A HISTORY OF OCEANOGRAPHY IN THE WATERS OF THE CONTINENTAL SHELF FROM CAPE SABLE TO CAPE HATTERAS. I. THE GULF OF MAINE

by

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INTRODUCTION

The original intent of this brief history of oceanography was to summarize past studies of the waters of the continental shelf from Cape Sable to Cape Hatteras as an aid in formulating future programs of oceanographic research at the Bureau of Commercial Fisheries Biological Laboratory, Woods Hole, Massachusetts. However, it was felt that such a summary might be useful to other laboratories and individuals concerned with the oceanography of continental shelf waters. In this history the term "oceanography" has been used in its broadest sense and includes basic studies of biology, chemistry, physics, geology, paleontology, ecology and fisheries hydrography. Published reports through June, 1962 of oceanographic surveys for the period of record through 1960 are included in this summary.

The offing of Cape Cod including Nantucket and Nantucket Shoals separates the coast line between Cape Sable and Cape Hatteras into two geographically distinct areas. The oceanic bight bounded by Nantucket Shoals and Cape Cod on the West and Cape Sable on the east (approximately 65° and 70° West longitude respectively) is known as the "Gulf of Maine" and by arbitrary definition (Bigelow, 1926) includes Georges and Browns Banks and waters out to the 200 meter contour. The area of the Gulf of Maine is approximately 36,000 square miles and the shore line from Cape Cod to Cape Sable is approximately 260 miles in length. The area bounded by Cape Cod and Cape Hatteras (approximately 36° North latitude) is known as the "Middle

Atlantic Bight" and has a surface area of about 29,000 square miles and 500 miles of shoreline and by arbitrary definition includes waters out to the 200 meter contour (Bigelow, 1933).

Not only are these two areas separable geographically, but there is rather an abrupt general division between the biological and hydrographic properties of the water east and west of Cape Cod (Bigelow, 1927, Parr, 1933). The boreal waters over most of the Gulf of Maine are well mixed by strong tidal currents while the circulation in the warmer coastal water to the west of Cape Cod is more sluggish and its chemical and physical characteristics less complex. Intrusions past Cape Cod of shelf water from the east come chiefly in the spring and the dominant westerly drift across the whole breadth of the continental shelf in the offing of Marthas Vineyard and Nantucket cannot be regarded as a continuation of the outdraft from the Gulf around the eastern edge of Georges Bank (Bigelow, 1927). The offing of Cape Cod also appears to be a definite transition zone (probably thermal) for some of the northern and southern species of fish and invertebrates, both pelagic and benthic (Bigelow and Sears, 1939). Usually the same species composition of plankton dominates the community to the east as well as to the west of Cape Cod, but there is in general a greater volume and more tropical forms to the west and more subartic forms in the Gulf of Maine. There is a different assemblage of foraminiferal faunas in the bottom sediments of the two areas (Parker, 1948) and the species composition and abundance of benthic and pelagic fish varies markedly between the two regions

with boreal species dominating in the Gulf of Maine and warm water species being more abundant in the Middle-Atlantic Bight. Also the spawning habits and the age of maturity of both invertebrates (Coe, 1938) and vertebrates (Bigelow and Schroeder, 1953) vary between the two areas.

Not only are the Gulf of Maine and the Middle Atlantic Bight separable physically and biologically, but for the most part, oceanographic surveys have been restricted to the confines of either one area or the other. Seldom have cruises been made in both areas in concurrent seasons or years. It appears best then to present this historical data for each area separately. An effort has been made to present this data in chronological order according to the year of the surveys and to describe in greater detail pertinent oceanographic studies which possibly are not ~~as~~ well publicized. Surveys of a strictly estuarine nature have not been included in this account.

HISTORY

The indentation of the coast between Cape Sable on the east and Cape Cod and Nantucket on the west was first referred to as the "Gulf of Maine" by Mitchell (1881). The most comprehensive and analytical of the early studies of the geology of the area and its contained banks and basins is that of Johnson (1925) who considered that the banks were erosional rather and depositional. Johnson postulated that the banks were cut in bedrock by streams at the end of the Tertiary, that Georges Bank was a submarine continuation of the coastal plane cuestus found to the southwest, and that the deep

portion of the Gulf of Maine was a drowned inner lowland and the product of mature river erosion.

Modern oceanographic research in the Gulf of Maine may be dated from the summer of 1878 when the steam - tug Speedwell took temperatures in Massachusetts Bay and off Cape Ann, including serials at 31 stations with reversing thermometers. Descriptive oceanography of the Gulf of Maine dates to the summer of 1912 when the U.S. Bureau of Fisheries and the Museum of Comparative Zoology of Harvard University jointly undertook an oceanographic and biological survey of the Gulf of Maine with special reference to its fishes, plankton, its physical and chemical state and the circulation of its water. The vessels principally used for these surveys were the schooner Grampus (1912-1916), the steamer Albatross (1920), and the steamer Halcyon (1920-1922). These surveys were under the direction of Dr. Henry Bigelow and the results were published in three monographs; on fishes, plankton, and hydrography which are the foundation of modern oceanography in the coastal waters of the United States.

The first of these classic monographs to be published concerned the fishery and the fishes of the Gulf of Maine (Bigelow and Welsh, 1925) and is based principally upon the observations made between 1912 and 1922, but also includes observations and references to studies of other workers previous to this period. The second monograph to be published is concerned with the zooplankton and phytoplankton of the area (Bigelow, 1926) and is based on the collections

of 1912-1922, although reference is made to the observations of other workers during and previous to this period. The third report describes the hydrography of the Gulf of Maine (Bigelow, 1927) based on observations made between 1912 and 1922 as well as considerable data collected by other workers during and previous to this period (notably Huntsman, 1924 and Mavor, 1921 & 1922).

