063	4.5	0.014
Siphonophores	0.126	42.9	0.00294
Copepods	0.024	1.3	0.01845
Copepods (Euphotic Zone Daytime)	0.0065		

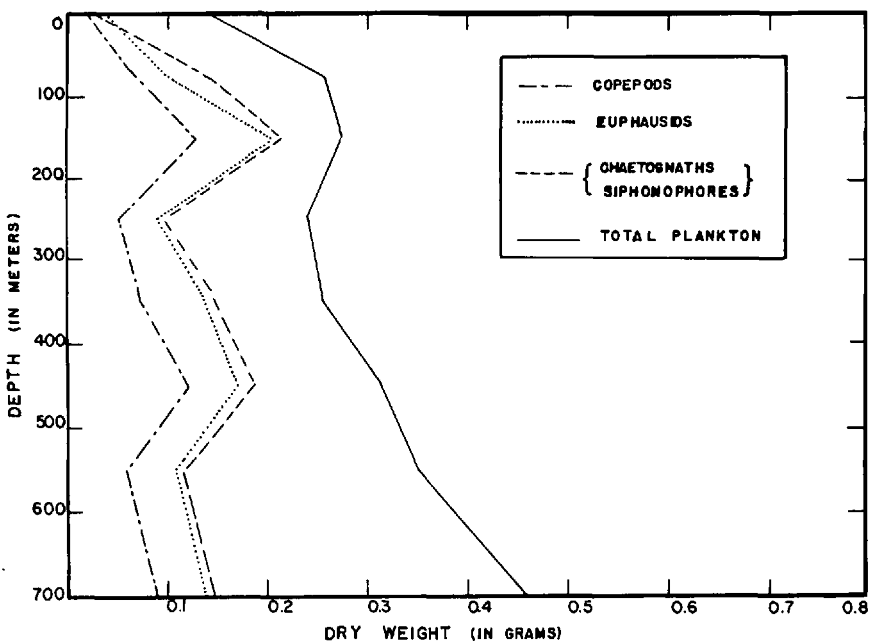

FIGURE 43. Accumulative totals of the dry weight of copepods, euphausids, chaetognaths and siphonophores, as portions of the dry weight of total plankton in day hauls at the Forty-Mile Station.

animals found in a typical plankton sample. For the copepods, it was essential to calculate a separate weight for copepods in the euphotic zone for the day hours.

This was necessary since a plankton sample from the euphotic zone during the daylight hours contained a very large number of small copepods, *Calanus minor,* etc. If the average weight of the deeper copepods was used, the combined weight of the copepod population would exceed, in most cases, the total weight of the bulk plankton. Outside the euphotic zone, there is an average distribution between the large and small species.

In the euphotic zone for the night hauls (Fig. 44) the large difference between the accumulative dry weights of the four predominant organisms and the total dry weight can be partially attributed to the large number of animals that migrate into this zone at night, which were not considered in the accumulative dry weight curve. These include such plankton forms as pteropods and post larval fish. A discrepancy may also result from a higher percentage of the larger animals concentrating in the surface waters. For the lower depths during

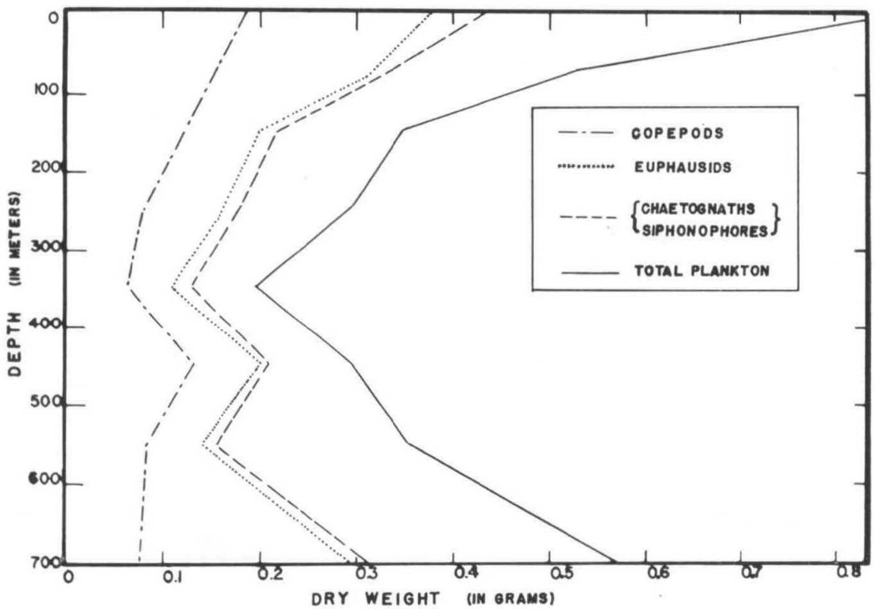

FIGURE 44. Accumulative totals of the dry weights of copepods, euphausids, chaetognaths and siphonophores, as portions of the dry weight of total plankton in night hauls at the Forty-Mile Station.

