INTRODUCTION

This memoir is the third and final part of the general report on the oceanographic survey of the Gulf of Maine.[1]

Key charts to the stations will be found in the preceding part of this volume (Bigelow, 1926, figs. 1–9); the dates and positions are tabulated below (p. 976) with the physical data.

The chapter on hydrodynamics has been made possible by Lieut. Commander E. H. Smith's collaboration; R. Parmenter tabulated the physical data for the *Fish Hawk* cruises of 1925, collaborating also in the charts and discussion based thereon.

Records of temperature or salinity have been contributed by R. A. Goffin, Wm. C. Schroeder, Capt. G. W. Carlson, Capt. G. W. Greenleaf, C. G. Corliss, and Dr. C. J. Fish of the Bureau of Fisheries. Capt. John W. MacFarland, from his schooner *Victor*, and Henry Stetson and T. C. Graves, from their yachts, also have taken welcome observations.

I owe a debt of gratitude also to Dr. A. G. Huntsman, who has generously allowed quotation from his report on Canadian drift-bottle experiments in advance of publication, and who contributed other data acknowledged in the appropriate connections; to Dr. J. P. McMurrich, who has offered the use of his unpublished data on temperatures at St. Andrews, New Brunswick; and to the late Dr. A. G. Mayor, who contributed the colorimetric tubes used in the determination of alkalinity on the *Albatross* and *Halcyon* cruises of 1920–21.

OCEANOGRAPHIC HISTORY

1. GULF OF MAINE PROPER

The first Gulf of Maine temperatures, so far as I can learn, were taken in October, 1789, by Benjamin Franklin's nephew, Jonathan Williams, who read the "heat of the air and water at sunrise, noon, and sunset" (1793, p. 83) on a voyage from Boston to Virginia, and found the surface 8.9° C. (48° F.) off the mouth of Massachusetts Bay on October 11, warming to 11.1° (52° F.) off Chatham on Cape Cod, to 15° (59° F.) over the outer part of the continental shelf south of Nantucket, and to 18.3°–19.4° (65° to 67° F.) in the inner edge of the Gulf Stream outside the edge of the continent on the 13th—readings that agree very well with the usual distribution of temperature for that season. On another voyage (from Halifax to New York) during the last week of July, 1790, he again took temperatures on Roseway Bank, Browns Bank, and in the gully between them; also along the southern side of Georges Bank (53° to 64° F.).

Enough readings of the surface temperature of the Gulf of Maine had accumulated during the first half of the nineteenth century to permit Maury (1855 and 1858) to show its coastal belt and the Bay of Fundy as between 50° and 60°, its southern side out to the continental edge as between 60° and 70° in July, and the entire gulf as colder than 50° in March.[2]

[1] The first part was devoted to the fishes (Bigelow and Welsh, 1925); the second to the plankton (Bigelow, 1926).

[2] Petermann (1870) more correctly interprets the individual readings reproduced on Maury's (1852) thermal chart by showing the inner parts of the Gulf of Maine as 54.5° to 59° and the Georges Bank-Nantucket Shoals region as about 59° to 65.5° in July about 32° and 32° to 41°, respectively, in January

The first attempt to measure the temperature of the gulf below the surface was made in the summer of 1870, when Verrill (1871, p. 3) found the water virtually homogeneous, surface to bottom, in Passamaquoddy Bay, though readings with thermometers of the maximum-minimum type established a considerable range of temperatures on the offshore slope of Georges Bank (Verrill, 1873; Sanderson Smith, 1889, p. 887).

Two summers later surface and bottom temperatures were taken at a large number of stations in the neighborhood of Casco Bay from the Fish Commission steamer *Blue Light* (Verrill, 1874, 1874a), and also at various localities in deep water in the western side of the gulf by the Coast Survey steamer *Bache* (Sanderson Smith, 1889, p. 885; Packard, 1876). As a result of this summer's work Verrill was able to bring to scientific attention the contrast between the low bottom temperature and the warm surface of the western side of the gulf.

The survey was continued by the *Bache* in the summer of 1874 at about 40 dredging stations in the western side of the Gulf of Maine, in depths of 27 to 113 fathoms (Sanderson Smith, 1889, p. 886). No observations were taken in the gulf in 1875 or 1876; but in 1877 the Fish Commission, from the *Speedwell*, in connection with a survey of the bottom fauna, took surface and bottom temperatures in the northern part of Massachusetts Bay, with serial observations at several stations on a line crossing the gulf to Cape Sable.

Unfortunately, none of the subsurface temperatures taken in the gulf up to that date were even approximately dependable, according to present-day standards, because the Miller-Casella thermometers employed were not only unreliable (Verrill, 1875, p. 413), but, being of the maximum-minimum type, they would register merely the lowest temperature at each station, which was not necessarily at the level at which the reading was ostensibly taken. Modern oceanographic research in the gulf may therefore be dated from the summer of 1878, when the *Speedwell* took temperatures in Massachusetts Bay and off Cape Ann, including serials at 31 stations (Sanderson Smith, 1889, p. 905; Rathbun, 1889, p. 1005), with reversing thermometers. This type, improved from time to time, has been employed regularly ever since. The *Speedwell* worked again in the gulf in the summer of 1879 (Sanderson Smith, 1889, p. 909; Rathbun, 1889, p. 1006). In June, 1880, the *Blake* took surface and bottom readings at three stations inside the 200-fathom contour on the eastern part of Georges Bank (Rathbun, 1889, p. 972, and A. Agassiz, 1881), while in August the *Fish Hawk* obtained similar data off Chatham, Cape Cod, in 10 to 43 fathoms (Rathbun, 1889, pp. 922–923), but did not visit the more northern parts of the gulf.

The year 1882 is an important one in the annals of North American oceanography, because that spring saw the oft-quoted destruction of the tilefish [3] and of the invertebrate fauna that inhabited the warm band along the edge of the continent, presumably by flooding with very cold water. During the following August the *Fish Hawk* took observations south of Marthas Vineyard and made one trip to the 100-fathom line east of Cape Cod (Rathbun, 1889, p. 925).

Surface and air temperatures were recorded from early spring to late autumn at several lighthouses and lightships along the coast of the gulf from Nantucket Shoals to Petit Manan during the years 1881 to 1885, the 10-day averages of which are

[3] For an account of this event and of the gradual reestablishment of the species see Bigelow and Welsh, 1925.

tabulated by Rathbun (1887). The very large number of temperatures taken on the lightships in the ordinary routine since that time have not been examined critically, however.

The *Albatross* occupied a large number of dredging stations along the offshore slope of Georges Bank during 1883, 1884, 1885, 1886, and 1887, but only five of her serial readings and a few of the bottom records fall within the limits of the Gulf of Maine.[4] An extensive series of temperatures taken by Dr. W. C. Kendall at the surface and at small depths in the western part of the gulf, in connection with mackerel investigations carried out by the *Grampus* in 1897, also deserves mention (p. 594).

A gap follows in the thermal history of the gulf until the summer and autumn of 1904, when the Tidal Survey of Canada took a large number of surface and subsurface temperatures in the Bay of Fundy region and off the west coast of Nova Scotia (Dawson, 1905, 1922). Many of these were repeated in 1907. In July, 1908, a few readings were taken from the *Grampus* in the region of Nantucket Shoals.

The reestablishment of the biological station of the Biological Board of Canada at St. Andrews, at the mouth of the St. Croix River, in 1908 marks an epoch in the oceanographic study of the Bay of Fundy region. The first published survey of the temperature and density (the latter determined by hydrometer) in the neighborhood of St. Andrews was carried out in July, 1910 (Copeland, 1912). Since then the taking of temperatures and of salinity has been a regular part of the station's work, and such of the data as have been published are mentioned below.

Although the preceding summary may seem somewhat formidable, very little was yet known of the subsurface temperatures of the offshore parts of the gulf, even in summer, for only one small area in its western side had been examined with satisfactory instruments. Nor had anything been learned of its winter state or of the salinity of its deep waters at any time of year until 1912. In that year the United States Bureau of Fisheries and the Museum of Comparative Zoology jointly undertook the general oceanographic exploration of the gulf, which, continued to date under my direction, has been the foundation of this report and of those that have preceded it (Bigelow, 1914 to 1926; Bigelow and Welsh, 1925).

The first fruits were the serial records at 46 stations (10001 to 10046) in the northern half of the gulf during that July and August (p. 978; Bigelow, 1913, 1914), including the first determinations of the salinity of the water of the gulf by the titration method (p. 976) that for some years had been in general use on the other side of the Atlantic. This, subsequently, has been a routine part of our station work. Observations were taken bimonthly off Gloucester by the *Blue Wing* during the winter of 1912–1913; north of Cape Cod during the following spring by W. W. Welsh (stations 10047 to 10056; W. W. Welsh stations 1 to 32; and Bigelow, 1914a); also a few temperatures and water samples between Massachusetts Bay and Georges Bank by Thomas Douthart and W. F. Clapp (table, p. 980).

The *Grampus* carried out a general survey of the western and northern parts of the gulf in the summer of 1913 (stations 10057 to 10061, 10085 to 10112, p. 982; Bigelow, 1915), as well as of the coastal waters between the longitudes of Marthas Vineyard and Chesapeake Bay. This was followed by a more comprehensive oceanographic examination of the offshore banks, as well as of the inner parts of the gulf and of the coastal

[4] For these *Albatross* data see Townsend (1901, dredging stations 2053, 2054, 2060–2064, 2068, and 2522).

shelf eastward along Nova Scotia to Halifax in the summer of 1914 (stations 10213 to 10264, p. 985; Bigelow, 1914b, 1917). Temperatures and water samples (density of the latter determined by hydrometer) were taken at many localities in the Bay of Fundy region that summer and the following winter from the biological station at St. Andrews (Mavor, Craigie, and Detweiler, 1916; Craigie, 1916, 1916a; McMurrich, 1917; and Doctor McMurrich's unpublished plankton lists). In 1915 the *Grampus* cruised in the gulf from spring to midautumn (stations 10266 to 10339, p. 987; Bigelow, 1917). Craigie (Craigie and Chase, 1918) likewise took serial temperatures in the Bay of Fundy, in Annapolis Basin, and in St. Marys Bay, as well as salinities in the latter (Vachon, 1918).

That same summer is memorable in oceanographic annals for the general survey of eastern Canadian waters carried out by the Canadian Fisheries Expedition (Hjort, 1919; Sandström, 1919; Bjerkan, 1919). This, however did not touch the Gulf of Maine region except for one profile crossing the shelf off Shelburne, Nova Scotia, in July.

It is a fortunate chance that the western and southwestern parts of the gulf, on the one hand (stations 10340 to 10357, 10398 to 10404; Bigelow, 1922[5]), and the Bay of Fundy, on the other (Vachon, 1918), both were studied in 1916, for that summer and autumn followed an almost Arctic winter and a backward spring.

Exploration of the offshore waters of the Gulf of Maine was interrupted by the war, except that serial observations were taken at a station between Grand Manan and Nova Scotia by the St. Andrews station at intervals from 1916 to 1918.

In 1919 work was resumed, when the United States Coast Guard cutter *Androscoggin*, on ice patrol, ran profiles across the gulf in March, April, and May (United States Coast Guard stations 1 to 3, 19 to 22, 35 to 38, p. 997; E. H. Smith, 1924, p. 103), while Mavor (1923) made an oceanographic survey of the Bay of Fundy in August. Study of the surface currents of the Bay of Fundy by drift bottles also was inaugurated by the St. Andrews station during that summer (Mavor, 1920 to 1923), and later was expanded into a joint project to cover northeastern American waters generally.

Prior to 1920 attention had been directed chiefly to the state of the gulf during the warm half of the year. To remedy this seasonal deficiency the *Albatross* carried out a general survey of the entire region from February to May, 1920 (stations 20044 to 20129, p. 998; United States Bureau of Fisheries, 1921), while the *Halcyon* cruised in the northern half of the gulf during the following December, January, and March. The *Halcyon* also occupied a net of oceanographic stations in Massachusetts Bay during August, 1922, and has made scattered observations at various seasons since then (stations 10631 to 10645, p. 995, and unnumbered stations, p. 1012). Finally, the *Fish Hawk* took temperatures and salinities at many stations in Massachusetts and Cape Cod Bays at intervals during the winter and spring of 1924–25 (p. 1004).

The following lines of drift bottles have been set out in the Gulf of Maine since 1919: July, 1922, one line running southeasterly from Cape Elizabeth to the center of the gulf; another from the southern angle of Cape Cod southeasterly out across the edge of the continent; and likewise a line off New York. A line also was set out

[5] The operations of the *Grampus* in 1916 were in the immediate charge of W. W. Welsh.

off Cape Sable that summer by the Biological Board of Canada, besides several other lines farther east (p. 908). During August, 1923, lines of bottles were set out normal to the coast line off Mount Desert, Cape Elizabeth, Cape Ann, and Cape Cod (p. 874); and a much larger number of bottles was put out in more eastern Nova Scotian waters by the Biological Board of Canada, some of which have drifted to the Gulf of Maine, as described below (p. 908). No bottles were put out in the Gulf of Maine proper in 1924, although lines were run across Vineyard and Nantucket Sounds. Some of the many Canadian bottles put out that summer off the outer coast of Nova Scotia have been picked up in the Gulf of Maine. Finally, bottles were put out in Massachusetts and Ipswich Bays in February, April, and May, 1925; in Massachusetts Bay again by Henry Stetson in April, 1926, and off Cape Nedick by T. E. Graves that July, from their yachts (pp. 878, 879).

The measurements of currents, which have been taken in the gulf by the Tidal Survey of Canada and by the United States Coast and Geodetic Survey, are mentioned in a later chapter (p. 857).

2. CONTINENTAL SHELF SOUTH OF NANTUCKET AND MARTHAS VINEYARD

The earlier explorations in this area are summarized in a previous report (Bigelow, 1915), hence they may be passed over briefly here.