Two other surveys made during the 1920's should be mentioned. The Fish Hawk made 14 cruises from December, 1924 to June, 1925 to study the production and distribution of cod eggs in relation to the inshore stock of cod in Massachusetts and Ipswich Bays. Observations included horizontal and vertical ring-net tows, temperature and salinity observations at specific depths, and drift bottle releases. An analysis of this data is given by Fish (1929). Serial telegraph snapper and boat dredge samples in 14 different areas in Massachusetts Bay and on Stellwagen Bank were obtained from the sloop Katherine in the summer of 1922. A description of the sedimentation in the area and an interpretation of the origin and condition of deposition of marine sediments based on a textural, mineral, and shape analysis of the bottom samples is given by Trowbridge and Shepard (1932).

Comparative values for the replacement of Bay of Fundy waters were determined by Hachey (1934) from differences in the annual range of temperature at various levels for each year of the period 1924 through 1930 inclusive. These differences in the annual range of temperature were correlated with the average amount of St. John river runoff and the direction and velocity of the wind.

An analysis of horizontal and vertical ring-net phytoplankton collections made at weekly intervals at a station of 30 m. depth in the St. Croix estuary and at monthly intervals at a station of 90 m. depth northeast of Campobello Island during the period 1924-1931 was made by Davidson (1934). Data is presented concerning the monthly, seasonal, and yearly fluctuations in the abundance and species composition of diatoms at the two stations and their relation to physical and biological factors. It was concluded that the turbulance of the waters in this area was the greatest single factor in determining phytoplankton abundance.

Many cruises to specific areas within the Gulf of Maine were made by United States and Canadian vessels during the 1930's. For the most part these surveys and especially the subsequent reports were concerned with specific details of the biological and physical oceanography. The following history and description of the most significant surveys and publications summarizes work done during this period. Where practical, the cruise data is presented in chronological order, but in situations where a single investigation involved cruises over a period of several years these data have been grouped.

During the summer seasons of 1930, 1931, and 1932, the United States Coast and Geodetic Survey had a fleet of four vessels engaged in the recharting of Georges Bank. The vessels were able to run closely spaced, accurately located lines of soundings using a combination of sound waves produced by explosives and radio signals. These soundings are the basis of the present day charts of the area. Collections of bottom sediments were also obtained to supplement

the bathymetric observations and this abundance of new information allowed for a more well-grounded hypothesis to be formulated as to the origin of Georges Bank than had been possible heretofore (Shepard, Trefethen, and Cohee, 1934) Shepard, et. al. postulated that Georges Bank owes its present form largely to glaciation and that waves and currents removed the finer material from the glacial till, leaving a surface concentrate of sand and gravel.

During 1931 and 1932, surveys were made by the U.S. Bureau of Fisheries on the Albatross II to study the early life history and abundance of haddock on Georges Bank. The only published data concerning these surveys was a report on the relation of currents to the distribution and survival of haddock eggs and larvae on Georges Bank (Walford, 1938). This paper is based on surveys made during March - June, 1931 and April, 1932 and includes data on the distribution and abundance of haddock eggs and larvae collected in oblique one-meter net tows, non-tidal drift as determined from drift bottles, and the distribution of density.

In 1930 the International Passamaquoddy Fisheries Commission, appointed a group of experts to undertake an oceanographic investigation of Passamaquoddy Bay and adjacent waters in connection with the proposal to install power dams across the mouths of Passamaquoddy and Cobscook Bays. This investigation took place in 1931 and 1932 and its objective was to determine the probable effect of these dams on the fisheries. The area of observation extended from the head of the Bay of Fundy to the vicinity of Massachusetts Bay, to

Browns Bank and as far east as Liverpool, Nova Scotia. The three principal vessels used in these surveys were the Biological Board of Canada's Prince and Nova and the U.S. Bureau of Fisheries vessel Pelican. The results of this investigation were published in a series of seven papers concerning the hydrography, fishery, phytoplankton, and zooplankton of the area. The report on phytoplankton (Gran and Braarud, 1935) is based on water bottle samples at depths of 1, 10, 35, 40, and 75 meters at 27 standard stations and includes information on the species composition and abundance of phytoplankton, measurements of temperature, salinity, phosphate, nitrate and oxygen, and a discussion of the relation of turbulance and nutrients to the productivity of the area. Gran and Braarud concluded that 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 paper on the fishery (Graham, 1936) includes a description of the commercial sardine fishery and its catch statistics, an analysis of the distribution of fry based on Peterson and meter-net hauls, and a discussion of the distribution and movements of sardine herring in relation to the physical and biological environment. The report on physical oceanography (Watson, 1936) is based on observations made exclusively in the Bay of Fundy and includes a detailed discussion of the tidal and non-tidal circulation and mixing processes as indicated by temperature and salinity observations at specific depths within this area. Four papers were published on zooplankton and the area of coverage included in these reports was consider-

ably greater than that for the reports on the hydrography, fishery, and phytoplankton as collections of the Albatross II in April, 1932 and the Atlantis in September, 1932 on the northern part of Georges Bank, the southeastern part of the Gulf of Maine, and off southern Nova Scotia were included in the analysis. The data are based on plankton pump samples at 0, 10, 30, and 50 meters and 1/2 meter-net and meter-net oblique tows from 50 meters to the surface. The first three zooplankton papers are concerned with the biology of the three numerically dominant species; Calanus finmarchicus (Fish, 1936a), Pseudocalanus minutus (Fish, 1936b) and Oithona similis (Fish, 1936c) with special reference to production and dispersal. Data is presented on the breeding seasons, number of broods, rate of growth, spawning areas, and dispersal of eggs and larvae of these three species. The fourth paper of the zooplankton series (Fish and Johnson, 1937) considers the zooplankton population (including fish eggs and larvae) as a whole and the essentials determined were the abundance, species composition, source and dispersal, recruitment and relations of zooplankton to the population of herring in the Quoddy region.

A discussion of the regional variations in productivity in relation to physical and biological conditions as determined during the 1931 - 1932 Passamaquoddy surveys is given by Huntsman (1952). Data is presented on the relative productivity of various parts of the Bay of Fundy in terms of the pounds of herring landed per acre and it was concluded that the abundance of herring in the Passamaquoddy

Bay area is to a considerable extent attributable to the transport and concentration of fish and zooplankton food organisms by the circulation of the water.

