History of Oceanography in the Offshore Waters of the Gulf of Maine

by John B. Colton, Jr.

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ABSTRACT

Published reports through June 1963 of oceanographic surveys of the offshore waters of the Gulf of Maine for the period of record through 1960 are summarized. Studies of biology, chemistry, physics, geology, paleontology, ecology, and fishery hydrography are included. Emphasis is given to oceanographic surveys which appear to be least publicized. Summaries are presented in chronological order according to the year of the surveys. A bibliography and subject index of papers referred to in the text are given.

INTRODUCTION

The original purpose of this brief history of oceanography in the Gulf of Maine was to summarize past studies of the waters of the Continental Shelf from Cape Sable to Cape Cod as an aid in planning oceanographic research at the U.S. Fish and Wildlife Service, Bureau of Commercial Fisheries Biological Laboratory, Woods Hole, Mass. I decided, however, that such a summary would be useful to other laboratories and individuals concerned with the oceanography of Continental Shelf waters. An oceanographic history and a summary of the developments in the study of Canadian Atlantic waters east of Cape Sable were given by Hachey (1961). I have used the term "oceanography" in its broadest sense; it includes studies of biology, chemistry, physics, geology, paleontology, ecology, and fishery hydrography. I have excluded publications which do not include environmental data or references. Published reports through June 1963 of oceanographic surveys for the period of record through 1960 are included in this summary.

The offing of Cape Cod including 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 long. 65° and 70° W. respectively) is known as the "Gulf of Maine", and by arbitrary definition (Bigelow, 1926) included Georges and Browns Banks and waters out to the 200-m. contour. The area of the Gulf of Maine is about 36,000 square miles, and the shoreline from Cape Cod to Cape Sable is approximately 600 miles. The area bounded by Cape Cod and Cape Hatteras (approximately lat. 36° N.) is known as the "Middle Atlantic Bight" and has a surface area of about 29,000 square miles and 500 miles of shoreline.

Not only can the two areas be separated 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 west of Cape Cod is more sluggish, and its chemical and physical properties are less complex. The offing of Cape Cod also appears to be a definite transition zone (probably thermal) for some 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 the west of Cape Cod, but there are, in general, more tropical forms and a greater plankton volume to the west and more subarctic 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 vary 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. In addition, oceanographic surveys have, for the most part, been restricted to the confines of either one area or the other and seldom have cruises been made in both areas in concurrent seasons or years.

In this history I have attempted to present data in chronological order according to the year of the surveys and to describe in greater detail pertinent oceanographic studies which are possibly not well publicized. I have tried also to make this history as comprehensive as possible, but I do not claim completeness. I excluded papers that I believed did not fall under the term oceanography, or papers reviewed by Bigelow (1926, 1927). In this history I have included estuarine surveys that covered some offshore areas and contributed to our knowledge of the oceanography of the Gulf of Maine proper. Surveys of a strictly estuarine nature will be included in a bibliography on the ecology of estuaries of the Eastern United States being prepared by the U.S. Fish and Wildlife Service, Bureau of Commercial Fisheries. A chart of the Gulf of Maine and the names of places referred to in the text are given in figure 1.

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). Johnson (1925), who considered the banks erosional rather than depositional, made the most comprehensive and analytical of the early studies of the geology of the area and its contained banks and basins. He postulated that streams at the end of the Tertiary cut the banks in bedrock, that Georges Bank was a submarine continuation of the coastal plane cuesta 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 was used to take 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 and plankton, its physical and chemical state, and its water circulation. The vessels principally used for the surveys were the schooner Grampus (1912-16), the steamer Albatross (1920), and the steamer Halcyon (1920-22). Henry Bigelow directed the surveys, and the results were published in three monographs--on fishes, plankton, and hydrography. These reports are the foundation of modern oceanography in the coastal waters of the United States. A description and summary of oceanographic observations made in the Gulf of Maine previous to this time and a bibliography of published material are included in these reports.

The first of these classic monographs to be published concerns the fishery and the fishes of the Gulf of Maine (Bigelow and Welsh, 1925). The second monograph concerns the zooplankton and phytoplankton of the area (Bigelow, 1926). The third monograph 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 before and during this period (notably Huntsman, 1924; 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. Horizontal and vertical ring-net tows, temperature and salinity observations at specific depths, and drift bottle releases were made. Fish (1928) analyzed these data. 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. Trowbridge and Shepard (1932) described the sedimentation in the area and interpreted the origin and condition of deposition of marine sediments based on a textural, mineral, and shape analysis of the bottom samples.

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 water levels for each year of the period 1924-30. He correlated the temperature differences with the average amount of St. John River runoff and the direction and velocity of the wind.