The general range of surface temperature south of Woods Hole is now well known for the summer season, thanks to the early explorations by the vessels of the Bureau of Fisheries, notably in 1880 to 1882 (Tanner, 1884 to 1884b) and in 1889 to 1891 (Libbey, 1891, 1895). Daily records of temperature of air and water also have been recorded for many years at Woods Hole,[6] and observations have been taken on the various collecting trips carried out summer after summer from that station. Dickson (1901) likewise has collected a large number of surface temperatures from the logs of vessels, and the *Grampus* has crossed this part of the continental shelf on several recent cruises.

A large number of subsurface temperatures and determinations of salinity by hydrometer also have been taken from Marthas Vineyard and Nantucket out to the edge of the continent and beyond, beginning with the early dredging trips of the vessels of the Fish Commission (1880 to 1881[7]) and continued by Libbey in 1889, 1890, and 1891. Libbey continued his study in subsequent years, but the results never have been published; nor, except in a few instances, have the bottom temperatures taken subsequently on the various dredging trips sent out to the waters south of Marthas Vineyard from the Woods Hole station of the Bureau of Fisheries.

In 1908 the *Grampus* took temperatures in 31 to 400 fathoms southward from Nantucket Shoals (p. 595; Bigelow, 1909). In July, 1913, she occupied several oceanographic stations in that general region, working southward thence to Chesapeake Bay (Bigelow, 1915; stations 10062 to 10084). During that August she took surface temperatures from Cape Cod to Cape May (Bigelow, 1915, p. 350); in 1914

[6] These are summarized by Sumner, Osburn, and Cole (1913) and by Fish (1925).

[7] For records of temperature during this period, see Sanderson Smith (1889); for the *Albatross* stations, see Tanner (1884a, 1884b) and Townsend (1901).

and 1915 she ran oceanographic profiles across the slope abreast of Marthas Vineyard in August and October, mentioned above (p. 517). In 1916 she again made summer and November cruises from Gloucester to Chesapeake Bay (Bigelow, 1922).

TOPOGRAPHY

The indentation of the coast between Cape Sable, at the southeast angle of Nova Scotia on the east, and Cape Cod and Nantucket Island, on the west, seems to have gone unnamed until late in the last century, when it was christened "Gulf of Maine." As outlined by the coast, the gulf is roughly rectangular, much wider (about 200 miles) than deep (about 120 miles). It is a far better marked natural province below the surface of the sea than the shallow recession of its shore line would suggest, for its southern boundary is marked by a shallow rim, or "sill," pierced by three narrow passages only. Passing eastward from Nantucket, with its off-lying shoals, these, successively, and the banks that separate them, are: The South Channel (not very well defined and only 40 to 50 fathoms deep), Georges Bank, the Eastern Channel, Browns Bank, the Northern Channel, and finally the Seal Island or coastal bank off Cape Sable. This rim, as Mitchell (1881) long ago pointed out, 259 miles in length from Nantucket to Cape Sable, follows, in its main outlines, the arc of a circle whose radius is about 167 miles. Along this arc the length of Georges Bank, from the deepest trough of the South Channel to the 50-fathom contour on the slope of the Eastern Channel, is about 140 miles, with a greatest breadth of about 80 miles from north to south between the 50-fathom contours. Between these same contours of the Eastern Channel and of the Northern Channel each occupies about 25 miles of the arc. In round figures, the area of Georges Bank is 10,000 square miles; that portion of Browns Bank west of longitude 65° 30′ W. (taken as the arbitrary boundary of the region under discussion) is about 550 square miles.

The area of the gulf north of the rim is given by Mitchell as about 36,000 square miles. The coast line of the gulf, as it would appear on a small-scale chart, follows a fairly regular curve, but in detail it is extremely complex; for the northern and eastern shores are not only frequently and deeply embayed, but are bordered by a perfect labyrinth of islands, large and small, extending in places 10 to 20 miles seaward from the mainland. Its largest bays (Massachusetts on the southwest and the still larger Bay of Fundy on the northeast) are too well known to need more than passing mention.

The coast of the Gulf of Maine falls into two main types, Cape Elizabeth marking the transition from one to the other. South of this headland the shore line is characterized by a succession of sand beaches alternating with bold headlands, notably Cape Ann, and with rocky stretches, which in Cape Cod Bay give place to the continuous sand strand of the cape. Along this part of the coast there are but few islands, except in Boston Bay, and the fjord type of indentation is notably absent. East of Cape Elizabeth, on the contrary, the shores of the State of Maine are almost continuously rocky, as are the islands of the outlying archipelago already mentioned; and deep bays succeed each other in close succession as far as the mouth of the Bay of Fundy. As a whole, the shores of the gulf are low, seldom rising to more than 100 to 200 feet in the immediate neighborhood of the sea; but the Camden hills and the mountains of Mount Desert (with the maximum elevation of 1,500 odd feet) are exceptions to this rule, while the cliffs of the north shore of Grand Manan rise to a height of 200 to 300 feet, almost sheer from the water.

DEPTH OF THE GULF[8]

If we take the 50-fathom (virtually the 100-meter) contour as marking the confines between the peripheral and central parts of the gulf (a natural boundary, because this level not only outlines the northern slope of Georges Bank but includes virtually all the outlying islands), the coastal shallows to the east, north, and west and the rim on the south inclose a bottle-necked basin that communicates with the open sea by two narrow channels only—the eastern and northern. The Eastern Channel, at its narrowest point between Georges and Browns Banks, is about 140 fathoms (256 meters) deep along its trough; the Northern Channel is 65 to 80 fathoms (120 to 145 meters), with a maximum of 78 fathoms (143 meters) in the narrows between Browns Bank and the Coast Bank. North of the rim the deepest water (100 fathoms, or 200 meters and over) takes roughly the form of a Y, with its two arms extending westward and northeastward. As these two troughs apparently were unnamed, I have christened them the "western" and "eastern" basins. They join in the southeast corner of the gulf, where they are continuous with the Eastern Channel. As Mitchell (1881) has pointed out, more than 10,000 square miles of the gulf are deeper than 100 fathoms. The gulf is deepest just inside the entrance to the Eastern Channel and close to the northern slope of Georges Bank as a trough some 50 miles long (west and east), with 150 fathoms (275 meters) or more, and a maximum of 184 fathoms (336 meters). There is also a second, smaller bowl, deeper than 150 fathoms (180 fathoms, or 329 meters, maximum) in the inner part of the western branch of the Y, off Cape Ann.

Over the south-central region of the gulf (that is, the region of union of the two arms of the basin) the depth is generally from 100 to 120 fathoms (180 to 220 meters), varied, however, by many shoaler spots of 90 to 100 fathoms and by occasional deeper soundings of 120 to 135 fathoms (220 to 250 meters). The configuration of the bottom makes the fathom a more instructive basis for contour lines than the meter in just this region; for whereas the 100-fathom curve includes the whole basin, the 200-meter contour, though differing so little in actual depth, is much interrupted here by ridges of 180 to 190 meters, obscuring the essential troughlike conformation of the basin. In the western arm of the basin the water is deepest 45 miles east of Cape Ann; in the eastern arm it is deepest in the extreme northeast corner (145 fathoms, or 265 meters). In both branches the general level of the basin floor is from 115 to 130 fathoms (210 to 238 meters).

BANKS AND SINKS

Isolated sinks or pot holes are numerous; indeed, the deeps of the two basins just mentioned are such. Most of these do not fall deep enough below the surrounding bottom to call for any special comment, but three such bowls are so deep

[8] On the ordinary navigational charts of the region, published by the United States Coast and Geodetic Survey and the United States Hydrographic Office, the depths are given in fathoms. Consequently, the following discussion is also in fathoms, but w th the equivalents in meters also stated.

and are inclosed by rims so much shallower that they have been made the field of considerable hydrographic investigation. These, for want of better names, I may christen (1) the Cape Ann sink, lying near Stellwagen Bank, centering about 12 miles southeast of Cape Ann, having a general depth of 50 to 70 fathoms (91 to 128 meters) and a greatest depth of 99 fathoms (181 meters), and inclosed by a continuous rim of 40 fathoms (70 to 75 meters) or shallower; (2) the Isles of Shoals sink, centering 28 miles northeast of Cape Ann, having a general depth of 80 to 100 fathoms (146 to 183 meters), and inclosed on the south and east by the shallows of Jeffreys Ledge and on the north by depths of 60 to 70 fathoms (110 to 128 meters). The Fundy deep, south of Grand Manan Island at the mouth of the Bay of Fundy, is a basin some 27 miles long, with 100 to 112 fathoms (183 to 205 meters) and its deepest spot 165 fathoms (302 meters).

The two arms of the deep trough or basin of the gulf are separated by a roughly triangular area, with depths ranging generally from 70 to 90 fathoms (128 to 165 meters) but rising at its apex (roughly, in the center of the gulf) to within 4½ fathoms (8 meters) of the surface, as the dangerous, rocky shoal known as Cashes Ledge, the patch less than 30 fathoms (55 meters) deep being about 6 miles long in a southwest northeast direction. Other offshore shoals in the gulf proper, which deserve mention here because I shall have occasion to refer to them later as landmarks, are as follows:

1. Stellwagen Bank, lying between Cape Cod and Cape Ann at the entrance to Massachusetts Bay, 9 to 20 fathoms (16 to 37 meters), with deeper channels north and south of it.

2. Jeffreys Ledge, a narrow ridge extending northeasterly from Cape Ann for about 45 miles, with depths less than 50 fathoms (91 meters), shoalest place 18 fathoms (33 meters).

3. Platts Bank, situated about 34 miles east–southeast from Cape Elizabeth, which rises to within 29 fathoms (53 meters) of the surface.

4. Jeffrey Bank, off Penobscot Bay, some 26 miles south of the outermost islet (Matinicus Rock), where there is a small area within the 50-fathom curve with a shallowest depth of 46 fathoms (84 meters).

5. Grand Manan Bank, a small shoal about 7 miles long lying about 18 miles south of Grand Manan Island; general depth 30 to 40 fathoms (55 to 73 meters).

6. Lurcher Shoal, a patch of broken, rocky bottom 1.5 to 20 fathoms (3 to 37 meters) deep, 15 miles off Yarmouth, Nova Scotia.

7. German Bank, a considerable but vaguely defined area west of Cape Sable, with depths of 30 to 35 fathoms (55 to 64 meters) bounding the debouchment of the Northern Channel into the basin of the gulf.

Mitchell (1881) has calculated that the mean depth of the gulf north of the sill, including its navigable bays and tributaries, is about 75 fathoms (137 meters).

The banks that form the southern sill of the gulf have been described frequently, and because of their importance in navigation their main features are summarized in the coast pilots issued by the British and United States Governments. The dimensions and area of Georges Bank, one of the most famous and productive fishing grounds in the North Atlantic, are mentioned above (p. 518). On the southern and eastern parts the depths range, in round numbers, from 30 to 40 fathoms (55 to 73 meters). Over its northwestern one-third the water is shallower, with a considerable but much broken area shallower than 20 fathoms (37 meters), culminating in the dangerous "Georges" and Cultivator Shoals, the former with only 2½ to 10 fathoms (4½ to 18 meters), the latter with 3 to 10 fathoms (6 to 18 meters). Both of these shoals break heavily in stormy weather, and both have proved graveyards for many fishing vessels. According to early rumor (Mitchell, 1881), Georges Shoal has been awash or even dry within historic times; but even as early as 1776 Hollingsworth decided that this tradition had no basis. It is worth noting that there is one well-marked sink situated on the northeast part of Georges Bank, centering at latitude 41° 59′ N., longitude 67° W. Prior to the spring of 1920 this was known (at least officially) from one sounding of 83 fathoms (152 meters) only, with neighboring depths of 30 to 40 fathoms (55 to 73 meters). On March 11 of that year the U. S. S. *Albatross* developed the region by a series of soundings, finding a maximum depth of 120 fathoms (220 meters) and an area of about 27 square miles deeper than 75 fathoms (about 140 meters).

Inside the 50-fathom (90-meter) contour Browns Bank is about 55 miles long from east to west, with an area about 700 square miles and a general depth of 30 to 50 fathoms.

Around most of the periphery of the basin of the gulf the slope is gradual, the 100-fathom (183-meter) curve lying about 12 miles from shore at its closest (off Cape Cod and about as near the outer islands in the northeast corner). The northern slope of Georges Bank is much more abrupt, falling from about 40 fathoms (73 meters) to 100 fathoms (183 meters) in a distance of only 3 to 5 miles.

The Gulf of Maine, with its southern sill, occupies the whole breadth of the Continental Shelf off northern New England and western Nova Scotia, with the south slopes of Georges and Browns Banks falling so steeply to the abyss of the North Atlantic that the zone between the 100 and 1,000 fathom contours (the "Continental Slope") is at one point (longitude about 66° W.) only 4 or 5 miles broad and not more than 20 miles anywhere abreast the mouth of the gulf between the longitudes of 65° and 71°.

WATERSHED

In more or less inclosed coastal seas, where the salinity of the water is influenced greatly by the amount of inflow from rivers and smaller streams, the extent of the watershed and amount of run-off of fresh water demand consideration. The land area tributary in this way to the Gulf of Maine includes something over one-third of the State of Massachusetts, two-thirds of New Hampshire, the entire State of Maine, half of the Province of New Brunswick, a small part of the Province of Quebec, and the northwestern and western coastal strips of Nova Scotia—altogether, in round numbers, some 61,300 square miles. No large rivers empty into the gulf south of Cape Ann; north of that point the chief tributaries, with their approximate drainage areas in square miles, are (1) the Merrimac, 4,553; (2) the Saco, 1,753; (3) the Presumpscot, 470; (4) the Androscoggin, 3,700; (5) the Kennebec, 6,330; (6) the Penobscot, 8,550; (7) the Machias, 800; (8) the St. Croix, 1,630; and (9), chief of all, the St. John, draining no less than 26,000 square miles. That is to say, the nine principal tributaries drain together over 53,000 square miles, or five-sixths of the total watershed.