Observations were made from the Atlantis on the vertical distribution of copepods and of submarine irradiation at four stations in the deep water of the Gulf of Maine in August, 1931 and July, 1932. Five closing nets were towed in series in depth strata of 0 to 50 meters and 50 to 100 meters and determinations of temperature, salinity, pH, oxygen, nitrate, nitrite, phosphate, and irradiation were made at the sampling depths. Reports on the vertical distribution of various sex- and age-groups of Metridia lucens, Centropages typicus, and Calanus finmarchicus in relation to temperature, light, and time were published by Clarke (1933 and 1934a). In July, 1933 the influence of temperature on the vertical distribution of Calanus finmarchicus and Metridia lucens was more carefully tested at two stations, one in the deep water of the Gulf of Maine and one on Georges Bank, using the same methods as were used in 1931 and 1932. Variations of light intensity, temperature, chemical constituents, and phytoplankton with depth were determined. Marked areal and species differences in vertical distribution and diurnal migration were observed and the vertical migration of these two species was found to be more closely correlated with changes in submarine irradiation than with changes in hydrographic conditions or in phytoplankton (Clarke, 1934b). A note on the abundance, species composition, and vertical distribution of the phytoplankton

at these two stations was published by Braarud (1934).

In August, 1932, nine stations were made from the Atlantis in the deep basin of the Gulf of Maine and on Georges Bank. Although the coverage was limited in time and space, three detailed reports on the biology and chemistry of the waters in these two areas were published. The first of these reports (Rakestraw, 1933) is concerned with the nutrients in the two areas and data is presneted on the horizontal and vertical distribution of phosphate, nitrate, nitrite, and dissolved oxygen. The second report (Gran, 1933) includes an analysis of the species composition of phytoplankton and its horizontal and vertical distribution, and the relation of the abundance and distribution of phytoplankton to chemical and physical factors. The third report (Waksman, et al., 1933) presents data on total bacterial plate counts at the surface, 50 meters, and bottom, on the occurrence of specific bacterial groups, and on the relation of the abundance of bacteria to the abundance of phytoplankton and zooplankton.

A report on the distribution and abundance of bacteria in the water and muds in Cape Cod Bay and over the continental slope east of Cape Cod is given by Reuzer (1933). Bacterial plate counts of samples of water and mud collected during September, 1932 as well as during the Atlantis cruise in August, 1932 are presented. A discussion of the variation in the number of bacteria with distance from shore, depth of water, depth in the mud, and carbon content of the mud is given.

In August, 1934, the Atlantis undertook a dredging trip to the three recently charted canyons (now known as Oceanographic, Gilbert, and Lydonia canyons) cutting the southern edge of Georges Bank for the purpose of obtaining specimens of material and fossils of which the continental margin is composed and of fixing at least the maximum age of the topographic features. The geological and paleontological results of this survey are reported in four papers; geology (Stetson, 1936), foraminifera (Cushman, 1936), molluscs and echinoderms (Stephenson, 1936), and Bryozoa (Bassler, 1936). A detailed description of the geology and paleontology of these canyons is given and evidence presented to the effect that Georges Bank is a submerged extension of the coastal plane covered with a mantle of glacial debris. To supplement the 1934 dredging trip observations, measurements of bottom currents in Gilbert and Lydonia canyons were made from the Atlantis in July, 1936 in order to form an estimate of the importance of currents (both tidal and non-tidal) in producing submarine canyons. Current measurements were made with an Ekman current meter suspended in a frame at ten stations in the canyons as well as on the flat surface of the shelf beyond the canyon rims. The velocities recorded in the canyons were similar to those on the shelf and it was concluded that these currents are merely flowing in pre-existing cuts and are not the cause of them (Stetson, 1937).

A study was made of the sediments of Cape Cod Bay from the Asterias during the summer of 1935 as part of the program of

the Woods Hole Oceanographic Institution relating to the investigation of sediments of the continental shelf and coastal waters of the eastern United States. Bottom samples were taken in series at one mile intervals and beach and cliff samples at specific locations. The characteristics and distribution of the sediments in Cape Cod Bay and a comparison with the sediments in other bays is given by Hough (1942).

A detailed oceanographic survey of the offshore waters of the Gulf of Maine was made by the Woods Hole Oceanographic Institution in 1933 and 1934 with the object of obtaining a more precise seasonal picture of its hydrography and biology than was available from the observations of Bigelow. Thirteen cruises were made in the Atlantis in the course of 15 months (July, 1933 to September, 1934), with the result that 684 hydrographic stations were occupied. A standard vertical haul (from bottom to surface) was made at each station using a Heligoland larva net. The dates of these cruises and the numbers of the stations occupied are given by Redfield (1941) and the routine hydrographic and chemical data are published in the Bulletin Hydrographic (1933, 1934). Supplementary cruises were made in May and August, 1936 to confirm certain observations made during the primary survey.

A number of reports concerning the distribution, abundance, and ecology of the phytoplankton and zooplankton collected during these cruises were published and these are described in their order of publication. Lillie (1938) published a preliminary report on the phytoplankton in which the species composition and abundance (cells per

liter) at 1, 10, 30, 50, and 80 meters at each station is presented in tabular form showing that the phytoplankton of the Gulf of Maine follows the cycle typical of boreal waters. The frequency and continuity of the cruises during this survey made it possible to follow the history of a rather definite population of the pteropod Limacina retroversa during the greater part of the year as it drifted across the Gulf of Maine, noting its rate of drift and spread, mortality, growth and reproduction and its replacement by another population of the same species (Redfield, 1939). This evidence demonstrated that the population of Limacina was not endemic, as Bigelow thought, but owed its origin to invasions of young individuals from offshore waters to the east of the Gulf of Maine and that the discontinuous character of these invasions accounted for the irregularity in occurrence of this species. The reproductive history and the sequence of the sexual phases of Limacina retroversa in relation to size based on this same data is described in detail by Hsiao (1939). This study indicated that the change in sexual constitution of the populations with time was due to a reversal of sex predominance of the individuals.