Davidson (1934) analyzed the horizontal and vertical ring-net phytoplankton collections made at weekly intervals at a station of 30 meters' depth in the St. Croix estuary and at monthly intervals at a station of 90 meters' depth northeast of Campobello Island during the period 1924-31. He presented data on 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. He concluded that the turbulence of the waters in this area was the greatest single factor in determining phytoplankton abundance.

During the 1930's United States and Canadian vessels made many cruises to specific areas within the Gulf of Maine. For the most part, these surveys and especially the subsequent reports deal with specific details of the biological and physical oceanography. The following history and description of the most

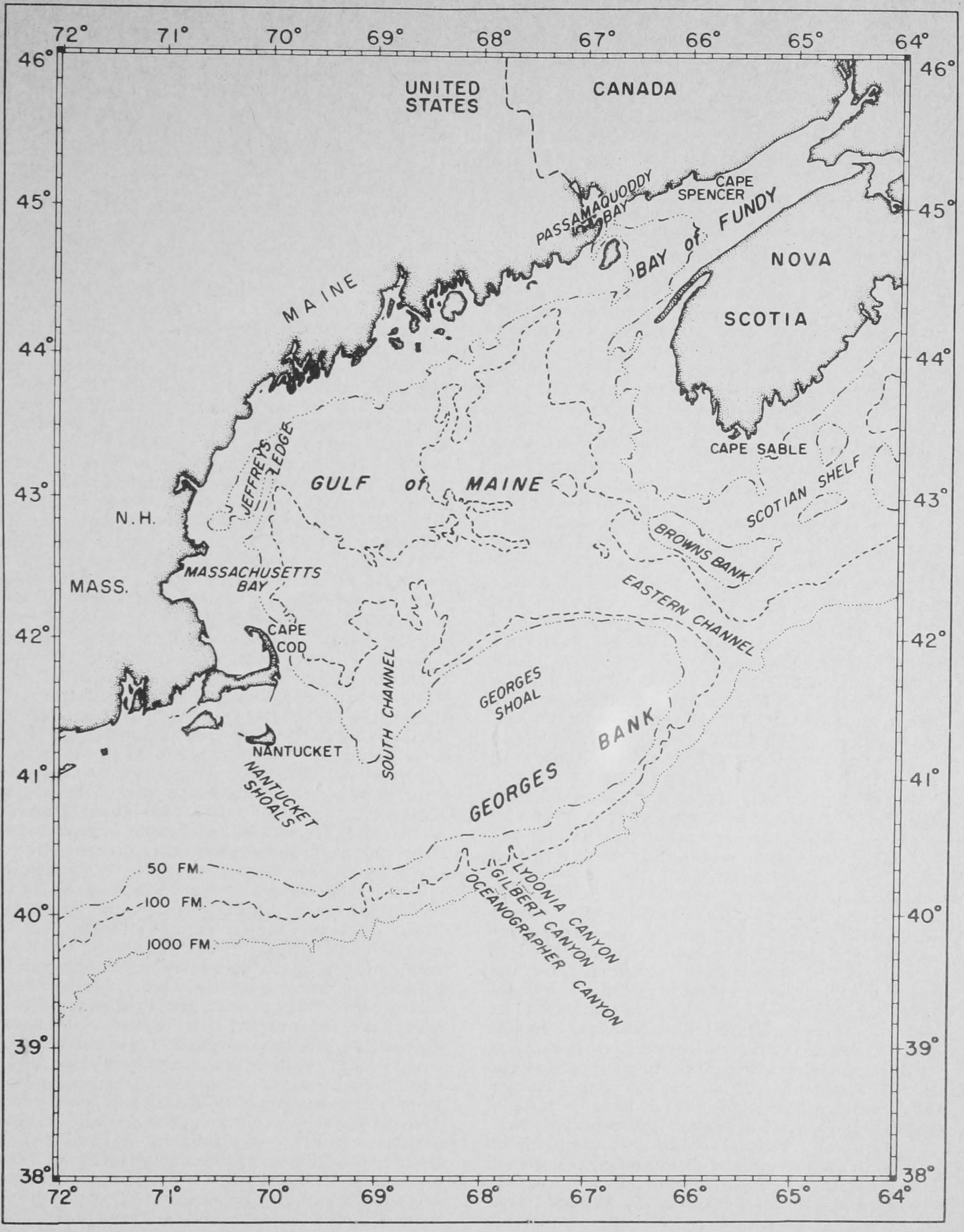

Figure 1.--Orientation chart of the Gulf of Maine.

significant surveys and publications summarize work done during this period. Where practical, I showed the cruise data in chronological order, but in situations where a single investigation involved cruises over a period of several years I grouped these data.