TEMPERATURE

FEBRUARY AND MARCH

It is most convenient to begin the account of the temperature of the Gulf of Maine with the late winter and early spring, when the water has cooled to its minimum for the year and before vernal warming has proceeded to an appreciable degree.

No definite date can be set for this state because of regional and annual variations, but experience in 1913, 1920, and 1921 suggests that the lowest temperatures are to be expected over the gulf as a whole during the last week of February and first few days of March, except from Cape Sable out to the neighboring part of the basin, where the surface is coldest some weeks later, when the Nova Scotian current is flowing from the east past Cape Sable in greatest volume (p. 832). The temperatures recorded during the February–March cruise of 1920 may not have been the absolute minimum for that year, but the preceding winter had been so cold, with snowfall so heavy, that probably the open gulf is never more than fractionally colder than we then found it. The coastal belt may then be expected to chill below 2° at the surface all around the gulf by the end of winter (fig. 1), its central and offshore parts continuing slightly warmer (about 2.5° to 3.5°). In 1920 a surface tongue equally cold had also developed off southern Nova Scotia by the middle of March, spreading westward across Browns Bank but separated from the coast by slightly warmer (2.2° surface) water close to Shelburne. Present knowledge of the seasonal fluctuations of the Nova Scotian current (p. 832) also make it likely that some such development is to be expected yearly.

SURFACE

The surface temperature falls fractionally below 0° in Cape Cod Bay during winters when ice forms there in any amount. Thus in 1925, for example, the whole column of water in its central and eastern sides, in 12 to 34 meters depth, chilled to $-0.4°$ to $-0.7°$ by February 6 to 7, warming again to 1° to 2° by February 24. Passamaquoddy Bay chills to nearly as low a figure (0.77° at 20 meters, February 23, 1917; Willey, 1921).

If the winter of 1924–25 can be taken as typical (as seems fair, because rather a greater amount of ice formed in Cape Cod Bay than usual, although the air temperatures averaged warmer than normal and the snowfall less), a line from the tip of Cape Cod to Boston Harbor will bound this 0° water in the Massachusetts Bay region. Equally low temperatures no doubt prevail on the surface in the inner parts of the bays and among the islands along the coast of Maine in winters when much ice forms there.

By contrast it is not likely that the surface of the basin of the gulf, including the western part of the Bay of Fundy, ever cools below 2° at any season except for a brief period later in the spring (p. 681), when the surface in the eastern side may be chilled to 0° by the icy Nova Scotian current flowing past Cape Sable from the east. Minimum readings of 3° to 4° are to be expected over the southern side of the basin and on the eastern part of Georges Bank; 4° to 5° over its western half and off its southwestern slope.

An extreme range of about 5° surface temperature thus may be expected over the whole area of the gulf at the end of the winter, and a range of about 4° in its inner parts.

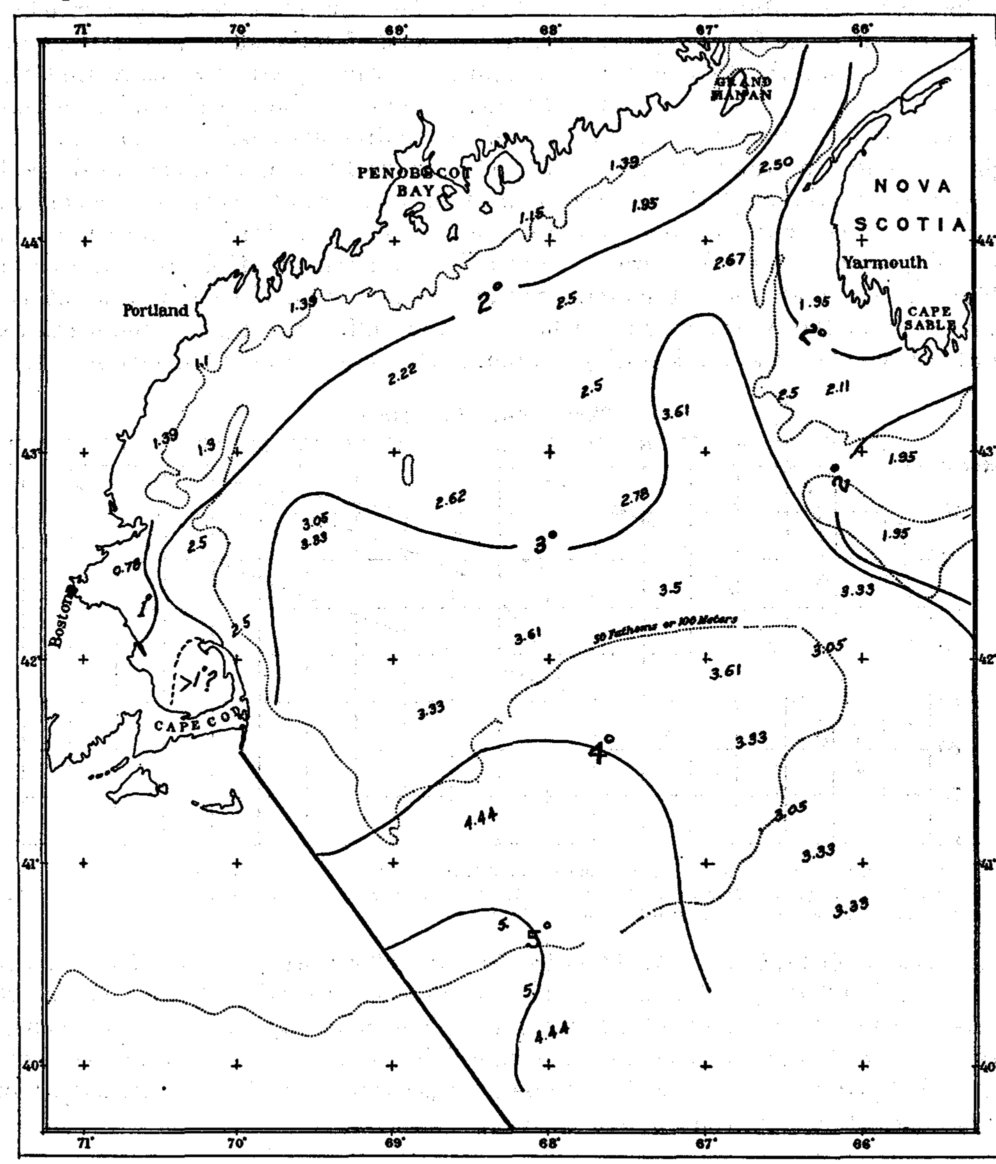

Fig. 1.—Temperature at the surface, February-March, 1920

VERTICAL DISTRIBUTION

At the end of the winter the temperature is very nearly uniform, vertically, down to a depth of 100 meters, rising slowly with increasing depth below that level. This state continues into March, until the climbing sun has warmed the surface appreciably. Whether the water is coldest immediately at the surface or 10 to 20 meters down at the end of February depends on the precise locality, on the state of the weather during the few days preceding, and, locally, on the stage of the tide, a question taken up in connection with the autumnal and winter cooling of Massachusetts Bay (p. 649). Our March cruise of 1920 began a few days after the temperature had passed its minimum for the year, the surface being fractionally warmer than the deeper water; but the temperature was still so nearly uniform vertically that the range was less than 1° in the upper 100 meters at most of the March stations within the outer banks (figs. 2 to 11). Most of the individual stations also showed a slight warming from the 20 to 40 meter level down to 100 meters, except in the sink off Gloucester (station 20050), where the bottom water was fractionally the coldest. Wherever the water was deeper than 100 meters a decided rise in temperature was recorded from that level downward. Thus the temperature off Cape Ann (station 20049) was 2.6° higher at 200 meters than at 100, and from 1° to 3° warmer at 175 meters than at 100 elsewhere in the basin of the gulf. The highest temperatures recorded inside Georges Bank during March, 1920, were at 150 to 250 meters, as fol-

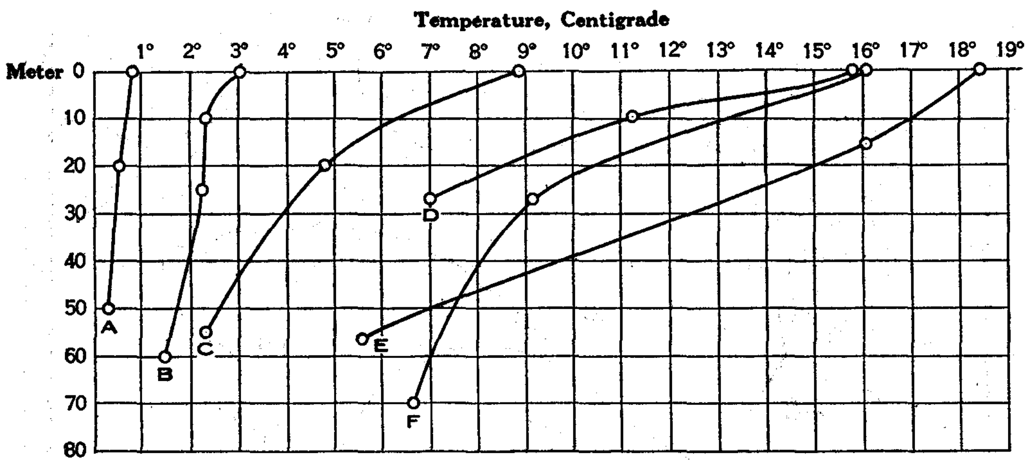

FIG. 2.—Vertical distribution of temperature in the inner part of Massachusetts Bay, March to August. A, March 8, 1920 (station 20062); B, April 6, 1920 (station 20089); C, May 16, 1920 (station 20123); D, August 23, 1922 (station 10632); E, August 23, 1922 (station 10640); F, August 20, 1915 (station 10106)

lows: Station 20049, 5.66° to 5.63° at 180 to 200 meters; station 20053, 5.39° at 225 meters; station 20054, 5.4° to 5.48° at 175 to 250 meters; station 20055, 5.59° at 220 meters; station 20081, 5.39° at 200 meters. Thus, generally speaking, the deepest water of the gulf is the warmest and the superficial stratum the coldest at the beginning of the spring. A glance at the temperature sections (figs. 2 to 11) will show how widely this differs from the summer state.

TEMPERATURE AT 40 METERS

It is probable that the narrow band of 0° to 1° water that skirts the whole coast line from Massachusetts Bay to the Grand Manan Channel on the 40-meter chart for February and March (fig. 12) reflects conditions as they existed at the surface a week or 10 days earlier in the season. Readings higher than 1° everywhere else, even after the unusually severe winter of 1920, make it seem unlikely that the offshore parts of the gulf ever chill below 1° at the 40-meter level. Temperatures of 1° to 2° at 40 to 50 meters in Massachusetts Bay early in February, 1925 (p. 658), contrasting with 0.4° on March 5, 1920 (station 20062), suggest that this stratum is about 1° warmer after a warm winter than after a cold one.

Rising temperature, passing offshore to 2° to 4° over the banks, with an abrupt transition to much higher values (9°) a few miles to seaward of the edge of the continent, is the most instructive general feature of this 40-meter chart. This, however,

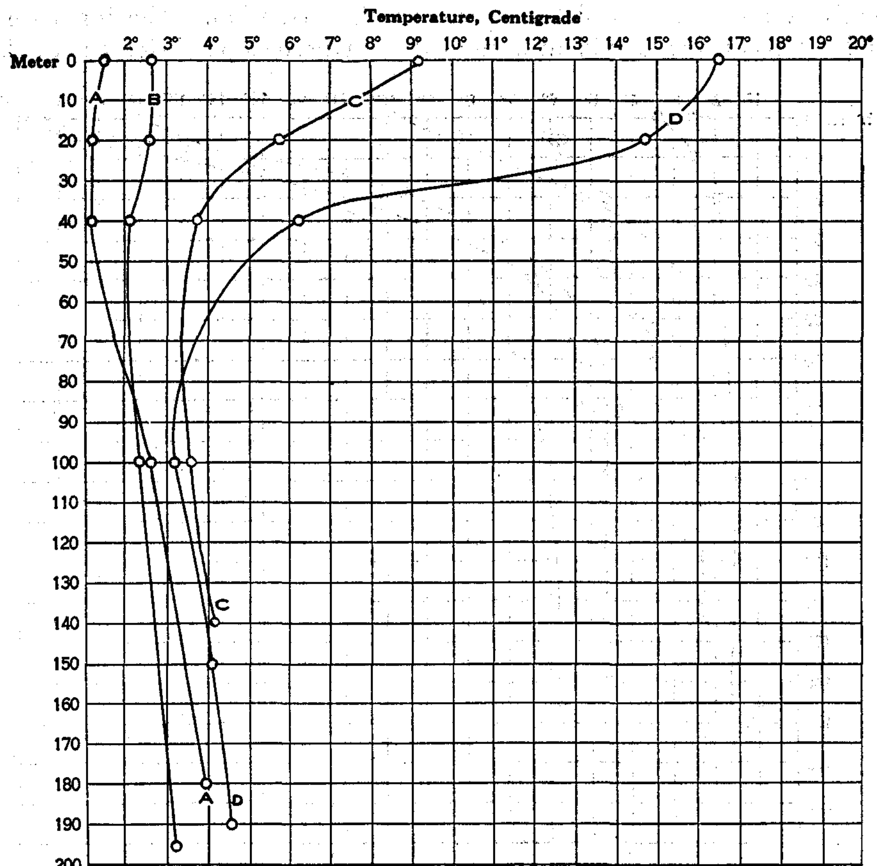

FIG. 3.—Vertical distribution of temperature off northern Cape Cod, March to July. A, March 24, 1920 (station 20088); B, April 18, 1920 (station 20116); C, May 16, 1920 (station 20125); D, July 19, 1914 (station 10214)

was complicated at the time by an expansion of water colder than that across the eastern end of Georges Bank from the neighboring part of the basin, alternating with a warm tongue that intruded inward along the Eastern Channel and a second area of cold (2°) water that reached Browns Bank from the eastward.[9]

[9] A profile run from Shelburne, Nova Scotia, to the edge of the continent in March (stations 20073 to 20077) affords a cross section of this.