The collections made in 1933 and 1934 provided the basis for a general survey of the numerical distribution of phytoplankton and planktonic protozoa and species composition of plankton flora of the Gulf of Maine from season to season. In the first part of this report (Bigelow, Lillick, and Sears, 1940), the seasonal and regional abundance of plant cells and planktonic protozoa and the relation of the planktonic cycle to nutrients, light, temperature, vertical circulation,

and grazing is described. The numerical distribution of plant cells (number per 0.1 square meter of sea surface) was based on water bottle samples at 1, 10, 30, 50 and 80 meters and vertical net haul samples. In the second part of this report, Lillick (1940) presents data on the species composition of the phytoplankton. These data corroborated the joint evidence of earlier years to the effect that in the Gulf of Maine, the major fluctuations in the total number of planktonic plant cells, both regionally and seasonally, were due chiefly to fluctuations in the abundance of diatoms and that the phytoplankton cycle in the Gulf of Maine paralleled that of other boreal waters in time sequence, differing only in the association of species concerned.

Redfield and Beal (1940) present data concerning the distribution and numerical abundance of chaetognaths taken during the 1933-1934 Atlantis cruises. Their data demonstrate that Eukrohnia hamata, Sagitta maxima and S. Lyra are carried into the Gulf of Maine by deep currents and do not breed there, that S. serrodentata is a terminal immigrant from the superficial waters of the Atlantic, and that S. elegans is the only chaetognath truly endemic to the region and the permanence of this stock is correlated with the stability of hydrographic conditions in various regions (notably Georges Bank). It is shown that in the main the character of the distribution is independent of the physical characteristics and nutritive conditions of the water and can be accounted for in terms of the biological characteristics of the species and the movement of the water stratum within which the

the species are found.

In the final paper to be published on the plankton collected during the Atlantis Gulf of Maine cruises, Redfield (1941) described the seasonal and geographical fluctuations in abundance of the calanoid community (total zooplankton minus Salpa, ctenophores, and medusa). The abundance figures are based on determinations of the dry volume of the vertical tow-net catches by the method of filtration and displacement. Redfield demonstrates that the center of abundance is closely associated with the surface circulation and that the principle factor influencing population density is the inflow of relatively barren coastal water from the Nova Scotian coast in winter. He concluded that the Gulf of Maine is the region of production of the calanoid community and supplies immigrants to the south, but receives no appreciable recruitment from regions to the eastward.

There are two papers describing the chemistry of the Gulf of Maine waters based on the 1933-1934 Atlantis cruises, one on the occurrence of nitrite (Rakestraw, 1936) and one on the distribution of ammonia (Redfield and Keys, 1938). Rakestraw's paper includes data collected in other areas as well as the Gulf of Maine. Stations in the Gulf of Maine were grouped into seven locations, one on Georges Bank and the other six in the deep water to the north. Data is presented showing the seasonal variations of nitrite and nitrate and the relation of nitrite to nitrate, phosphate, density and temperature at the surface and depth. A detailed discussion of these relationships in the Gulf of Maine and other areas is given. Redfield and Keys

present results on the occurrence of ammonia in various sections of the Gulf of Maine in September, 1933 and May, 1934. They showed that in the deeper basin of the Gulf of Maine in May, ammonia occurred in maximal concentration in a definite stratum between 30 and 60 meters, while in September the concentration of ammonia was uniform at all depths. In the strong tide ways of the South and North Channels, ammonia was distributed uniformally with depth and in the shallow water over Georges Bank, its occurrence showed no regularity. The distribution of ammonia paralleled the distribution of organic phosphorous compounds, nitrate, and zooplankton, indicating that its distribution marks the location and intensity of organic decomposition.

Several other studies of the oceanography of the Gulf of Maine during the 1930's should be noted. Enough new information on fishes in the Gulf of Maine had accumulated during this period to warrant the issuance of a supplement to the "Fishes of the Gulf of Maine" (Bigelow and Welsh, 1925). Such a supplement containing data on the abundance, distribution, breeding habits, and food habits of 88 species of cartlagenous and bony fishes and a revised key to the skates and rays was published by Bigelow and Schroeder (1936). The distribution of phosphorous present as inorganic phosphorous, as dissolved organic compounds, and as particulate matter were determined for specific depths at a standard station in the western part of the Gulf of Maine during May, August, and November, 1935 and February and May, 1936. A report on the cycle of phosphorous throughout the year and on the methods for analyzing quantitatively the factors

producing seasonal changes in the distribution of such a compound are given by Redfield, Smith, and Ketchum (1937).

Ketchum and Keen (1953) made a study of the exchange of fresh and salt waters in the Bay of Fundy and in Passamaquoddy Bay based on an analysis of salinity observations made during the 1930's. The distribution of river water within the Bay of Fundy and in Passamaquoddy Bay was determined and the rate of transport of river water was evaluated. Empirical calculations of exchange ratios and of total accumulation of river water were also made. The close agreement between the calculated and observed accumulations of river water indicated that such tidal-exchange calculations would be useful in any area having vigorous tidal mixing.

In August, 1936, the Atlantis made 22 hauls with Norwegian shrimp trawls over mud bottoms in deep water in the western and northern parts of the Gulf to determine the abundance of Pandalus borealis and of associated fishes. The faunal community of the water just above these deep-mud bottoms was reported on by Bigelow and Schroeder (1939). The most significant faunal contrast noted was that P. borealis has a well marked center of population in the deep bowl west of Jeffrey's Ledge where bottom currents are weak and where the supply of organic debris on the bottom is relatively large. No regional contrast was evident in the qualitative composition of the fish fauna found over mud bottoms in different parts of the Gulf.

The Atlantis made 11 cruises from September, 1939 to June, 1941 in connection with a study of the productivity of Georges Bank

undertaken by various members of the staff of the Woods Hole Oceanographic Institution. Stations covered the region from the South Channel on the southwest to the eastern tip of Georges Bank and from the deep basin of the Gulf of Maine on the northwest to the edge of the continental shelf on the southeast. Standard hydrographic observations for salinity and temperature were made at every station, transparency measurements were obtained during daylight hours, and phytoplankton collections and specific chemical data were obtained at selected stations. Zooplankton was collected at each station by means of oblique hauls with Plankton Samplers (Clarke and Bumpus, 1950) and stramin nets. The dates of these cruises and the station number and location are given by Clarke, Pierce, and Bumpus (1943). A number of papers concerned with the distribution, abundance and ecology of zooplankton and phytoplankton based on information collected during these cruises were published. In the following brief summary, these reports are discussed in the order of their publication.