During the summers of 1930, 1931, and 1932, the U.S. Coast and Geodetic Survey had four vessels recharting Georges Bank. Using a combination of radio signals and sound waves produced by explosives, researchers ran closely spaced, accurately located lines of soundings. 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 permitted a more well-grounded hypothesis to be formulated on the origin of Georges Bank than had been possible heretofore. Shepard, Trefethen, and Cohee (1934) 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, the [U.S.] Bureau of Fisheries made surveys on the Albatross II to study the early life history and abundance of haddock on Georges Bank. Walford's report (1938) on the relation of currents to the distribution and survival of haddock eggs and larvae on Georges Bank is the only published data concerning these surveys. He based his paper on surveys made during March - June 1931 and April 1932 and included data on the distribution and abundance of haddock eggs and larvae collected in oblique 1-m. net tows, the pattern of nontidal 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. A study was made in 1931 and 1932 to determine the probable effect of the dams on the fisheries. The area of observation extended from the head of the Bay of Fundy to Massachusetts Bay, to Browns Bank, and as far east as Liverpool, Nova Scotia. The 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 were published in a series of eight papers concerning the hydrography, sardine fishery, phytoplankton, and zooplankton of the area. Gran and Braarud (1935) based their report on phytoplankton on water bottle samples at depths of 1, 10, 35, 40, and 75 m. at 27 standard stations and included information on the species composition and abundance of phytoplankton, measurements of temperature, salinity, phosphate, nitrate, and oxygen, and discussed the relation of turbulence and nutrients to the productivity of the area. They 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. Graham's paper (1936) on the fishery describes the commercial sardine fishery and its catch statistics, analyzes the distribution of fry based on Peterson-net and meter-net hauls, and discusses the distribution and movements of sardine herring in relation to the physical and biological environment. Watson (1936) based his report on physical oceanography on observations made exclusively in the Bay of Fundy and included a detailed discussion of the tidal and nontidal circulation and mixing processes as indicated by temperature and salinity observations at specific depths within this area. He demonstrated that in stratified regions tidal mixing causes an outflow of mixed water at an intermediate depth with an inflow both at the surface and bottom. In regions where a local supply of fresh water is mixed with more saline water, there is an outflow at the surface and a compensating inflow at the bottom only.

Five papers were published on zooplankton. The area of coverage included in these reports was considerably greater than that for the reports on the hydrography, fishery, and phytoplankton, because collections of the Albatross II in April 1932 and the Atlantis in September 1932 were included. The collections were made on the northern part of Georges Bank, the southeastern part of the Gulf of Maine, and off southern Nova Scotia. The data are based on plankton pump samples at the surface and 10, 30, and 50 m., 1/2-m.-net oblique tows from 50 m. to the surface, and meter-net oblique tows from the bottom to 50 m. and from 50 m. to the surface. The first three zooplankton papers concern the biology of the three numerically dominant species with special reference to production and dispersal: Calanus finmarchicus (Fish, 1936a), Pseudocalanus minutus (Fish, 1936b), and Oithona similis (Fish, 1936c). They present data on the breeding seasons, number of broods, growth rate, 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 describes the abundance, species composition, source and dispersal, recruitment, and relations of zooplankton to the population of herring in the Quoddy region. In the final paper, Fish (1955) described the biology of the microcopepod Microsetella norvegica. He presented data on regional distribution and abundance of this species, on the production and dispersal of eggs and larvae, and on its role in the natural economy of Gulf of Maine waters.

Huntsman (1952) discussed the regional variations in productivity in relation to physical and biological conditions determined during the 1931-32 Passamaquoddy surveys. He presented data on the relative productivity of various parts of the Bay of Fundy in terms of the pounds of herring landed per acre. He concluded that the abundance of herring in the Passamaquoddy Bay area resulted to a considerable extent from 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. The vessel towed five closing nets in series in depth strata from the surface to 50 m. and 50 to 100 m., and the researchers determined the temperature, salinity, pH, oxygen, nitrate, nitrite, phosphate, and irradiation at the sampling depths. Clarke (1933, 1934a) reported 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. Using the same methods in July 1933 that were used in 1931 and 1932, he more carefully tested the influence of temperature on the vertical distribution of Calanus finmarchicus and Metridia lucens at two stations, one in the deep water of the Gulf of Maine and the other on Georges Bank. He determined variations with depth of light intensity, temperature, chemical constituents, and phytoplankton, and observed marked areal and species differences in vertical distribution and diurnal migration. 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 phytoplankton (Clarke, 1934b). Braarud (1934) reported on the abundance, species composition, and vertical distribution of the phytoplankton at these two stations.