TEMPERATURE AT 100 METERS AND DEEPER

In February and March, 1920, the entire basin of the gulf was warmer than 1.5° at 100 meters (fig. 13); all but its northwestern margin was warmer than 2°. The most noteworthy features of the chart for this level are the very striking contrast between the cold inner waters of the gulf (1° to 3°) and the high temperature (7° to 13°) outside the edge of the continent, with the clearly outlined tongue of comparatively warm (4° to 6°) water entering via the Eastern Channel (better defined at this level than at 40 meters) to extend northward and northwestward along the eastern branch of the trough, which deserves special attention. The influence of this warm indraft also is made evident around the northern slope of Georges Bank, west-

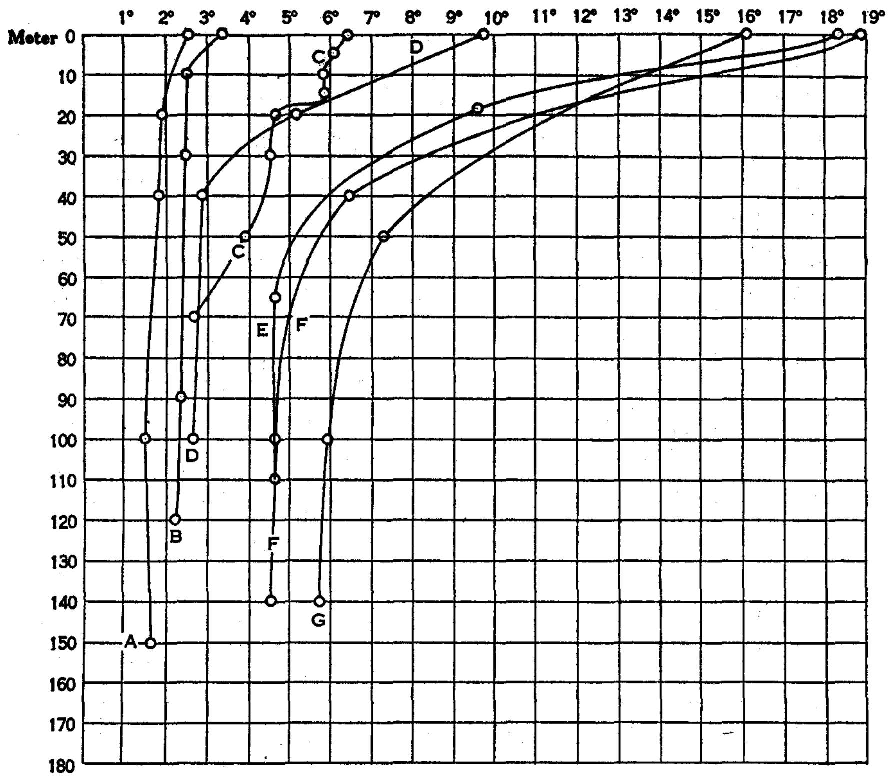

FIG. 4.—Vertical distribution of temperature at the mouth of Massachusetts Bay, March to August. A, March 1, 1920 (station 20050); B, April 9, 1920 (station 20090); C, May 4, 1920 (station 20120); D, May 16, 1920 (station 20124); E, July 20, 1912 (station 10002); F, August 22, 1914; G, August 31, 1915 (station 10306)

ward to the Cape Cod slope, in readings of 3° to 3.6°. With this warm tongue as clearly defined by high salinity as it is by temperature, its nature as an actual current flowing into the gulf via the Eastern Channel from outside the continental edge is sufficiently established. Seldom, in fact, do the curves for salinity and for temperature correspond as closely as they do in this case, even to the pooling of the warm, saline water off the mouth of the Bay of Fundy. This phenomenon, of which we have had frequent evidence in other years and at other seasons, is discussed more

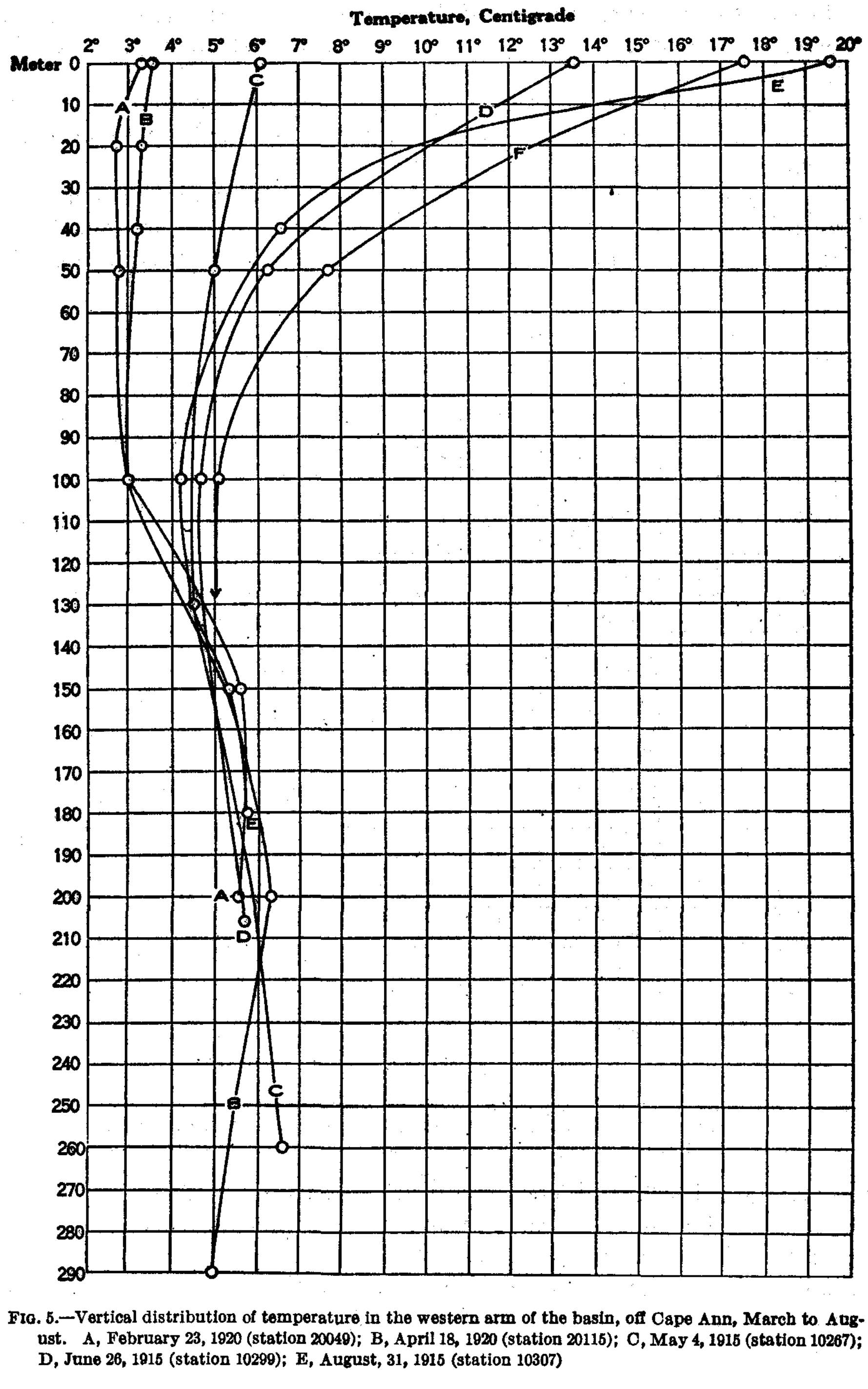

FIG. 5.—Vertical distribution of temperature in the western arm of the basin, off Cape Ann, March to August. A, February 23, 1920 (station 20049); B, April 18, 1920 (station 20115); C, May 4, 1915 (station 10267); D, June 26, 1915 (station 10299); E, August, 31, 1915 (station 10307)

fully in the chapter on the circulation of the gulf (p. 921). Its existence and its effect on the bottom temperatures of the gulf are among the most interesting facts brought out by the survey.

A counter expansion of water colder than 6° and fresher than 33 per mille, out of the gulf and around the southeast face of Georges Bank, also adds interest to the 100-meter chart.

In February and March, 1920, the gulf proved warmer at 200 meters than at 100. Probably the 200-meter level is never as cold as 4°; in fact, most of the readings were fractionally higher than 5°, being from 4.29° in the Fundy Deep to 6.85° in the

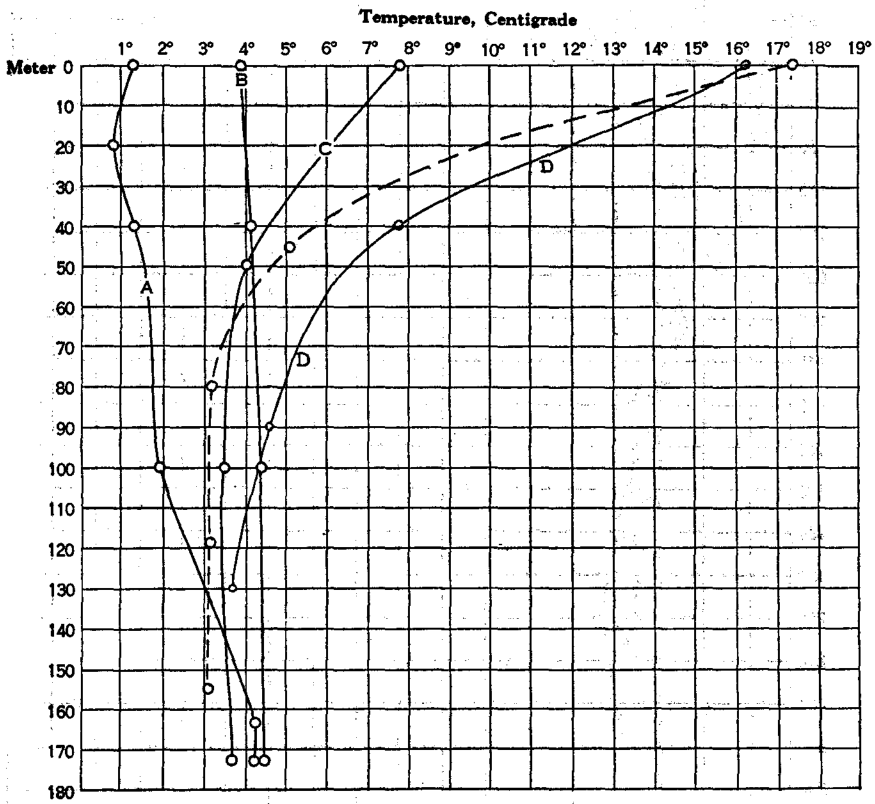

FIG. 6.—Vertical distribution of temperature in the deep trough between Jeffreys Ledge and the coast, March to August. A, March 5, 1920 (station 20061); B, March 5, 1921 (station 10509); C, May 14, 1914 (station 10278); D, August 22, 1914 (station 10252). The broken curve is for August 9 of the cold summer of 1923

Eastern Channel, with 5.2° to 5.6° at most of the stations. The 200-meter temperature at the three February-March stations outside the edge of the continent were as follows: 12.39° off the southwest face of Georges Bank on February 22 (station 20044), 5.9° off its southeast slope on March 12 (station 20069), and 7.89° off Shelburne, Nova Scotia, on March 19 (station 20077).

PROFILES

Several profiles of the gulf are added, further to illustrate the distribution of temperature in March as exemplified by the year 1920. The first of these, running eastward from Massachusetts Bay to the neighborhood of Cape Sable (fig. 14), shows the spacial relationship between the comparatively high temperature (upward of 4°) in the bottom of the two arms of the basin, below about 120 to 160 meters, the banking up of 4° to 5° water in the eastern side just mentioned, and the colder (0° to 2°) water in the inner part of Massachusetts Bay in the one side of the gulf and along western Nova Scotia in the other. It also affords evidence more graphic than the charts that this warm bottom water, as it drifts in through

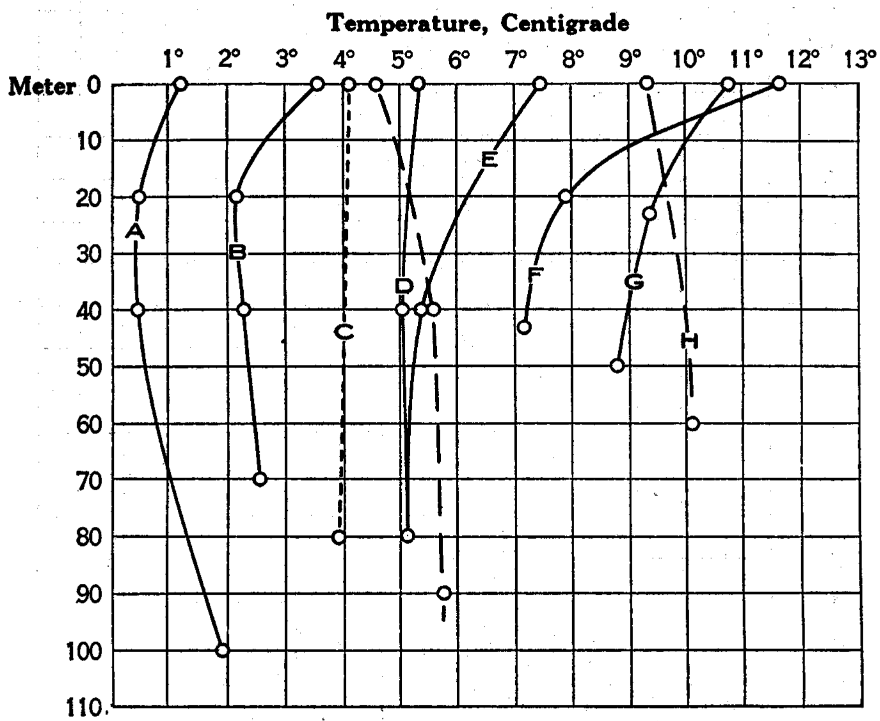

FIG. 7.—Vertical distribution of temperature near Mount Desert Island in various months. A, March 3, 1920 (station 20056); B, April 12, 1920 (station 20099); C, May 10, 1915 (station 10274); D, June 11, 1915 (station 10284); E, June 14, 1915 (station 10286); F, July 19, 1915 (station 10302); G, August 18, 1915 (station 10305); H, October 9, 1915 (station 10328); I, January 1, 1921 (station 10497)

the Eastern Channel, makes itself felt right up to the surface in the coldest season by temperatures about 1° higher than those either to the west or to the east of it. A much lower temperature in the bottom of the bowl off Gloucester (1.5° to 1.6°) than at equal depths in the neighboring basin (5°) deserves attention as evidence of the efficacy of its barrier rim. Because so protected by the contour of the bottom, the low temperatures of the preceding winter persist until much later in the season in the deeper levels of sinks of this type than in other parts of the open gulf.