A detailed report of the productivity of Georges Bank based on data from 120 stations made on the cruises during September, 1939 and January, March, April, May, and June, 1940 is given by Riley (1941). Included in this report is an analysis of the methods of measuring phytoplankton which show that the plant pigment method gives results most nearly representative of the abundance of phytoplankton. The main body of this work is concerned with the vertical and horizontal distribution of plant pigments, nitrate, phosphate and

oxygen at various seasons of the year. The data show that the quantity of plant pigments have marked seasonal and regional variations, that the quantity of plant pigmants was lowest and of nutrients highest in January, that the spring diatom burst began in March and lasted until May, and that during the spring diatom bloom there was a pronounced inverse relation between plant pigments and nutrients. Plant pigments, the percent saturation of oxygen, and experimental determinations of oxygen production showed positive correlations with light and negative ones with temperature. The seasonal cycle of productivity and the physical and biological factors effecting productivity are discussed. Measurements are given of the mean standing crop of plankton and of the mean total productivity.

Sears (1941) analyzed the abundance, distribution, and species composition of diatoms collected during the surveys of Georges Bank from the latter part of March to the end of June, 1940. Water bottle samples of phytoplankton were obtained at depths of 1, 10, 30, 50 and 80 meters and the number of cells per 0.1 square meter of sea surface were determined. These data showed that the period of diatom abundance was more prolonged on Georges Bank than in most parts of the Gulf of Maine, and that in general production was greatest in the deep water along the periphery of the bank. Chaetoceros decipiens and Ch. dibilis were the most characteristic species of the spring flora and Leptocylindrus minimus was the most abundant diatom in late June.

In a study of the causes underlying the initiation of spring

diatom flowering, Riley (1942) made an analysis and an extensive statistical treatment of the relationship of the phytoplankton crop (as indicated by the quantity of plant pigments) to depth and stability (as indicated by the difference in density between the surface and 30 or 50 meters) based on observations made during March, April, and May, 1941. The relationship between plankton and stability was zero in March, positive in April, and negative in May. Data from April cruise support the theory that when the thickness of the euphotic zone and rates of photosythesis and respiration are constant, the rate of increase in the plankton population is a linear function of the reciprocal of the zone of vertical turbulance. A discussion is presented of the reasons for the seasonal change in the relationship of plankton abundance to stability.

As a continuation of these studies Riley (1943) compared laboratory experiments on the growth of Nitschia closterium with experiments of natural phytoplankton associations on Georges Bank during the spring of 1941 in an attempt to describe some of the physiological factors involved in spring diatom flowerings. The growth curves of the laboratory culture of Nitschia under varying conditions of light, temperature, and nutrients is described and a discussion is presented of the relative importance of certain chemicals and physical factors at different stages of the population cycle. In a parallel study made on natural populations on Georges Bank it was found that many of the species passed through a similar population cycle as that of the laboratory culture of Nitschia,

and similarities were also noted in the relationships of the population curves with respiration and photosynthetic activity. A general discussion is presented of physiological factors involved in spring flowerings.

A study of the abundance, distribution and seasonal cycle of reproduction of Sagitta elegans on Georges Bank based on collections made during all eleven Atlantis cruises was made by Clarke, Pierce, and Bumpus (1943). The greatest concentrations of S. elegans were found within the central homogeneous water mass of the bank throughout the year and the species recommends itself as an indicator for tracing movements of the mixed bank water. The chief period of reproduction centered in April and May. S. serratodentata and S. enflata occurred entirely outside the margin of the mixed area. Comparison is made with a similiar case of reciprocal distribution found for two species of copepods: Calanus finmarchicus and Pseudocalanus minutus.

Riley and Bumpus (1946) discuss phytoplankton-zooplankton relationships on Georges Bank based on estimates of the abundance of total phytoplankton and of total and of individual species and genera of zooplankton during the period from September, 1939 through June, 1940. A significant inverse relationship between the horizontal distribution of phytoplankton and of total and individual species of zooplankton was demonstrated and evidence presented that grazing was the cause of this inverse relationship. It is suggested that turbulent mixing tended to redistribute the populations so that correlation was

not fully developed. An attempt was made on theoretical grounds to determine grazing rates and to estimate the effect of turbulent mixing on the populations of zooplankton and phytoplankton.

In an effort to establish continuity between the descriptive data concerning the Georges Bank phytoplankton populations based on cruise data and mathematical concepts based on assumptions about plankton physiology, Riley (1946) developed multiple correlation equations by which variations in the horizontal distribution of plant pigments during each of the 1939-1940 cruises are calculated according to variations in depth, temperature, phosphate, nitrate, and zooplankton and by which it is possible to determine the amount of variation in phytoplankton crop obtained by varying any one or all of these environmental factors. The seasonal cycle of phytoplankton was also evaluated from a more theoretical standpoint and an equation derived expressing the seasonal rate of change of the phytoplankton population.

An application of the basic concepts of productivity (standing crop, material removed, and production rate) to a marine area is illustrated by Clarke (1946) using data from the 1939-1941 Georges Bank cruises. Diagrams are presented illustrating the interrelations between the processes of production, consumption, and decomposition at the various levels of the ecological complex. Values for the standing crop and for the net production of phytoplankton and zooplankton are presented with a discussion of the controlling influence of light and currents. Values for the yield of the commer-

cial catch of fish are compared with yields from fresh-water and terrestrial areas.

In a theoretical analysis of the seasonal cycle of zooplankton on Georges Bank, Riley (1947) established an equation in which the rate of change of the herbivore population in respect to time is equal to the difference between the rate of assimilation of organic material by feeding on phytoplankton and the rate of dissapation by respiration, predation, and other losses. Numerical values were assigned the constants in the equation and a theoretical curve for the herbivore seasonal cycle was constructed which was in general agreement with the observed population.