In August 1932, the Atlantis occupied nine stations in the deep basin of the Gulf of Maine and on Georges Bank. Although the coverage was limited in time and space, information for three detailed reports on the biology and chemistry of the waters in these two areas was obtained. The first report (Rakestraw, 1933) concerns the nutrients in the two areas and presents data 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, Reuszer, Carey, Hotchkiss, and Renn, 1933) presents data on total bacterial plate counts at the surface, 50 m. 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.

Reuszer (1933) reported 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. He presented bacterial plate counts of samples of water and mud collected during September 1932 and during the Atlantis cruise in August 1932. The well-mixed sea water in shallow regions contained a greater abundance of bacteria than offshore water, and this was associated with a higher nutrient and richer plankton content of the inshore water. Bacteria were much more numerous in the bottom deposits than in the overlying water, and muds contained many more bacteria than sands. The number of bacteria decreased regularly with distance from land. Reuszer discussed the variation in the number of bacteria with distance from shore, depth of water, depth in the mud, and carbon content of the mud.

In August 1934, a dredging trip was made aboard the Atlantis to the three recently charted canyons (now known as Oceanographer, Gilbert, and Lydonia Canyons) which cut the southern edge of Georges Bank. Specimens of material and fossils of which the continental margin is composed were obtained in order to fix at least the maximum age of the topographic features. Four papers report the geological and paleontological results of this survey: geology (Stetson, 1936), Foraminifera (Cushman, 1936), mollusks and echinoderms (Stephenson, 1936), and Bryozoa (Brassler, 1936). They describe in detail the geology and paleontology of these canyons and show that Georges Bank is a submerged extension of the coastal plain, covered with a mantle of glacial debris. To supplement the 1934 dredging trip observations, researchers on the Atlantis in July 1936 measured velocities of bottom currents in Gilbert and Lydonia Canyons. They made the measurements to estimate the importance of currents (both tidal and nontidal) in producing submarine canyons. They used an Ekman current meter suspended in a frame to make current measurements at 10 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 Stetson (1937) concluded that these currents merely flow in preexisting cuts and are not the cause of them.

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 (WHOI) 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 1-mile intervals, and beach and cliff samples were obtained at specific locations. Hough (1942) described the characteristics and distribution of sediments in Cape Cod Bay and compared them with the sediments in other bays.

In 1933 and 1934, WHOI made a detailed oceanographic survey of the offshore waters of the Gulf of Maine to obtain a more precise seasonal picture of its hydrography and biology than was available from Bigelow's observations. The Atlantis made 13 cruises in 15 months (July 1933 to September 1934) and occupied 684 hydrographic stations. A standard vertical haul (from bottom to surface) with a Heligoland larva net was made at each station. Redfield (1941) gave the dates of these cruises and the numbers of the stations occupied. The Bulletin Hydrographique (1934, 1935) published the routine hydrographic and chemical data. Supplementary cruises were made in May and August 1936 to confirm certain observations made during the primary survey.

A description of published reports concerning the distribution, abundance, and ecology of the phytoplankton and zooplankton collected during these cruises follows. Lillick (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 m. at each station are 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 enabled Redfield (1939) 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; he noted its rate of drift and spread, mortality, growth, reproduction, and replacement by another population of the same species. 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. The discontinuous character of the invasions accounted for the irregularity in occurrence of this species. Hsiao (1939) described in detail the reproductive history and sequence of the sexual phases of Limacina retroversa in relation to size. His study indicates that the change in sexual constitution of the populations with time resulted from 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) described 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. They based the numerical distribution of plant cells (number per 0.1 $m.^2$ of sea surface) on water bottle samples at 1, 10, 30, 50, and 80 m. and vertical net haul samples. In the second part of this report, Lillick (1940) presented data on the species composition of the phytoplankton. These data corroborate the joint evidence of earlier years that in the Gulf of Maine the major fluctuations in the total number of planktonic plant cells, both regionally and seasonally, resulted chiefly from fluctuations in the abundance of diatoms. The phytoplankton cycle paralleled that of other boreal waters in time sequence, differing only in the association of species concerned.

Redfield and Beale (1940) presented data concerning the distribution and numerical abundance of chaetognaths taken during the 1933-34 Atlantis cruises. Their data demonstrate that deep currents carry Eukrohnia hamata, Sagitta maxima, and S. lyra into the Gulf of Maine (they 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. The permanence of this stock is correlated with the stability of hydrographic conditions in various regions (notably Georges Bank). The character of the chaetognath 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 species are found.