The considerable stratum of water colder than 3° (1.89° to 2.76°) in the mid levels of the west-central part of the basin is made conspicuous on this profile by contrast with the warm core that splits it in the eastern side. Had the profile been run a few miles farther north, the contrast in temperature would have appeared still sharper in this relative region (at station 20054); less so a few miles farther south (at station 20053), as the charts for the surface and for the 40-meter level (figs. 1 and 12) make clear.

The most notable features of a profile running south from the offing of Cape Elizabeth, across Georges Bank and the continental slope (fig. 15), is its demonstra-

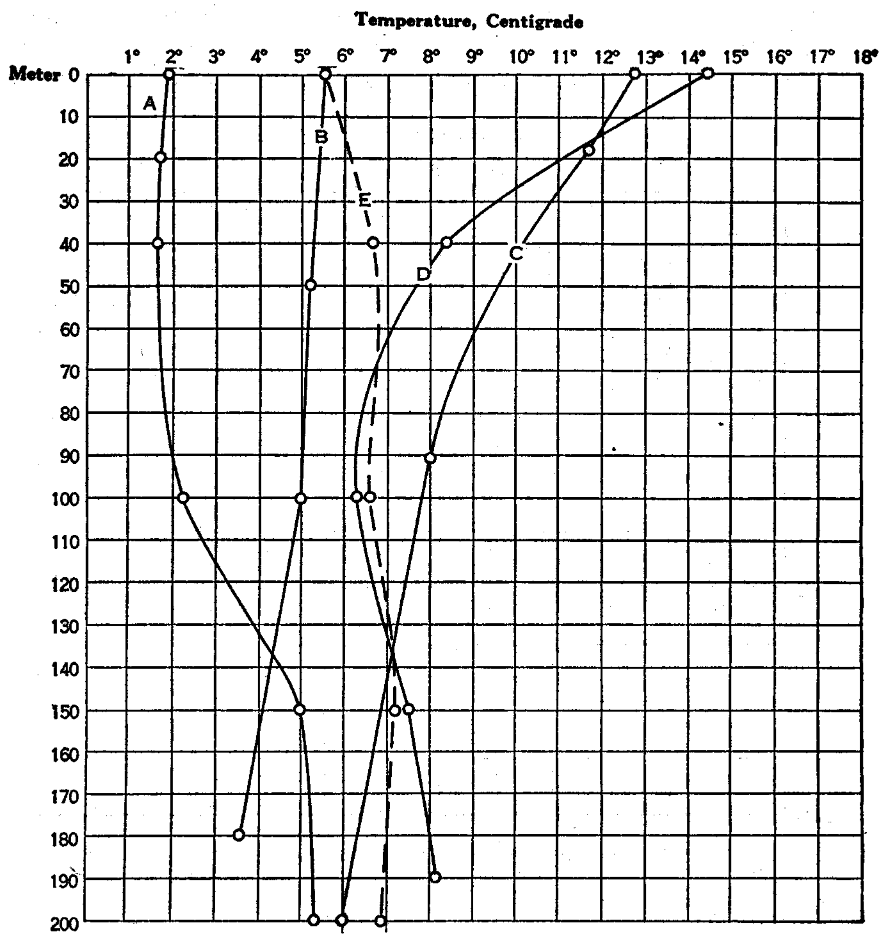

FIG. 8.—Vertical distribution of temperature in the northeastern corner of the Gulf of Maine. A, March 22, 1920 (station 20081); B, June 10, 1915 (station 10283); C, August 12, 1913 (station 10097); D, August 12, 1914 (station 10246); E (broken curve), January 5, 1921 (station 10502)

tion (*a*) that the transition in temperature from the boreal waters of the gulf, on the one hand, to the oceanic water outside the continental edge, on the other, is hardly less abrupt along this line in the last week of February and first week of March than it is in midsummer (p. 615); and (*b*) that the bottom at 75 to 300 meters was bathed by water as warm as 8° to 11° as far east as longitude 68° along the continental slope. Equally high bottom temperatures on the upper part of the slope in the latitude of Chesapeake Bay (station 20041), off Delaware Bay (station 20042), and off New York (station 20043), that same February, also off Chesapeake

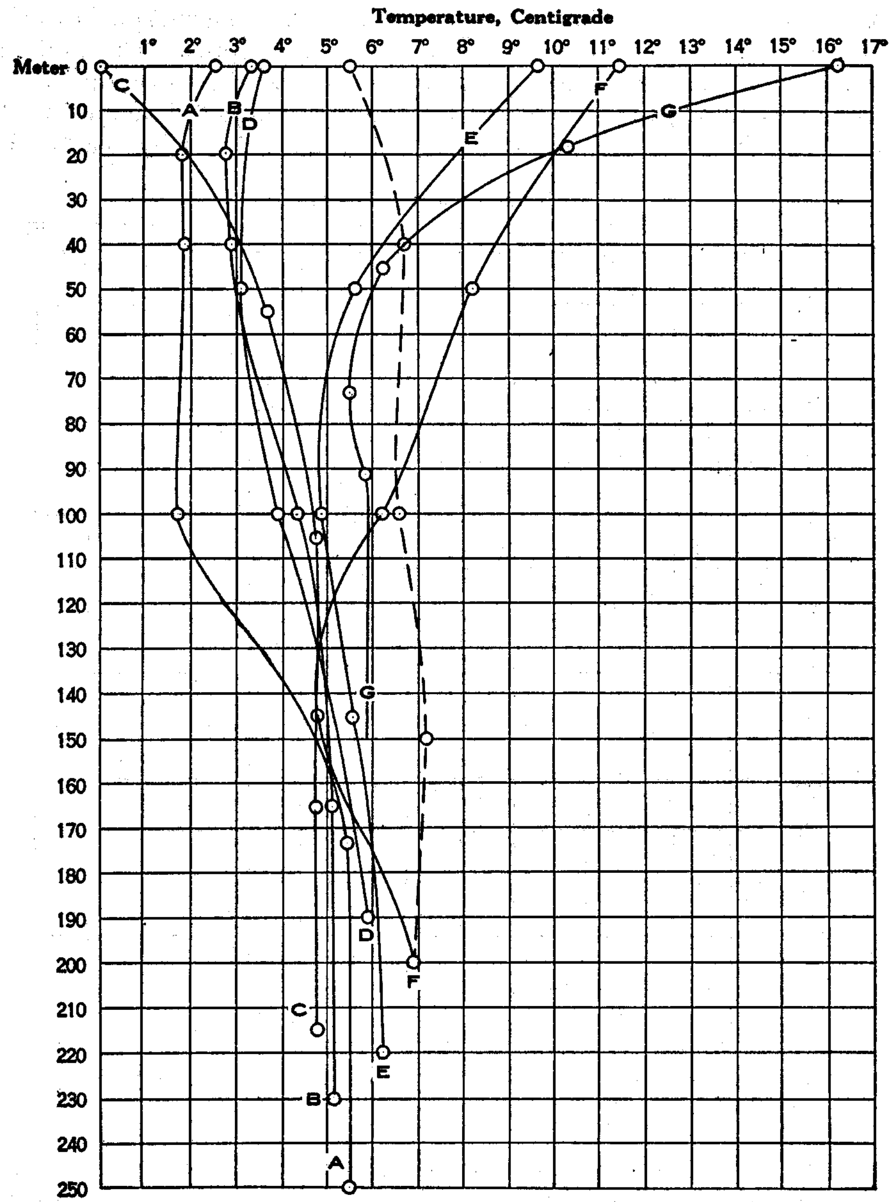

FIG. 9.—Vertical distribution of temperature in the eastern side of the basin of the Gulf of Maine. A, March 3, 1920 (station 20054); B, April 17, 1920 (station 20113); C, March 28, 1919 (Ice Patrol Station No. 3); D, May 6, 1915 (station 10270); E, June 19, 1915 (station 10286); F, August 7, 1915 (station 10304); G, September 1, 1915 (station 10309). The broken curve is for January 5, 1921 (station 10502)

Bay in January, 1914 (Bigelow, 1917a, p. 60), make it likely that a warm band of this sort (often spoken of as the "inner edge of the Gulf Stream") touches the bottom along this depth zone throughout most winters. The March profile of the eastern end of the bank (fig. 16), however, shows much less contrast in temperature between the two sides of the latter, with the oceanic water (warmer than 8° and salter than 34 per mille) so much farther out from the edge of the continent that even the outermost station (20069) did not touch it, leaving the bottom down the continental slope bathed with water colder than 5° at all depths. The profiles thus corroborate the temperature charts (figs. 12 and 13), to the effect that the warm bottom zone was obliterated somewhere between longitudes 67° and 68° W. (about midway the length of Georges Bank) in February and March by the "cold wall"

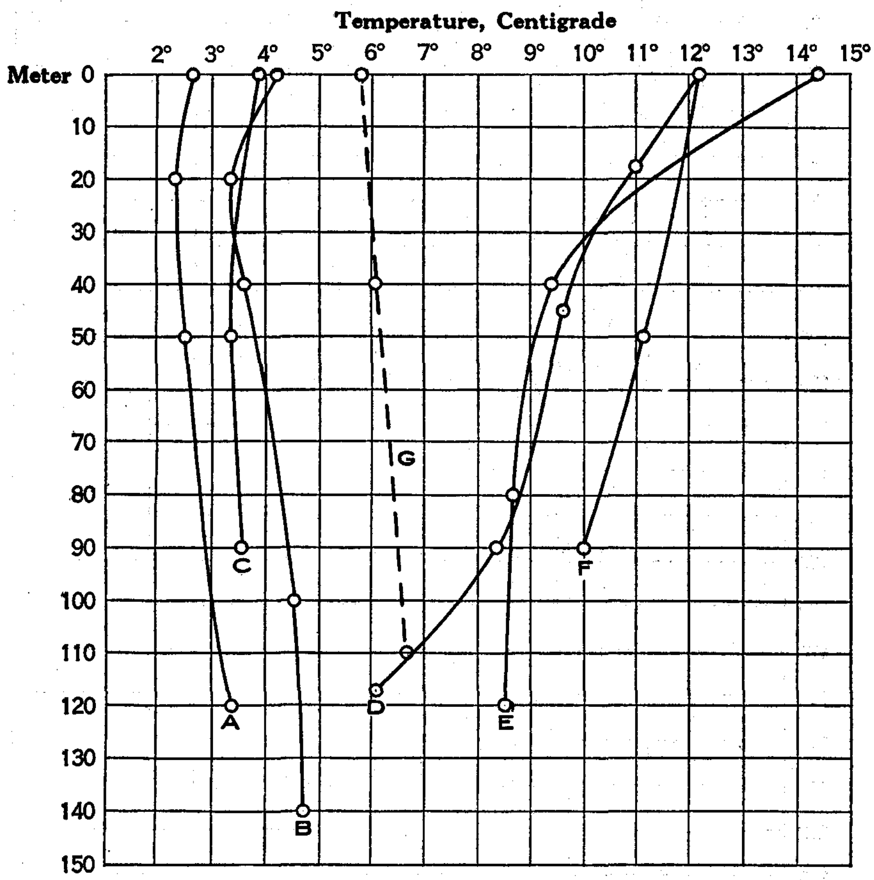

FIG. 10.—Vertical distribution of temperature near Lurcher Shoal in various months. A, March 23, 1920 (station 20082); B, April 12, 1920 (station 20101); C, May 10, 1915 (station 10272); D, August 12, 1913 (station 10096); F, August 12, 1914 (station 10245); G, January 4, 1921 (station 10500)

that wedges in between the slope and the oceanic water. As it is the existence of this warm zone that permits the year-round existence of warm-water subtropical invertebrates and of the tilefish along this stretch, the definite location of its eastern limit is a matter of some biological importance. The contrast between the graph for our outermost station off the western end of Georges Bank and two other deep stations off its eastern end and off Shelburne, Nova Scotia (fig. 18), is an additional illustration of the sudden dislocations about midway of the bank, with a difference of about 5° to 6° between the two ends of the latter at all levels from 20 meters down to 300.