The final paper to be published on the 1939-1941 Georges Bank surveys was a study of the distribution of the larger plankton Crustacea (amphipods, euphausiids, mysids, and decapods) based on oblique stramin net and Plankton Sampler tows (Whiteley, 1948). A detailed account is given of the abundance, distribution, and species composition of the predominating species and the effect of drift, temperature, and depth on distribution are discussed.

During the war years, personnel at the Woods Hole Oceanographic Institution were principally engaged in studies for the Navy. During the post-war years emphasis at this Institution was shifted from studies of shallow-water circulation to the study of deep water current systems. The only other oceanographic surveys undertaken in the Gulf of Maine by the Woods Hole Oceanographic Institution during the 1940's were in connection with a study of shallow-water

benthonic Foraminifera off Portsmouth, New Hampshire during the summer of 1946. The area of coverage extended from Ipswich Bay to Portsmouth and to approximately 30 miles offshore on the north and to 18 miles offshore to the south. Over 700 bottom samples were obtained in a gridwork of stations spaced approximately one mile apart. A discussion of the distribution and ecology of the Foraminifera in the area is given by Phleger (1952) and a description of the species of Foraminifera is given by Parker (1952).

With the commissioning of the Albatross III by the U.S. Fish and Wildlife Service, in 1948, surveys of the populations of groundfish on the New England Fishing banks were initiated. During these cruises, data was obtained on the distribution and abundance of the various species of groundfish and other bottom fauna and on the distribution of temperature and of bottom sediments. The distribution of haddock on Georges Bank by age, area, depth and bottom type based on Albatross III cruises made in the summers of 1948 and 1949 and the spring of 1950 was analyzed by Colton (1955). The age composition and the abundance of haddock were shown to vary markedly with location, depth, and season. During the summer, few haddock of any age were found in the area bounded by the 60 and 90 fathom contours separating the shallow bank water and the deeper water of the Gulf of Maine basin. Haddock occurred in greater numbers over sand than over mud bottoms, but this distribution was incidental to the depth distribution.

Chase (1955) established an empirical formula for predict-

ing the brood strength of Georges Bank haddock which made use of geostrophic wind data from February through April and Nantucket winter air temperatures. The brood strength estimate was based on the commercial catch of 3-year-old haddock. "Damage counts" were assigned for offshore components of wind beginning on a date 18 days after the minimum Nantucket air temperature. With a few exceptions, there was good agreement between the actual and indicated brood strength data for the years 1928 through 1951.

An analysis of the annual variations of temperature and salinity in the Bay of Fundy was made by Bailey, MacGregor and Hachey (1954) based on monthly observations at three different layers (0-25m, 25-75m, and 75-90m) obtained at a station in the outer Quoddy region from 1924-1952. Normal temperature, salinity and T-S curves for the three different layers are shown. The normal annual range of temperature was 10° C. for the surface layer and 8.6 C. for the bottom layer and the normal annual range of salinity was from 31.1 percent to 32.5 percent for the surface layer and from 31.9 percent to 32.8 percent for the bottom layer. The stability of the water column reached two maxima, one in May and one in August.

Three papers by Mclellan (1954a, 1954b, and 1957) should be mentioned here as they include data for the southwestern extremity of the Scotian Shelf, contiguous to the Bay of Fundy and the Gulf of Maine. The first two papers describe bottom temperatures, temperature-salinity relations, and mixing processes on the Scotian

Shelf based on seasonal observations made during 1950, 1951, and 1952 and include a description of mixing processes and characteristics of the water over the Browns Bank area. The third paper is a study of the origin of the Slope Water south of Nova Scotia and the currents within it. The temperature - salinity characteristics, rate of production and currents of the Slope Water are described in detail on the basis of investigations carried out by the Atlantic Oceanographic Group during the period 1950-52 and in previous years.

A new edition of "Fishes of the Gulf of Maine," entailing a general revision and the addition of much new material was prepared by Bigelow and Schroeder (1953). In this same year, the U.S. Fish and Wildlife Service inaugurated a program to study the early life history of haddock in the Gulf of Maine in an attempt to relate spawning location and the pattern of drift of eggs and larvae to the success of year class. Cruises were made on the Albatross III during the spring months of 1953, 1955, 1956 and 1957 and the procedure involved Continuous Plankton Recorder tows at the surface and 10 meters, temperature and salinity observations, drift bottle releases and meter net tows. The methods and operational procedures pertinent to the surveys of 1953, 1955 and 1956 are described by Marak and Colton (1962). The basic data on the distribution of fish eggs and larvae of all species and of surface temperature and salinity for the 1953 cruises are presented in tabular and graphic form in this same report. The basic data for the 1955 cruises is

given by Marak, Colton, and Foster (1962) and for the 1956 cruises by Marak, Colton, Foster and Miller (1962). A similar program of study of the early life history of herring in the Gulf of Maine was started in 1956 by the U.S. Fish and Wildlife Service in cooperation with the Fisheries Research Board of Canada. The vessels Albatross III, Silver Bay, Delaware, and Harengus were used in these surveys and cruises were made from September through February in 1956-57 and 1957-58. A number of papers describing the results of various phases of these two investigations were published and these are summarized in the order of their publication.

Bumpus et al. (1957) launched radio drift buoys in the Trinity Ledge area off Yarmouth, in Grand Manan Channel and off Cape Spencer in October, November, and December, 1956. These experiments added some detail to the earlier descriptions of the circulation in the Bay of Fundy and confirmed the existence of the same general pattern observed previously for other seasons of the year. The current velocities observed, however, were greater than those observed by earlier investigators using drift bottles.

The surface circulation patterns in the Gulf of Maine from late February through June as deduced from drift bottles are described by Day (1958). The greater bulk of these drift bottle releases were made on the Albatross III cruises of 1953, 1955, and 1956, but for comparative purposes data from Albatross II cruises in April, 1931 and 1932 and in May, 1931 the Atlantis cruises in April, 1934 and June, 1933 are also included. The basic data used in this paper

have been tabulated by Bumpus and Day (1957). Seasonal and yearly differences in surface circulation were noted and it was shown that Bigelow's (1927) July-August pattern of a relatively closed circulation appears to evolve with the seasons as a result of vernal warming and the consequent formation of density structure. It was demonstrated that the prevailing circulation may be strongly modified by winds and that this accounted for the marked differences between conditions in the 1930's and 1950's.