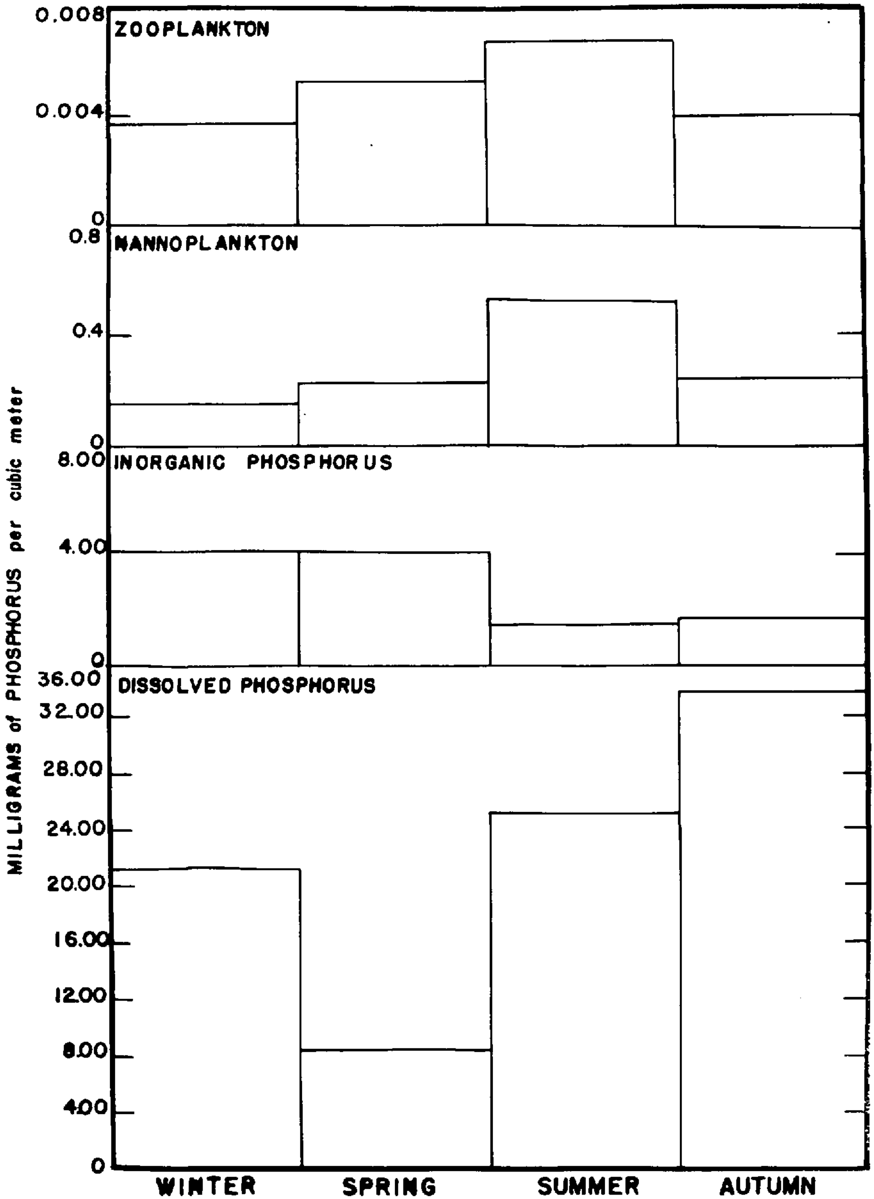

FIGURE 45. Diagram showing distribution of total phosphorus in euphotic zone at Forty-Mile Station.

the day, it is assumed that the larger animals, which concentrate at the surface at night, would migrate to the deeper waters so that the value used for their dry weights would be much too low. Even though these graphs are rather crude due to insufficient data, they can still be successfully used to obtain a rough estimate of the percentage composition of a bulk plankton sample from the Florida Current in this immediate area.