The fact that the two eastern stations (20069 and 20077) did not differ from each other by more than 2° in temperature at any depth is evidence that the cold wedge that they illustrate was itself nearly uniform in temperature for a considerable distance from west to east. The difference between station 20044, on the one hand, and stations 20069 and 20077, on the other, was greatest at the stratum where all three were warmest—100 to 200 meters. Below this, at depths greater than 300 meters, the curves for all three of these deep stations converge, the readings for all

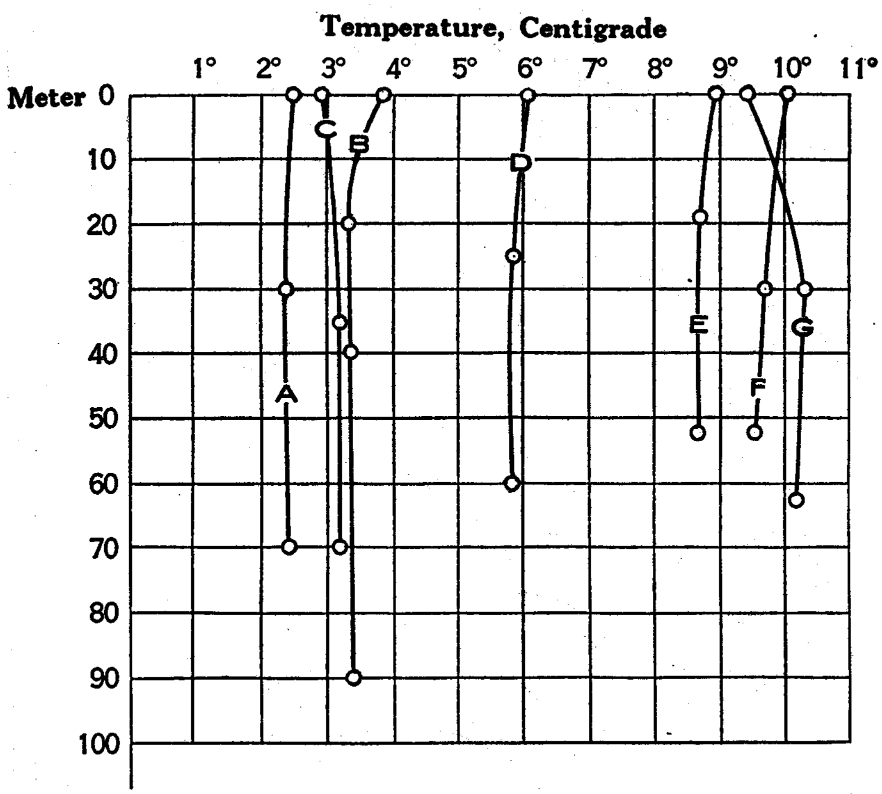

FIG. 11.—Vertical distribution of temperature on German Bank, March to September. A, March 23, 1920 (station 20085); B, April 15, 1920 (station 20103); C, May 7, 1915 (station 10271); D, June 19, 1915 (station 10290); E, August 12, 1913 (station 10095); F, August 12, 1914 (station 10244); G, September 2, 1915 (station 10311)

falling within a range of 0.5° at 1,000 meters (station 20044, 4.2°; station 20069, 3.77°; station 20077, 3.9°), approximately at the temperature that is typical of the abyssal waters of the North Atlantic as a whole and differing little from the readings obtained at corresponding depths and locations along the slope in summer between Nova Scotia and the latitude of Chesapeake Bay (p. 605; Bigelow, 1915, 1917, 1922).

Unfortunately the data are not complete for the February station on the northern part of Georges Bank (20047), but it is probable (hence so designated on the profile) that 3° to 4° water was continuous right across the western end of the bank at the 10 to 30 meter level.

Our experience has been that the water is so actively mixed by tidal currents on the shoaler parts of Georges Bank that a complete equalization of temperature may

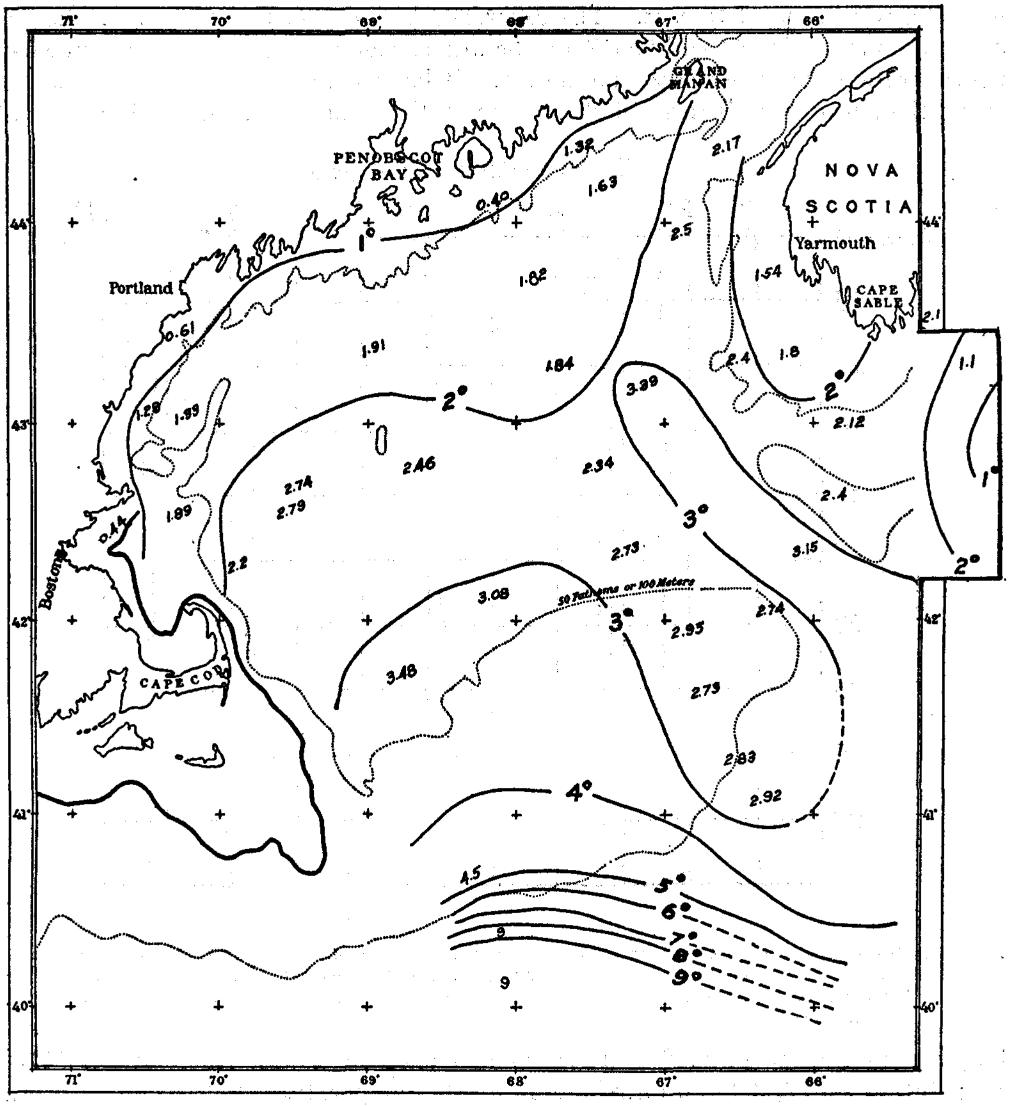

FIG. 12.—Temperature at a depth of 40 meters, Febuary-March, 1920

be expected there locally at any season. Had the western profile (fig. 15) cut such a location, the readings would have been about 4° to 4.5° from surface to bottom; but with a difference of about 0.1 per mille of salinity between the surface and the bottom in 50 meters at station 20047 (p. 998), evidently such was not the case.

Only one other feature of this end of the profile calls for attention—the encroachment of water warmer than 7° on the southern side of Georges Bank and the abrupt transition in bottom temperature across the latter from north to south (4° to 12°).

The inner parts of the gulf at the coldest season are warmest (5° to 6°) at the bottom, coldest (2°) along shore and within 10 to 20 meters of the surface.

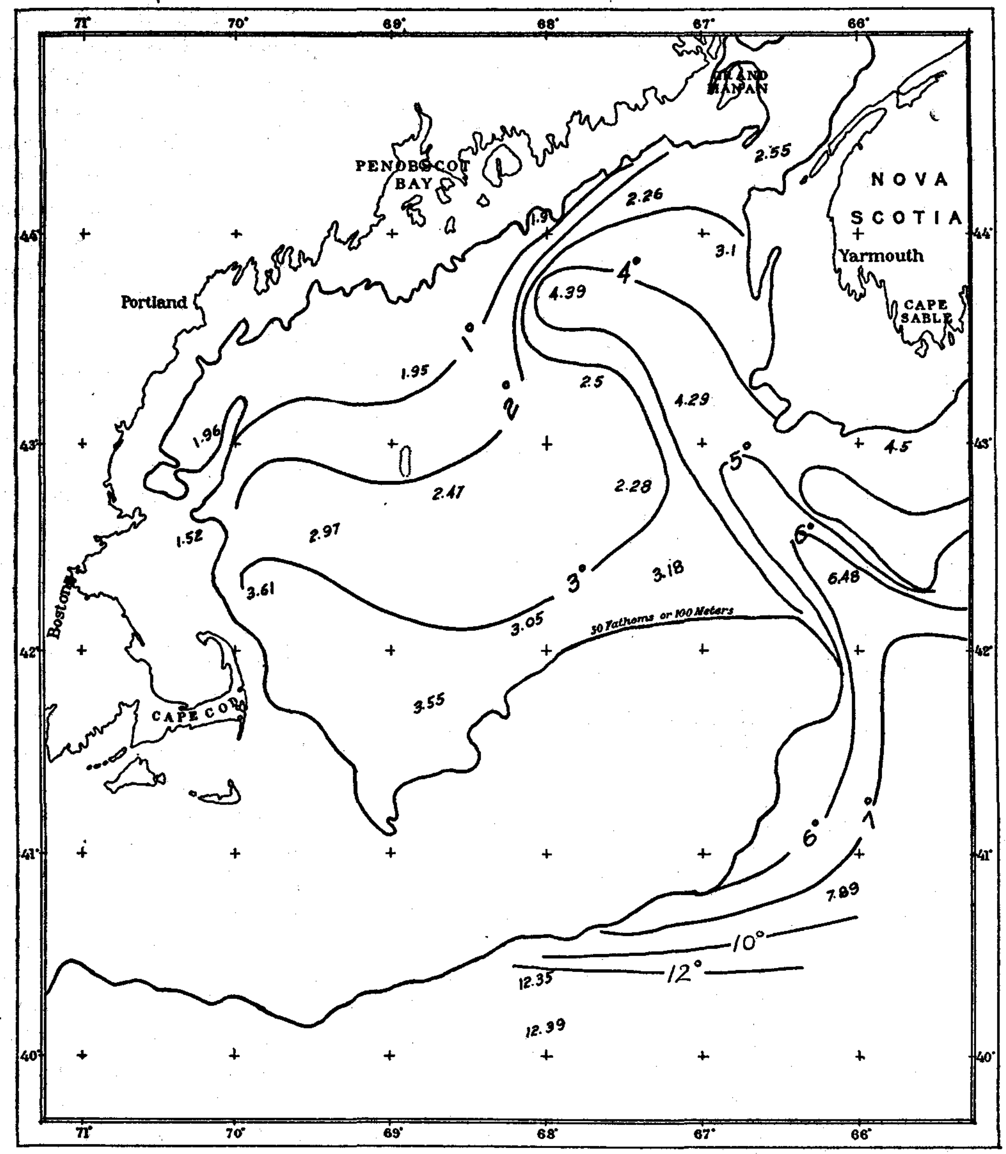

FIG. 13.—Temperature at a depth of 100 meters, Febuary–March, 1920

The wedge-shaped contour of this coldest water (3°), projecting shelflike over the basin, with slightly higher temperatures above it as well as below (fig. 15), taken by itself might suggest some overflow by warmer surface water from the south. The vertical uniformity of salinity in the upper stratum (p. 705), however, favors

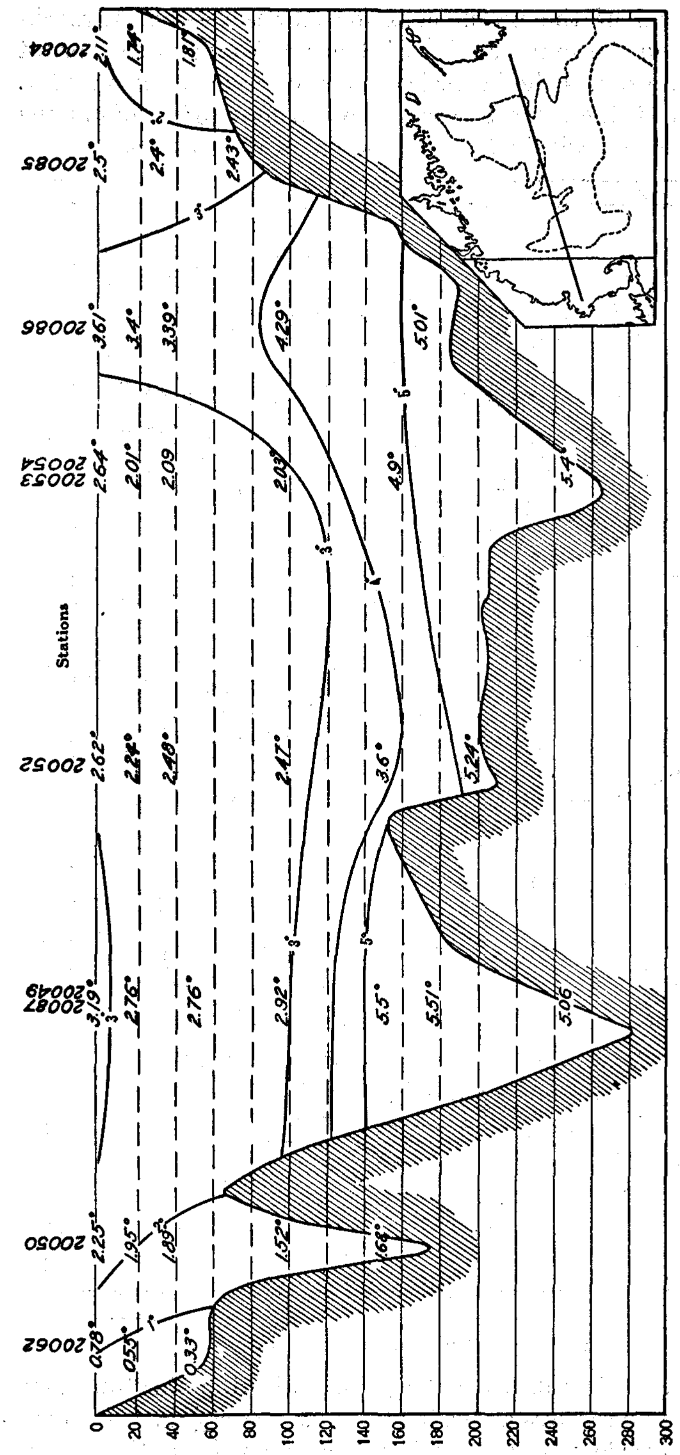

FIG. 14.—Temperature profile crossing the gulf from Massachusetts Bay to the vicinity of Cape Sable, March 5 to 23, 1920

the simpler explanation that temperatures slightly higher at the surface than a few meters down merely reflect the first stage in the vernal warming by the sun, which proceeds throughout the spring months. Probably the upper 10 meters would have been found homogeneous in temperature in the coastal zone, or the surface slightly the coldest level then, had the profile been run two weeks earlier in the season.