An analysis of the abundance and distribution of larval herring in the offshore waters of the Gulf of Maine during the fall and winter of 1956-57 and 1957-58 was made by Tibbo, et al. (1958). The spawning areas and seasons were determined, and data presented on the length composition, rate of growth, and day and night variations in the catch of larval herring. The major spawning area was on the northern edge of Georges Bank, but appreciable spawning also occurred off the western coast of Nova Scotia. It was concluded that spring spawnings are of minor importance and that late summer and autumn spawnings are the major contributors to the herring stocks in the Bay of Fundy and Gulf of Maine.

The mortality of marine fish larvae due to warming as a result of the intrusion of slope water over the southern edge of Georges Bank during May, 1956 was noted by Colton (1959). The hydrographic conditions occurring at that time are described and a discussion is given of the consequence of such intrusions of relatively warm slope water on the populations of boreal fish species

inhabiting Georges Bank.

Bumpus (1960) reviewed the surface circulation in the Gulf of Maine and southwestern Scotian Shelf on the basis of an analysis of the returns from drift bottles released in the Gulf of Maine since 1919. The majority of the bottles were launched during the 1953-1958 larval fish surveys, but data is also included concerning drift bottles released previous to this period as well as bottles launched monthly from Lurcher Lightship during 1957 and 1958. This analysis showed that the source of surface flow into the Bay of Fundy expands from a minimum during January in the immediate approaches of the bay to a maximum in May which includes most of Georges Bank and the southwestern Scotian Shelf, then commencing towards September contracts towards the minimum. Evidence is given of secular variations in the removal of surface water from the Bay of Fundy during 1957 and 1958.

In a study of the food habits of larval gadoids, Marak (1960) examined the stomachs of specimens of larval cod, haddock, and pollock taken in 1-meter-net tows during the 1953 - 1957 larval haddock surveys. A comparison of the species composition of zooplankton in the stomachs with that in the environment as indicated by the meter-net catch showed that of the many kinds of food available, adults and juveniles of four species of copepods and larval copepods contributed the major portion of the diet. Fish larvae ranging in size from 4 to 18 mm. fed mainly on larval copepods; whereas the bulk of the food of fish larger than 18 mm. was adult

copepods. The composition of the food was essentially similar for all years.

A detailed analysis of the meter-net and Continuous Plankton Recorder material collected during the larval herring surveys in the fall and winter of 1956-57 was made by Colton, Honey, and Temple (1961) to determine the efficacy of the sampling techniques in estimating the abundance and distribution of larval herring. This analysis showed that a greater average abundance and a more detailed picture of the distribution of larval herring was indicated by the Continuous Plankton Recorder data than by the meter-net collections and that the greater average length of the Recorder-caught larvae was due to escapement of the larger larvae from the meter-nets during the daylight hours. It was demonstrated that in the Gulf of Maine larval herring moved up to the surface layers during the night, but that the depth of maximum abundance was below 10 meters during both the day and night so that a true picture of the distribution of larval herring is not obtained when sampling is confined to the upper 10 meters of water.

The effects of offshore drift, time and location of spawning, vertical distribution of eggs and larvae, and the length of pelagic life on the dispersal and survival of eggs, larvae, and juveniles of commercially important food fishes in the Gulf of Maine are discussed by Colton and Temple (1961) on the basis of observations made during the larval haddock and herring surveys of 1953 - 1958. The drift of bottles and of transponding buoys showed that with the

exception of midsummer when the Georges eddy is most pronounced, surface drift is offshore in the direction of the slope water band. From observations on the time and location of spawning of haddock and herring it was concluded that under average conditions most fish eggs and larvae were carried away from Georges Bank and that only under unusual hydrographic conditions were eggs and larvae retained in the area.

The occurrence of tropical fish larvae and of oceanic copepods in the Gulf of Maine during September, October, November, 1956 and January, 1957 are reported on by Colton (1961) and by Colton, Temple and Honey (1962). Considerable numbers of eyed flounder and myctophid postlarvae were collected and a marked correlation between the distribution of these tropical fish larvae and of temperature was observed. Twenty-two species of oceanic copepods and fragments of Gulf weed (Sargassum natans) were also found over a wide area. These collections yielded evidence of an intrusion of oceanic water into the Gulf of Maine. The general distribution patterns of the various species of larval fish and copepods indicated that this intrusion resulted for the most part from an overflow of oceanic water across the southern edge of Georges Bank.

A number of other papers concerned with the oceanography of the Gulf of Maine emanating from observations made during the 1950's have been published and are summarized in the order of their publication. A study of the food habits of Georges Bank

haddock based on an analysis of the stomach contents of fish caught by commercial trawlers and the Albatross III during the period April, 1953 to February, 1954, was made by Wigley (1956). The haddock's diet consisted principally of sedentary or slow moving invertebrate animals and the primary food groups in decreasing order of importance were crustaceans, mollusks, echinoderms, annelids and fish. Marked regional differences in the stomach contents were observed, but seasonal trends in diet composition were not apparent.

Taylor, Bigelow and Graham (1957) described the trends in air and sea surface temperatures and in the distribution of certain species of marine fish and invertebrates in New England based on an analysis of data from shore stations as well as from the offshore waters of the Gulf of Maine. A long-term upward trend since about 1900 in winter air and sea surface temperatures was demonstrated. A comparison of temperature observations made in the offshore waters of the Gulf of Maine during the spring and fall in the period 1912-26 (Bigelow, 1927) and during the spring and fall of 1953 on Albatross III cruises indicated an increase of from 1° to 5° F. throughout the water column for most parts of the Gulf. Northward shifts in the abundance and distribution of commercial species of fish and the northward extension of the recorded ranges of southern species of fish and invertebrates were noted. It was concluded, however, that the upswing in temperature was not accompanied by a general alteration of the faunal characteristics

of the Gulf of Maine.