Discussion

The Florida Current is a fast moving body of water whose composition is somewhat intermediate between the open waters of the Atlantic Ocean and the more sheltered coastal waters. It is only partially cut off from the Atlantic Ocean on the eastern edge by the Bahama Banks and is bound on the western edge by the Florida Coast. The waters forming this current originate, as indicated by salinity measurements, mainly from waters flowing through the Yucatan Channel. At various times during the year, the more shallow western edge along the Florida Coast is somewhat modified by intrusion of waters from the Gulf of Mexico.

Any marine population is controlled quantitatively by certain processes, the rates of which are determined by a complicated series of environmental factors. These factors exert great influence on the physiology and physical distributions of the planktonic organisms. The production of the zooplankton population may be modified by temperature and the available food supply. Under oceanic conditions it is doubtful if either oxygen or salinity vary significantly. The standing crop reflects the balance between rates of productivity and predation. Therefore, in the present study a distinction was drawn between the major herbivores—copepods and euphausids; and the major carnivores—siphonophores, chaetognaths, and fishes. Unfortunately, the last of these were inadequately sampled. Phytoplankton production depends on illumination, temperature and nutrients. The standing crop reflects the balance between productivity and grazing. The general procedure here has been to consider the planktonic and chemical conditions in two units, as euphotic and deep zones.

The physical composition of the planktonic organisms in the Florida Current is mainly nannoplankton and zooplankton. The nannoplankton comprise the bulk of the phytoplankton present, the net-caught phytoplankton being of little value in the estimation of productivity, since they are far outnumbered by the quantity of nannoplankton present, the weight ratio being about 1000:1. The herbivore population is well represented by the copepods which comprise approximately one third of the zooplankton. The chaetognaths represent the carnivores which form the second major division of the zooplankton. Together with the euphausids and siphonophores they form the major groups of zooplankton found in this area. However, there are other minor groups.

Present data on the nannoplankton indicate that between 85 and 90 per cent of these organisms are found in the euphotic zone. Below the compensation depth, the quantity of nannoplankton was found to diminish rapidly. The greatest concentration appeared during the late summer months and in the upper 35 meters where the light intensity is high. The dissolved nitrate values in the immediate surface area (10 meters) were not large, being less than five microgram-atoms per liter. For the remaining portion of the euphotic zone, the nitrate values ranged from 5 to 10 microgram-atoms per liter. The inorganic dissolved phosphate values were even lower in this zone and, during the nannoplankton bloom, the values were 0.1 microgram-atoms or less. The N:P ratio for the waters of the euphotic zone were very high, the average value being around 60:1. Both nitrate and phosphate were low at all times in the euphotic zone, but of the two, phosphate appears likely to be the limiting factor. Salinity and temperature effects on the nannoplankton are not known since the identification and physiology of these organisms has been little investigated. The extent to which nannoplankton utilize organic nutrients is not known. Some forms at least can utilize amino acids. It is permissable to speculate that, under tropical conditions, much decaying organic matter may be removed from solution by nannoplankton before it has had time to break down into the simple salts which can be utilized by diatoms. The latter might, thereby, be largely eliminated from the phytoplankton population in those regions where conditions particularly favor the nannoplankton.

All zooplankton showed diurnal migration, with considerable variation occurring among the species present. This greatly affected the general constitution of the plankton samples. A marked increase occurred in the plankton volumes of the surface waters during the night, while at the lower levels, as deep as they were sampled, the total volume remained rather constant.

The copepods performed a smaller diurnal migration than some other groups. Although there was an increase in the number of copepods during the night at the surface, the relative per cent of the total plankton dropped to approximately one third of the day value. It should be noted that during the day, the copepods found in the surface layers were generally very small and the larger animals migrated to this area at night. Thus the copepods in the euphotic zone were much more important constituents of the plankton during the day. By the same token, in the deeper layers they were more important at night.

Pteropods and chaetognaths showed strong diurnal migration. In the euphotic zone the pteropods at night increased about 19 fold and the chaetognaths 5 fold. These observations were based on one station only and may need revision as more data becomes available. Euphausids also showed a marked diurnal migration with an increase of around 7 fold in the euphotic zone at night. Siphonophores revealed a definite diurnal migration although, in general, the range was not as large as in the pteropods and chaetognaths. Thus the siphonophores assumed at all depths an importance which depended on the extent of the migration of the other zooplankton.