In the final paper 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 medusae). He based the abundance figures on determinations of the dry volume of the vertical tow-net catches by the method of filtration and displacement. He demonstrated that the center of abundance is closely associated with the surface circulation and that the principal factor influencing population density was the inflow of relatively barren coastal water from the Nova Scotia 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.

Three papers describe the chemistry of the Gulf of Maine waters based on the 1933-34 Atlantis cruises. Rakestraw's paper (1936) on the occurrence of nitrite includes data collected in other areas as well as in the Gulf of Maine. He grouped stations in the Gulf of Maine into seven locations, one on Georges Bank and the other six in the deep water to the north. He presented data showing the seasonal variations of nitrite and nitrate and the relation of nitrite to nitrate, phosphate, density, and temperature at the surface and depth. These relations in the Gulf of Maine and other areas are discussed in detail. Redfield and Keys (1938) presented 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 m., while in September the concentration of ammonia was uniform at all depths. In the strong tide ways of the deep channels ammonia was distributed uniformly 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 marked the location and intensity of organic decomposition.

Redfield (1948) estimated the seasonal variation in the magnitude of oxygen exchange across the sea surface as it occurs in the Gulf of Maine and evaluated the factors responsible for this exchange. He determined the quantity of dissolved oxygen to a depth of 200 m. and inorganic phosphate to a depth of 100 m. at stations in a 35-mile square area in the western basin of the Gulf from July 1933 through September 1934. He estimated that about 30×10^4 cc. of oxygen per $m.^2$ leaves the surface of the Gulf of Maine between the end of October and the latter part of March and that a similar amount enters during winter. Of the annual exchange across the sea surface he attributed only two-fifths to net production or consumption of oxygen by organisms. The remainder presumably resulted from the effects of temperature on the solubility of oxygen. In spring the production of oxygen in photosynthesis was sufficient to account for the entire surface exchange; during summer the exchange was attributable to decreasing solubility because of warming; in late fall and winter, excess oxygen consumption and increasing solubility caused the exchange. He estimated the exchange coefficient of oxygen to be 13×10^6 cc. per $m.^2$ per atmosphere per month in winter and 2.8×10^6 in summer. These seasonal differences were attributed to differences in sea surface conditions.

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 "Fishes of the Gulf of Maine" (Bigelow and Welsh, 1925). Bigelow and Schroeder (1936) published a supplement containing data on the abundance, distribution, breeding habits, and food habits of 88 species of cartilaginous and bony fishes and a revised key to the skates and rays.

Redfield, Smith, and Ketchum (1937) determined the distribution of phosphorus present as inorganic phosphorus, as dissolved organic compounds, and as particulate matter 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. They reported on the cycle of phosphorus throughout the year and on the methods for analyzing quantitatively the factors producing seasonal changes in the distribution of such a compound.

Ketchum and Keen (1953) studied 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. They determined the distribution of river water within the Bay of Fundy and in Passamaquoddy Bay and evaluated the rate of transport of river water. They also made empirical calculations of exchange ratios and of total accumulation of river water. 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, researchers on 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 associated fishes. Bigelow and Schroeder (1939) reported on the faunal community of the water just above these deep-mud bottoms. The most significant faunal contrast noted was that P. borealis had a well-marked center of population in the deep bowl west of Jeffreys Ledge where bottom currents are weak and 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 during a study of the productivity of George Bank 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. Clarke, Pierce, and Bumpus (1943) gave the dates of these cruises and the station numbers and locations. A discussion of papers concerned with the distribution, abundance, and ecology of zooplankton and phytoplankton based on information collected during these cruises follows.

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 was given by Riley (1941). His report includes an analysis of the methods of measuring phytoplankton which shows that the plant pigment method gives results most nearly representative of the abundance of phytoplankton. The main body of this work concerns 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 has marked seasonal and regional variations, that the quantity of plant pigments was lowest and of nutrients highest in January, that the spring diatom bloom 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. He discussed the seasonal cycle of productivity and the physical and biological factors affecting productivity and gave measurements of the mean standing crop of plankton and 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. She obtained water bottle samples of phytoplankton at depths of 1, 10, 30, 50, and 80 m., and determined the number of cells per 0.1 $m.^2$ of sea surface. These data show that the period of diatom abundance was more prolonged on Georges Bank than in most parts of the Gulf of Maine, and that production generally 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 extensive statistical analysis of the relation 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 m.) based on observations made during March, April, and May, 1941. He found the relation between plankton and stability zero in March, positive in April, and negative in May. Data from the 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 turbulence. He discussed the reasons for the seasonal change in the relation of plankton abundance to stability.