The increase of temperature from the shore seaward is again illustrated on the corresponding profile of the eastern side of the gulf (fig. 16). In this case, however, the courses of the isotherms are complicated by the fact that this particular profile cuts the westward extension of the warm core that enters the gulf via the Eastern Channel (pp. 526 and 529). Consequently, the profile shows the curves for 2, 3, 4, and 5 degrees, rising considerably nearer to the surface over the northern slope of the basin (station 20055) than closer inshore, on the one hand (station 20056), or in the deeper water of the basin, on the other (station 20054), indenting the cold (1° to 2°) surface layer from belo . Readings taken at a depth of 40 to 50 meters

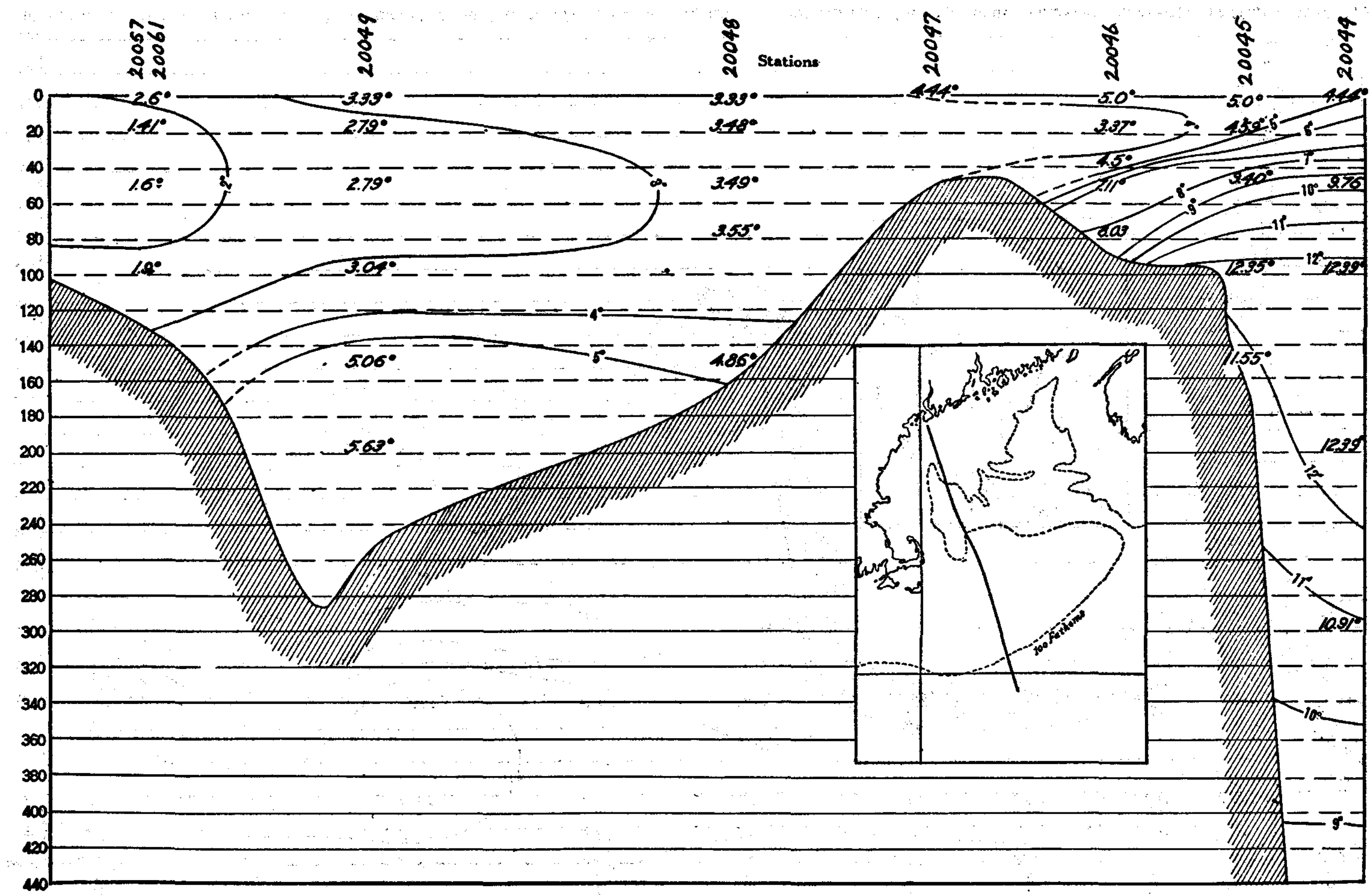

Fig. 15.—Temperature profile running southeasterly from the northwestern part of the gulf, off Cape Elizabeth, across Georges Bank to the continental slope, February 22 to March 4, 1920

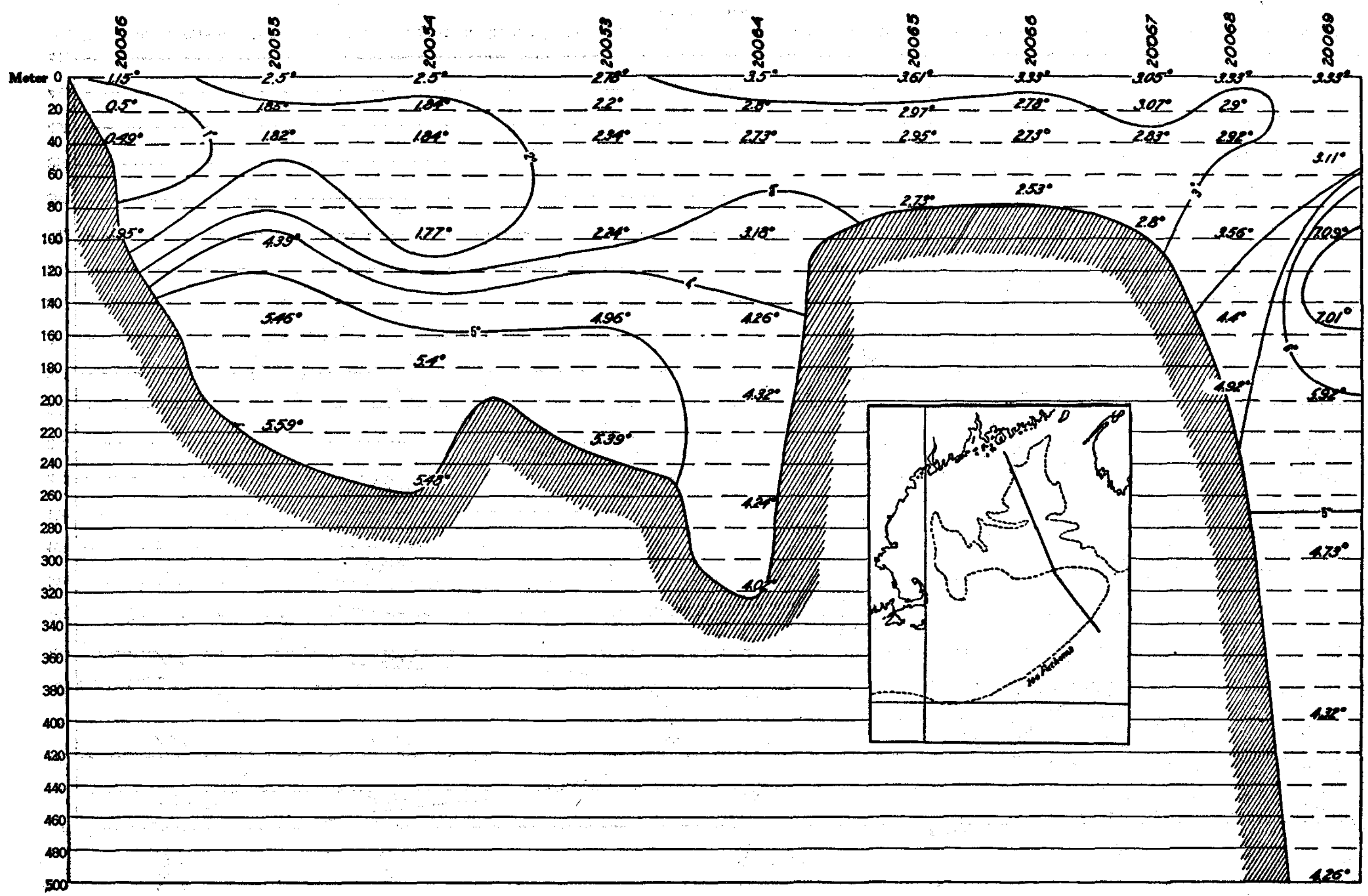

FIG. 16.—Temperature profile running from the vicinity of Mount Desert Island, southeasterly across the eastern part of Georges Bank to the continental slope, for March 3 to 12, 1920

along the axis of this cold stratum then rose fairly uniformly from about 0.5° close to land to from 2.4° to 2.7° in the southern side of the basin, to 2.7° to 2.9° over Georges Bank, and to 3.1° over the continental slope, as just described. On the other hand, the water as warm as 5° that floods the greater part of the basin at depths greater than 120 to 150 meters did not then touch the northern slope of Georges Bank, off which the water was fractionally colder than 5° right down into the deepest fold of the trough (station 20064).

The fact that the southern end of this profile crossed one of the chief breeding grounds for haddock in North American waters, and at the height of the spawning

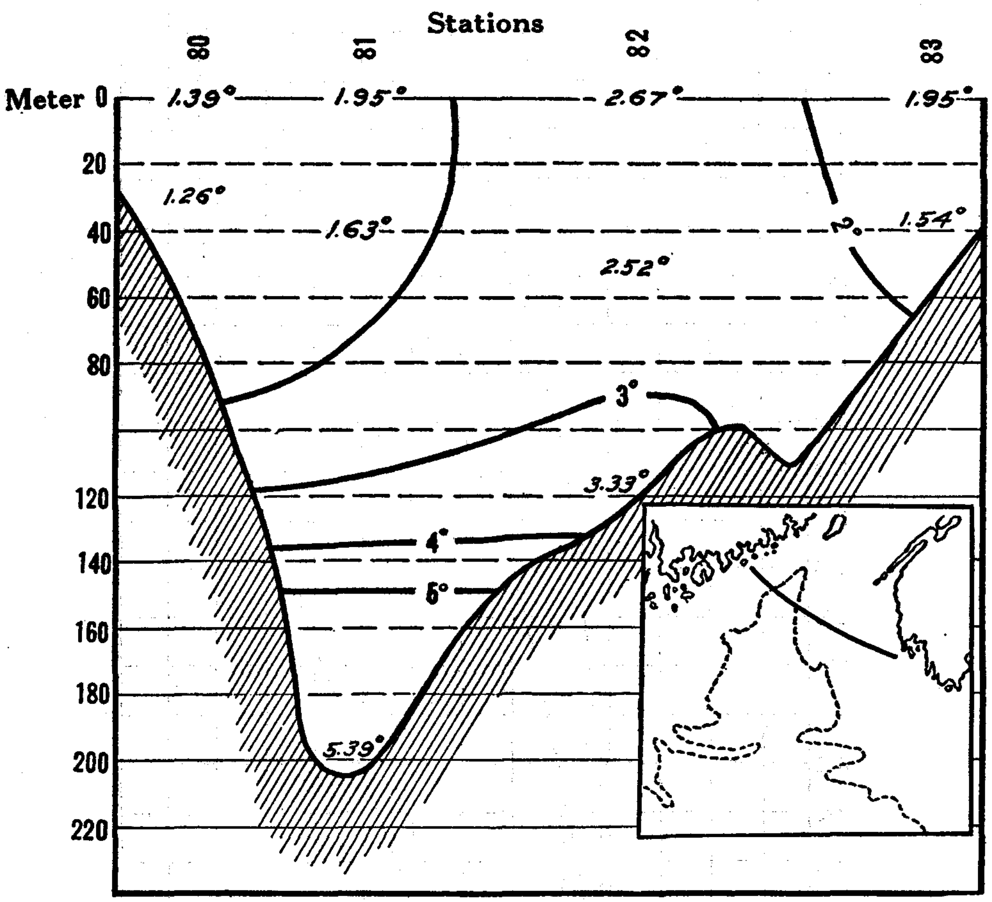

FIG. 17.—Temperature profile crossing the northeastern part of the gulf, off the mouth of the Bay of Fundy, for March 22 and 23, 1920 (stations 20080 to 20083)

season, lends biological interest to the temperatures at stations 20061 to 20068. Evidently the eggs were being set free in water of about 2.5° to 2.7°.