A small seasonal variation has been observed for the zooplankton in this area of the Florida Current. The maximum increase, which occurs from March through June, was of the order of three times the average for the remainder of the year. Small seasonal changes of the zooplankton have been reported for the Bermuda area (Moore, 1949) and for the Ten-Mile Station off the Miami coast (Miller, *et al.*, 1953). However, in both of these areas, it is not definitely known if the changes are due to production or to the continual fluctuations in the water masses. Smith, *et al.* (1950) have shown that for the organisms of Biscayne Bay, a two fold increase occurs in July and in December-January periods. Fish (1956) reports a seasonal variation for the zooplankton of the North Sargasso Sea, with the maximum abundance occurring for a period from April through June. At the height of this maximum, the increase is approximately thirty fold over the rest of the year. Minor fluctuations occur in the cycle until a minimum is reached during the November-December period. In comparing the abundance of zooplankton in the Sargasso Sea with that of the Labrador Sea, he found the latter to be approximately three times as rich; the yearly average number of organisms per cubic meter being 239 for the Sargasso Sea and 690 in the Labrador area. The yearly average number of plankton calculated for this area of the Florida Current is 12 per cubic meter. The present work utilized a considerably coarser net than was used by Fish and such smaller forms as copepod nauplii were undoubtedly missed. On the other hand, he used a smaller net, for which the escape factor, in the more active forms, would be greater. The 20 fold difference between Fish's values and those of the Florida Current cannot be attributed entirely to differences in collecting methods. However, plankton volumes reported by Jespersen (1923) for shallow hauls show that the region east of Florida contains about one third of the plankton volumes found in the area covered by the Fish survey. Plankton volumes given by Moore (1949) for ocean waters near Bermuda, caught with identical nets, were considerably greater than the values found for Florida Current waters in the present study.

Nitrogen and phosphorus analyses were carried out on dried zooplankton samples of 10-30 milligram fractions. A series of random samples yielded an average nitrogen content of 6.84 per cent of the dry weight. Phosphorus values averaged 0.65 per cent, thereby giving a N:P ratio of 10.6:1. Harris and Riley (1956) obtained for the zooplankton in Long Island Sound, average nitrogen and phosphorus values of 8.9 per cent and 0.82 per cent, respectively, and an N:P ratio of 10.9:1.

Figure 45 shows the seasonal variations of the nannoplankton and zooplankton expressed as phosphorus and of dissolved inorganic and organic phosphates. It is readily seen that a large percentage of the total phosphorus in a given water mass is in the form of dissolved organic phosphorus, the value being over 90 per cent for the summer and autumn periods. This large value follows the summer nannoplankton bloom. The dissolved inorganic phosphorus attains its highest percentage of the total phosphorus during the winter and spring seasons. The phosphorus fixed in plankton organisms, as expected, attained its greatest values in the spring and summer months. However, at all times phosphorus was present in largest concentration in the dissolved organic form.

Yearly averages of dry weights for the standing crop of plankton in the Florida Current have been computed for the euphotic zone. Zooplankton dry weights were found to be 0.45 milligrams per cubic meter. This, however, is probably, as mentioned previously, an underestimate. Nevertheless, this value is much smaller than those reported by Riley (1949) for the Gulf Stream and Sargasso Sea, namely, 148 milligrams for the former and 10 to 87 milligrams for the latter. Nannoplankton dry weight was found to be 46.1 milligrams, a hundred fold increase over the zooplankton. It must be remembered that the nannoplankton represents not only the small phytoplankton but also non-photosynthetic protista and particulate matter. It is believed that the particulate matter comprises only a small percentage of the total dry weight, since the concentration decreases so rapidly below the euphotic zone. Debris from zooplankton would be expected to concentrate deeper, that is at or below the maximum concentration of the zooplankton. Matter of terraqueous origin can reach these waters to any extent only when airborne. However, identification of the nature of this particulate phosphorus will require further study.

There is a considerable seasonal change in the total phosphorus content of the euphotic zone and the waters slightly deeper. Winter mixing cannot enrich these surface waters as it does in colder regions. The seasonal differences might reflect changes in the water mass flowing through the Florida Straits although other characteristics of the water do not confirm this. We know little at present about the vertical transfer of organic and inorganic phosphorus by diurnal migrating plankton, but this may well prove to be significant in quantity. It may, at least, be significant that the maximum total phosphorus content of the euphotic zone is in the summer and winter, following closely the early summer maximum in the zooplankton populations.

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