As a continuation of these studies, Riley (1943) compared laboratory experiments on the growth of Nitschia closterium (= Phaeodactylum tricornatum) 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. He described the growth curves of the laboratory culture of Nitschia under varying conditions of light, temperature, and nutrients and discussed the relative importance of certain chemical and physical factors at different stages of the population cycle. In a parallel study on natural populations on Georges Bank, he found that many of the species passed through a population cycle similar to the laboratory culture of Nitschia, and noted similarities in the relations of the population curves with respiration and photosynthetic activity. He discussed generally the 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 11 Atlantis cruises was made by Clarke, Pierce, and Bumpus (1943). They found the greatest concentrations of S. elegans within the central homogeneous water mass of the bank throughout the year; this 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. They compared the distribution of S. elegans to that of two species of copepods, Calanus finmarchicus and Pseudocalanus minutus.

Riley and Bumpus (1946) discussed phytoplankton-zooplankton relations on Georges Bank based on estimates of the abundance of total phytoplankton and of total and of individual species and genera of zooplankton from September 1939 through June 1940. They demonstrated a significant inverse relation between the horizontal distribution of phytoplankton and total and individual species of zooplankton and presented evidence that grazing caused this inverse relation. They suggested that turbulent mixing tended to redistribute the populations so that correlation was not fully developed. They attempted on theoretical grounds to determine grazing rates and to estimate the effect of turbulent mixing on the populations of zooplankton and phytoplankton.

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 at which variations in the horizontal distribution of plant pigments during each of the 1939-40 cruises are calculated according to variations in depth, temperature, phosphate, nitrate, and zooplankton. Thus, it is possible to determine the amount of variation in phytoplankton crop obtained by varying any one or all of these environmental factors. He evaluated also the seasonal cycle of phytoplankton from a more theoretical standpoint and derived an equation expressing the seasonal rate of change of the phytoplankton population.

Using data from the 1939-41 Georges Bank cruises, Clarke (1946) illustrated an application of the basic concepts of productivity (standing crop, material removed, and production rate) to a marine area. His diagrams illustrate the interrelations between the processes of production, consumption, and decomposition at the various levels of the ecological complex. He presented values for the standing crop and the net production of phytoplankton and zooplankton and discussed the controlling influence of light and currents. He compared values for the yield of the commercial catch of fish with yields from fresh-water and terrestrial areas.

Riley (1947) made a theoretical analysis of the seasonal cycle of zooplankton on Georges Bank. He established an equation in which the rate of change of the herbivore population in respect to time equals the difference between the rate of assimilation of organic material by feeding on phytoplankton and the rate of dissipation by respiration, predation, and other losses. He assigned numerical values to the constants in the equation, and constructed a theoretical curve for the herbivore seasonal cycle which generally agreed with the observed population.

The final paper to be published on the 1939-41 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). He gave a detailed account of the abundance, distribution, and species composition of the predominating species, and discussed the effects of drift, temperature, and depth on distribution.

During World War II, WHOI personnel engaged principally in studies for the Navy. During the postwar years, they shifted emphasis 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 WHOI during the 1940's were in connection with a study of shallow-water benthonic Foraminifera off Portsmouth, N.H., during the summer of 1946. The area covered extended from Ipswich Bay to Portsmouth and to approximately 30 miles offshore on the north and 18 miles offshore to the south. Over 700 bottom samples were obtained in a gridwork of stations spaced approximately 1 mile apart. Phleger (1952) discussed the distribution and ecology of the Foraminifera in the area, and Parker (1952) described the species of Foraminifera.

Using the newly commissioned Albatross III, the Fish and Wildlife Service in 1948 initiated surveys of the populations of groundfish on the New England fishing banks. During these cruises, data were obtained on the distribution and abundance of the various species of groundfish and other bottom fauna and the distribution of temperature and bottom sediments. Using data collected on Albatross III cruises made in the summers of 1948 and 1949 and in the spring of 1950, Colton (1955) analyzed the distribution of haddock (Melanogrammus aeglefinus) on Georges Bank by age, area, depth, and bottom type. The age composition and the abundance of haddock varied 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 predicting the brood strength of Georges Bank haddock which used geostrophic wind data from February through April and Nantucket winter air temperatures. He based the brood strength estimate on the commercial catch of 3-year-old haddock. He assigned "damage counts" 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 1928-51.

Using monthly observations at three different layers (0-25 m., 25-75 m., and 75-90 m.) obtained at a station in the outer Quoddy Region from 1924 to 1952, Bailey, MacGregor, and Hachey (1954) analyzed the annual variations of temperature and salinity in the Bay of Fundy. They showed normal temperature, salinity, and T-S curves for the three different layers. 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 to 32.5‰ for the surface layer and from 31.9 to 32.8‰ for the bottom layer. The stability of the water column reached two maxima, one in May and the other in August.