Monthly and annual mean surface water temperatures for shore stations and lightships between Nantucket and Eastport for the period of record through 1955 are tabulated by Bumpus (1957a). Daily surface water temperatures at Grand Manan, daily surface water temperatures and salinities at Texas Tower No. 2 on Georges Shoal, and daily water temperatures at the surface and at 30, 50, 100 and 150 feet and salinity at the surface and at 150 feet at Portland, Boston and Nantucket Shoals Lightships for the year 1956, 1957, 1958, 1959 are tabulated by Bumpus (1957b) and Day (1959a, 1959b, 1960). Mean temperatures for each level for three equal time periods per month are plotted as time profiles for the year for each station. The one-third monthly mean surface temperature and the one-third monthly mean surface salinity and the weekly mean bottom salinity values for each station are plotted and the general hydrographic conditions at each station are discussed.

A study of distribution and species composition of zooplankton in the inner Bay of Fundy was made by Jermolajev (1958) on the basis of ring-net tows made in August and September, 1920 and in July, 1951. He found the inner Bay of Fundy to be practically devoid of locally produced plankton and the few species present to be either esturine species from Minas Basin and Chignecto Bay or immigrants from the open Gulf. The endemic species were found along the shore while the immigrant species were most abundant in the mouth of the Bay. The extreme paucity of the plankton

in the inner Bay as well as the poor condition of the few immigrant species were associated with the low productivity of the area.

The distribution, and the temperature and bottom sediment relationships of four species of pandalid shrimp in the Gulf of Maine and off southern New England as determined by otter trawl catches of the Albatross III during November, 1956 are described by Wigley (1960). Dichelopandalus leptocerus was found over the entire area, in a wide range of depths and temperature, and over sediments of varying quantities of organic matter. Pandalus borealis occurred in a limited area of the central and western Gulf of Maine, in water of moderate depth and low temperatures, and over sediments of high organic content. P. montagui was found along the periphery of the Gulf, in water of moderate depth and low temperature, and over sediments of relatively low organic content. P. propinquus was found in deep and moderately cold water in the central Gulf and over sediments containing medium or high quantities of organic matter.

The seasonal pattern of surface circulation in the Quoddy Region and contiguous areas of the Gulf of Maine is described by Chevier and Trites (1960) on the basis of drift bottle releases in the period January, 1957 through December, 1958. In the outer Quoddy Region, the non-tidal drift was usually southerly and surface waters leaving the area moved outward between the Wolves and Point Lepreau, then southward off the eastern side of Grand Manan Island, and then either across the mouth of the Bay of Fundy

to Nova Scotia or along the coast of Maine.

Bumpus (1961) recorded the release and recovery points of drift bottles released in the Gulf of Maine from research vessels, lightships and the Georges Bank Texas Tower during the period 1956 - 58. The listings include all recoveries as of August, 1960. Diagrams of the surface circulation as deduced from the recoveries accompany the data.

Quantitative samples of the sediments and benthic fauna were obtained at locations on and adjacent to Georges Bank aboard the Albatross III in August, 1957, to ascertain particle size composition and related components and to make a preliminary quantitative study of the benthic fauna. The partical size composition, type, sorting, organic content, shell content, and color of the sediments in various regions of Georges Bank are described by Wigley (1961a). The distribution and abundance of benthic fauna in relation to the sediment and geographic location is discussed by Wigley (1961b). The bulk of the Georges Bank benthic fauna was composed of four major taxonomic groups: Crustacea, Mollusca, Echinodermata, and Annelida and pronounced differences in the quantity and species composition in relation to geographic location and bottom sediments were observed.

The final paper to be published, based on observations made in the Gulf of Maine during the 1950's, was a study of the vertical distribution of young redfish during the summers of 1957 and 1958 by Kelly and Barker (1961). A mid-water trawl was towed at a series of depths from the surface to 150 meters at stations in the south-

western part of the Gulf of Maine. There was no evidence from these data of diurnal vertical movements of the planktonic larvae. Newly spawned larvae were found concentrated in the upper 10 meters of water, 10 - 20 mm. larvae were concentrated at a depth of 20 meters and within the thermocline and fish exceeding 25 mm. were concentrated in deeper water below the thermocline. The length of the redfish which had moved to the bottom was between 40 and 50 mm.

A seasonal and yearly summary of the principal oceanographic surveys of Gulf of Maine waters during the period 1912-60 is given in Table 1. The surveys have been separated into four general subdivisions: Physical Oceanography (physics, chemistry, and hydrography), Biology (plankton and plankton ecology), Geology (geology, bathymetry, and paleontology), and Fisheries Hydrography.

Table 1. --Principal Oceanographic Surveys in the Gulf of Maine, 1912-1960

Season*/	Physical Oceanography				Biology				Geology				Fisheries Hydrography			
	W	SP	S	F	W	SP	S	F	W	SP	S	F	W	SP	S	F
1912			x				x								x	
13			x			x	x								x	x
14	x		x	x	x		x	x							x	x
15		x		x		x		x							x	x
16							x	x							x	x
17																
18																
19		x														
1920	x	x	x		x	x							x	x		
21					x	x							x	x	x	
22			x				x				x				x	
23			x													
24		x	x		x								x			
25		x	x			x								x		
26			x													
27																
28																
29																
1930											x					
31	x	x	x	x	x	x	x	x			x			x	x	
32	x	x	x	x	x	x	x	x			x			x		
33			x	x			x	x								
34	x	x	x		x	x	x				x					
35		x	x	x							x					
36			x		x	x					x				x	
37																
38																
39				x					x							
1940	x	x	x		x	x	x									
41																
42																
43																
44																
45																
46											x					
47																
48															x	
49															x	
1950	x	x	x	x										x		
51	x	x	x	x			x									
52	x	x	x	x												
53														x		
54																
55													x	x		

Table 1. -- Principal Oceanographic Surveys in the Gulf of Maine, 1912-1960 (continued)

Season*/	Physical Oceanography				Biology				Geology				Fisheries Hydrography			
	W	SP	S	F	W	SP	S	F	W	SP	S	F	W	SP	S	F
1956									x			x	x	x		x
57	x	x	x	x	x			x			x		x	x	x	x
58															x	
59																
60																

*/ W, Dec. - Feb.
SP, March - May
S, June - Aug.
F, Sept. - Nov.

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