McLellan's papers (1954a, 1954b, 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, T-S relations, and mixing processes on the Scotian Shelf based on seasonal observations made during 1950, 1951, and 1952, and describe 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. On the basis of investigations carried out by the Atlantic Oceanographic Group during the period 1950-52 and in previous years, McLellan described in detail the T-S characteristics, rate of production, and currents of the slope water.

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 1953, the 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. The Albatross III made cruises during the spring of 1953, 1955, 1956, and 1957. The procedure involved Continuous Plankton Recorder tows at the surface and 10 m., T-S observations, drift bottle releases, and meter net tows. Marak and Colton (1961) described the methods and operational procedures pertinent to the surveys of 1953, 1955, and 1956. They presented in tabular and graphic form the basic data on the distribution of fish eggs and larvae of all species and surface temperature and salinity for the 1953 cruises. Marak, Colton, and Foster (1962) gave the basic data for the 1955 cruises; and Marak, Colton, Foster, and Miller (1962) for the 1956 cruises. In 1956, the U.S. Fish and Wildlife Service in cooperation with the Fisheries Research Board of Canada began a similar program of study of the early life history of herring (Clupea harengus) in the Gulf of Maine. In these surveys they used the vessels Albatross III, Silver Bay, Delaware, and Harengus and made cruises from September through February in 1956-57 and 1957-58. A summary of papers describing the results of various phases of these two investigations follows.

Bumpus, Chase, Day, Frantz, Ketchum, and Waldan (1957) launched radio drift buoys in the Trinity Ledge area off Yarmouth, Nova Scotia; in Grand Manan Channel, and off Cape Spencer, New Brunswick, in October, November, and December, 1956. The 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.

Day (1958) described the surface circulation patterns in the Gulf of Maine from late February through June as deduced from drift bottles. The greater bulk of these drift bottle releases was 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, and the Atlantis cruises in April 1934 and June 1933 also are included. Bumpus and Day (1957) tabulated the basic data used in this paper. They noted seasonal and yearly differences in surface circulation and showed 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. They demonstrated that winds may strongly modify the prevailing circulation and that this accounted for the marked differences between conditions in the 1930's and 1950's.

Tibbo, Legaré, Scattergood, and Temple (1958) analyzed 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. They determined the spawning areas and seasons and presented data on the length composition, growth rate, 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. They concluded that spring spawnings are of minor importance and that late summer and fall spawnings are the major contributors to the herring stocks in the Bay of Fundy and Gulf of Maine.

Colton (1959) noted that the mortality of marine fish larvae resulted from warming because of the intrusion of slope water over the southern edge of Georges Bank during May 1956. He described the hydrographic conditions occurring at that time, and discussed 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. Most of the bottles were launched during the 1953-58 larval fish surveys, but data are also included concerning drift bottles released before this period as well as bottles launched monthly from Lurcher Lightship during 1957 and 1958. His analysis shows 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. By September, the flow again contracts toward the minimum. He gave evidence 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 (Gadus callarias), haddock, and pollock (Pollachius virens) taken in 1-m. net tows during the 1953-57 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, while 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.

Colton, Honey, and Temple (1961) analyzed in detail meter-net and Continuous Plankton Recorder material collected during the larval herring surveys in the fall and winter of 1956-57 to determine the efficacy of the sampling techniques in estimating the abundance and distribution of larval herring. Their analysis shows 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 resulted from escapement of the larger larvae from the meter nets during daylight hours. They 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 m. during both 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 m. of water.

Colton and Temple (1961) examined the spawning of commercial fish species in the Gulf of Maine on the basis of observations made during the larval haddock and herring surveys of 1953-58. They discussed the effects of offshore drift, time and location of spawning, vertical distribution of eggs and larvae, and length of pelagic life on the dispersal and survival of eggs, larvae, and juveniles. 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, they 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.

Colton (1961) and Colton, Temple, and Honey (1962) reported the occurrence of tropical fish larvae and oceanic copepods in the Gulf of Maine during September, October, and November, 1956 and January 1957. They collected considerable numbers of eyed flounder (Bothus ocellatus) and myctophid postlarvae and observed a marked correlation between the distribution of these tropical fish larvae and temperature. They found 22 species of oceanic copepods and fragments of Gulf weed (Sargassum natans) 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 summary of other papers concerned with the oceanography of the Gulf of Maine emanating from observations made during the 1950's follows. Wigley (1956) studied 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 from April 1953 to February 1954. The 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. He observed marked regional differences in the stomach contents, but did not find seasonal trends in diet composition.

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 off New England based on an analysis of data from shore stations as well as from the offshore waters of the Gulf of Maine. They demonstrated a long-term upward trend since about 1900 in winter air and sea surface temperatures. 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 a general alteration of the faunal characteristics of the Gulf of Maine did not accompany the upswing in temperature.

Bumpus (1957a) tabulated monthly and annual mean surface water temperatures for shore stations and lightships between Nantucket and Eastport for the period of record through 1955. Bumpus (1957b) and Day (1959a, 1959b,

1960) tabulated 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 Shoal Lightships for 1956, 1957, 1958, and 1959. They plotted mean temperatures for each level for three equal time periods per month as time profiles for the year for each station. They plotted also the 10-day mean surface temperature and the 10-day mean surface salinity and the weekly mean bottom salinity values for each station and discussed the general hydrographic conditions at each station.

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 practically devoid of locally produced plankton, and the few species present were estuarine 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, was associated with the low productivity of the area.

Wigley (1960) described the distribution and the temperature - bottom sediment relations 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. Dichelopandalus leptocerus was found over the entire area, in a wide range of depth 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.

Chevrier and Trites (1960) described the seasonal pattern of surface circulation in the Quoddy Region and contiguous areas of the Gulf of Maine on the basis of drift bottle releases in the period January 1957 through December 1958. In the outer Quoddy Region, the nontidal drift was usually southerly. Surface waters leaving the area moved outward between the Wolves and Point Lepreau, then southward off the eastern side of Grand Manan Island. The final movement was 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 Texas Tower No. 2 on Georges Shoal during 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. Wigley (1961a) described the particle size composition, type, sorting, organic content, shell content, and color of the sediments in various regions of Georges Bank. He discussed (1961b) the distribution and abundance of benthic fauna in relation to the sediment and geographic location. Four major taxonomic groups (Crustacea, Mollusca, Echinodermata, and Annelida) composed the bulk of Georges Bank benthic fauna. Pronounced differences in faunal abundance and species composition in relation to geographic location and bottom sediments were observed.

Kelly and Barker (1961) discussed the results of a study of the vertical distribution of young redfish (Sebastes marinus) during the summers of 1957 and 1958. A midwater trawl was towed at a series of depths from the surface to 150 m. at stations in the southwestern part of the Gulf of Maine. These data do not show diurnal vertical movements of the planktonic larvae. Newly spawned larvae concentrated in the upper 10 m. of water, 10 - 20 mm. larvae concentrated at 20 m. and within the thermocline, and fish exceeding 25 mm. concentrated in deeper water below the thermocline. The length of the redfish that had moved to the bottom was between 40 and 50 mm.

Miller, Colton, and Marak's paper (1963), the final one to be published based on observations made in the Gulf of Maine during the 1950's, was a study undertaken in May 1958 of the vertical distribution of larval haddock at three locations on Georges Bank. Modified Hardy plankton samplers towed at 7 knots for 30 minutes at depths of 1, 10, 20, 30, 40, 50, and 75 m. collected simultaneous samples of larvae at 2-hour intervals. The results showed that the sampling technique employed eliminated differences in the day and night catches resulting from avoidance, and that although haddock larvae were found throughout the upper 50 m. of the water column, maximum concentrations occurred between 20 and 30 m. Over 80 percent of the larvae occurred within the depth limits of the thermocline. There was no indication of a diurnal change in depth distribution, although periodic changes in larval depth coinciding with periodic fluctuations in the depth of the thermocline were demonstrated.

SUBJECT INDEX TO LITERATURE CITED

An index to the literature cited according to seven general subject headings is given in table 1.

Table 1.--Subject index to literature cited

Subject	Reference number
Circulation	3, 16, 17, 18, 19, 21, 33, 37, 50, 54, 59, 66, 67, 69, 70, 71, 74, 79, 80, 82, 96, 100, 101
Chemistry and Physics	1, 3, 12, 13, 14, 15, 38, 39, 40, 49, 63, 64, 65, 67, 68, 69, 74, 76, 78, 81, 83, 84
Zooplankton	2, 5, 22, 23, 24, 25, 26, 27, 34, 42, 43, 44, 45, 46, 53, 56, 72, 79, 80, 81, 85, 86, 90, 91, 100, 103
Phytoplankton	2, 4, 10, 36, 48, 49, 60, 61, 87, 88, 89, 91, 92
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Fishery Hydrography	6, 8, 9, 20, 29, 30, 31, 32, 33, 41, 47, 55, 58, 62, 63, 64, 65, 72, 97, 98, 101, 104
Geology	11, 35, 52, 56, 71, 73, 93, 94, 95, 99, 107

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