The boundaries of the comparatively warm (5°) bottom water in the eastern arm of the basin, for March, are outlined further by a profile from Maine to Nova Scotia, opposite the mouth of the Bay of Fundy (fig. 17, stations 20080 to 20083). Temperatures higher than 5° were confined to depths greater than 150 meters along this line, but the isotherm for 3° shows the warmer bottom water banking up against the

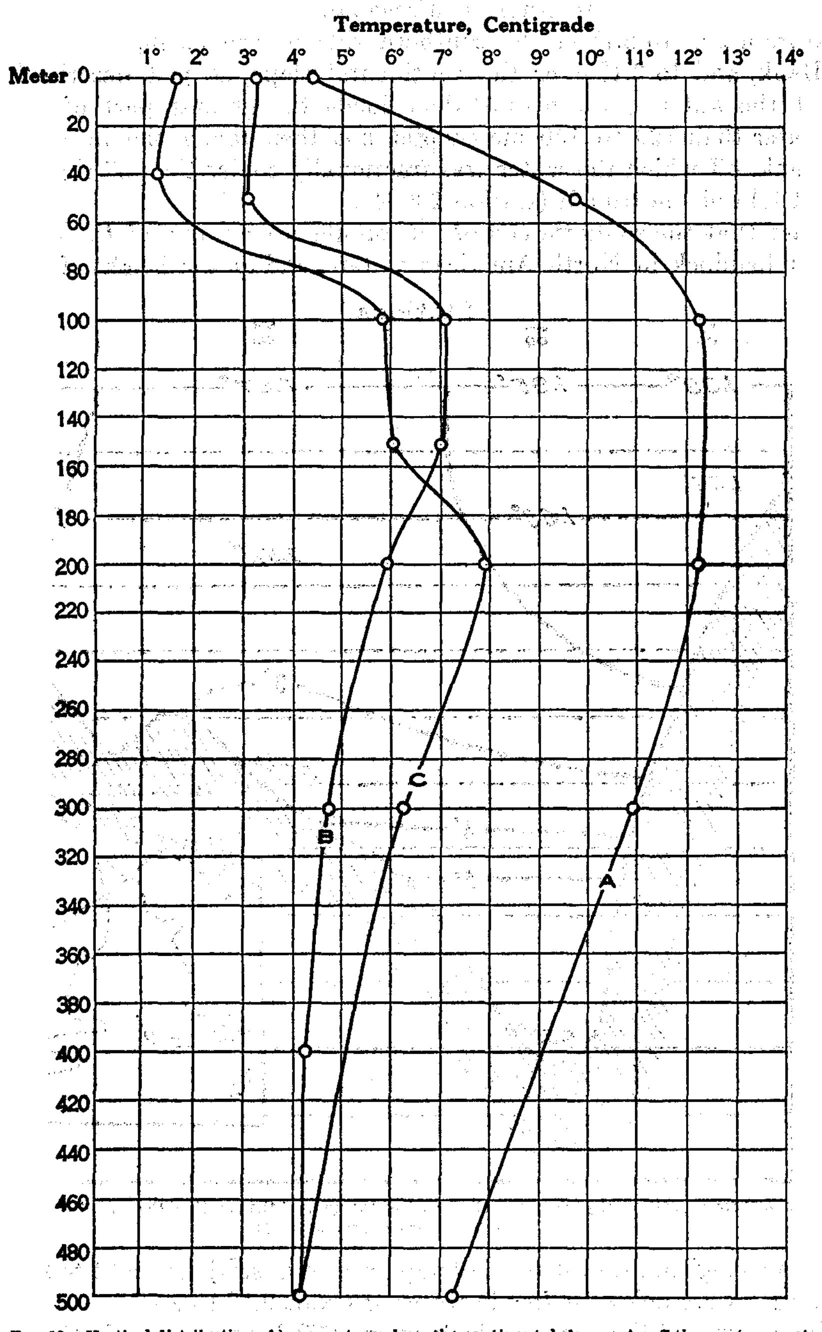

FIG. 18.—Vertical distribution of temperature along the continental slope. A, off the western part of Georges Bank (station 20044); B, off the eastern end of Georges Bank (station 20069); C, off Shelburne, Nova Scotia (station 20077), February-March, 1920.

eastern slope of the gulf (against the right-hand side for an entrant current) to within 90 meters of the surface in the manner with which cruises at other times of year have made us familiar (p. 619). Temperatures are slightly lower in the shore ends of this profile, as is usual for the cold season. Failure to obtain readings lower than 1° may be explained on the assumption that solar warming is propagated downward to a greater depth off Maine and off Nova Scotia by the strong tides of those localities during the first three weeks of March, than in the western side of the gulf, where tidal stirrmg is less active.

The relationship existing in March between the cold waters over Georges and Browns Banks and in the Northern Channel, on the one hand, and the warm indraft into the Eastern Channel, on the other, is illustrated by a profile following the arc of the banks (fig 19) Bottom water of 6° to 7° in the Eastern Channel, banked

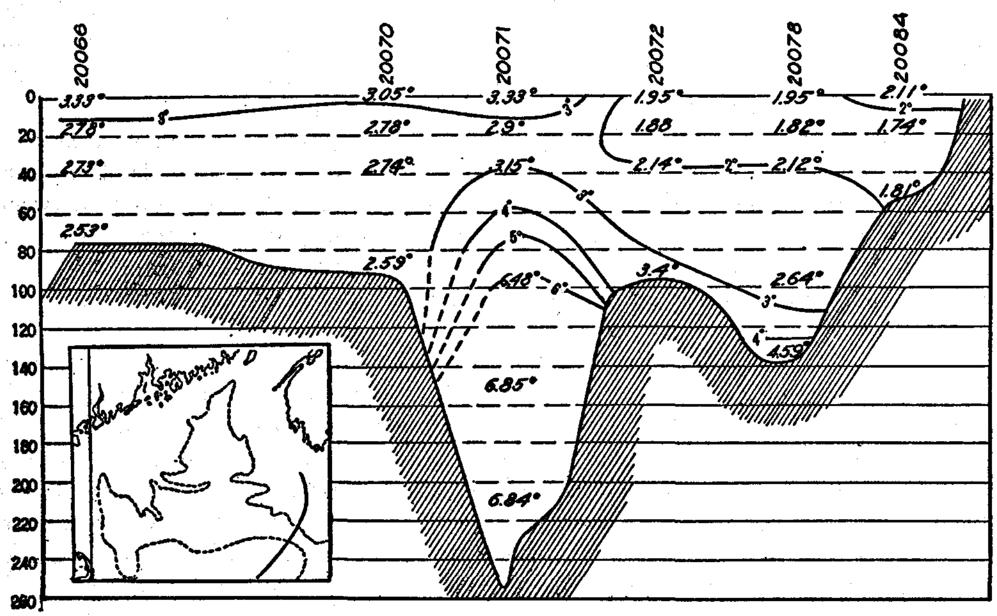

FIG. 19.—Temperature profile running from the eastern part of Georges Bank, across the Eastern Channel, Brown's Bank, and the Northern Channel, March 11 to 23, 1920

up like a ridge along its trough (isotherms for 3° to 6°), contrasts with 3° to 4.5° at equal depths in the Northern Channel, where temperatures higher than 4° were confined to a thin bottom layer deeper than 110 meters (station 20048). A bottom temperature fractionally higher than 3° on Browns Bank points to some tendency for the warm water that drifts in through the Eastern Channel to overflow the eastern rim of the latter; but the March data show that this circulatory movement was limited to depths greater than 70 meters. Probably the fact that the readings on Georges Bank showed no sign of any encroachment of the warm water in that direction, which is corroborated by salinity (p. 719), is due to the deflective effect of the earth's rotation, deflecting the current to the right (p. 849). Other features of the profile that claim attention are the uniformity of temperature over the eastern part of Georges Bank from east to west; the fact that the surface was fractionally warmer than the 20-meter level there and over the Eastern Channel (a first sign of vernal warming); and that while the inshore (Cape Sable) end of the profile was coldest as is usual at this season, the temperature was fractionally higher close in to the land near the cape than a short distance out at sea. A differential of this same sort would have been more apparent had the profile been located a few miles farther east, because the whole column in 75 meters depth, close in to Shelburne (station 20073), was fractionally warmer than 2° (p. 1000), while the water farther out on the shelf (stations 20074 and 20075) was colder.

BOTTOM

The temperature of the bottom water, in depths greater than 200 meters, varied in March from 4.02° off the northern slope of Georges Bank in 330 meters (station 20064) to 6.84° in the Eastern Channel in 215 meters (station 20071), with readings of 5.06° to 5.59° at depths of 225 to 250 meters elsewhere in the basin. It is interesting to find the deepest water coldest just north of Georges Bank at the location just mentioned, for this was also the case at 200 meters; whereas the northern side of the basin, not the southern, was the coldest at 100 meters.

For the biologist, the bottom temperature of the gulf at the coldest season is interesting as evidence of the greatest cold that bottom-dwelling animals of any sort must endure in various regions. In general, a parallelism then obtains between temperature and depth, the bottom being warmer the deeper the water. This relationship is complicated, however, by the increase in temperature from the shore seaward (p. 525), independent of depth, illustrated by the charts for the 40-meter and 100-meter levels (figs. 12 and 13.)

With more or less ice forming every winter in shoal bays and among the islands, the littoral zone is chilled from time to time to the freezing point of salt water in such situations. In Cape Cod Bay the *Fish Hawk* had a reading as low as −1.5° in 17 meters and −0.4° on the bottom in 34 meters on February 6, 1925 (cruise 6, station 6a, p. 1005); and while these readings are the lowest so far recorded for the open gulf, the data for that year and for station 20062 show that in Massachusetts Bay generally the bottom may be expected to chill to about 0° out to about the 30 to 40 meter level at some time during most winters, perhaps every year. No doubt this applies equally to the bays along the coast of Maine and to the tributaries of the Bay of Fundy; but along the open northern shores of the gulf, where strong tides produce an interchange of water more active than in Massachusetts Bay, it is not likely that the bottom temperature ever falls as low as 0° except within the littoral zone. Our two March stations (20083 and 20084) similarly show the bottom slightly warmer at 50 meters along western Nova Scotia at that season than in Massachusetts Bay; but later in the spring, when the icy Nova Scotian water from the east is flowing in greatest volume past Cape Sable, the bottom of the eastern side of the gulf may also be chilled to 1° - 0° down to a depth of 50 meters—perhaps still deeper, for a brief period, in some years. On the other hand, it seems that the bottom temperature of the deep troughs of the gulf never falls below 4°, except, perhaps, in very exceptional years.

Thus, any animal dwelling on bottom in the inner part of Cape Cod Bay, or anywhere among the islands of the coastal zone shoaler than 40 to 50 meters, is apt to be subjected to a temperature close to zero or lower at the end of winter. There is no danger of temperatures lower than about 1.5° to 2°, however, either on the slopes of the basin or in any one of the deep isolated bowls at depths of 100 meters or more, nor of temperatures lower than 4° on the bottom of the basin. A corresponding difference in the upper strata also may explain the disappearance of sundry planktonic animals from the coastal zone in winter, though they occur the year around in the gulf out at sea (Bigelow, 1926).

The contour of this mass of comparatively warm bottom water in the deeps of the gulf is graphically illustrated by a chart showing the isothermobath for 4° in February and March (fig. 20), for wherever temperatures as high as this were recorded within the gulf the underlying strata were still warmer. In 1920 (probably this applies yearly) there was no water as warm as 4° at this season at any level in the coastal zone, out to the 100-meter contour, on either side of the gulf. However (without attempting to draw too close a parallel between the intricate contour of the bottom and the temperature), the floor of the whole gulf at depths greater than 150 meters was bathed with water warmer than 4°, filling the whole basin below a uniform level of 120 to 130 meters in the western side and rising to within 60 to 80 meters of the surface in the eastern, as a well-defined ridge extending northward from the Eastern Channel, with a tendency to pool off the mouth of the Bay of Fundy.

It is not likely that this warm water ever overflows Browns Bank or the eastern half of Georges at that season, although not barred from them by the contour of the bottom. Certainly it did not in March, 1920; but the whole column of water over the western half of Georges Bank was then warmer than 4°, so that the chart (fig. 20) shows the isothermobath in question as rising to the surface there and dipping steeply toward the basin to the northwest. A contrast of 5° to 6° in bottom temperatures between the southwestern and southeastern parts of the bank (station 20046, 8°; station 20067, 2.8°) illustrates the wide differences in the physical conditions to which animals living on bottom are subject in winter and early spring on various parts of the bank.

It seems that at this season the fauna of the so-called "warm zone," which characterizes the upper part of the continental slope off southern New England and farther west (p. 531), must meet its eastern boundary at about longitude 67°, because the bottom temperature was only 4.9° at 190 meters off the southeastern face of Georges Bank on March 12 (station 20068), contrasting with 11.55° at a depth of 120 meters off its southwestern slope on February 22 (station 20045).

ANNUAL VARIATIONS IN TEMPERATURE IN EARLY SPRING

Slight variations are to be expected, of course, in the temperature of the gulf from one winter and spring to the next, even in what we may roughly term "normal" years; still more so between the exceptionally cold and warm winters that no doubt fall at intervals. The station data for 1920 and 1921 allow a thermal comparison for the northwestern parts of the gulf for early March of those years, amplified by the *Fish Hawk* survey of Massachusetts and Ipswich Bays in 1925 and by readings taken at a few localities in 1913.

At the head of Massachusetts Bay, off Boston Harbor, the readings for early March, 1921, and for February 24, 1925, are from 1° to 2° higher at all levels than those for 1290, although the dates were within a few days of one another. As the observations were made so soon after the coldest time of year that the temperature had not risen more than fractionally, it seems safe to say that the water did not cool below 1.5° to 2° in the northern half of the bay during the winters of 1921 or 1925, except right along the land, where it is most subject to winter chilling instead of close to 0°, as in 1920.

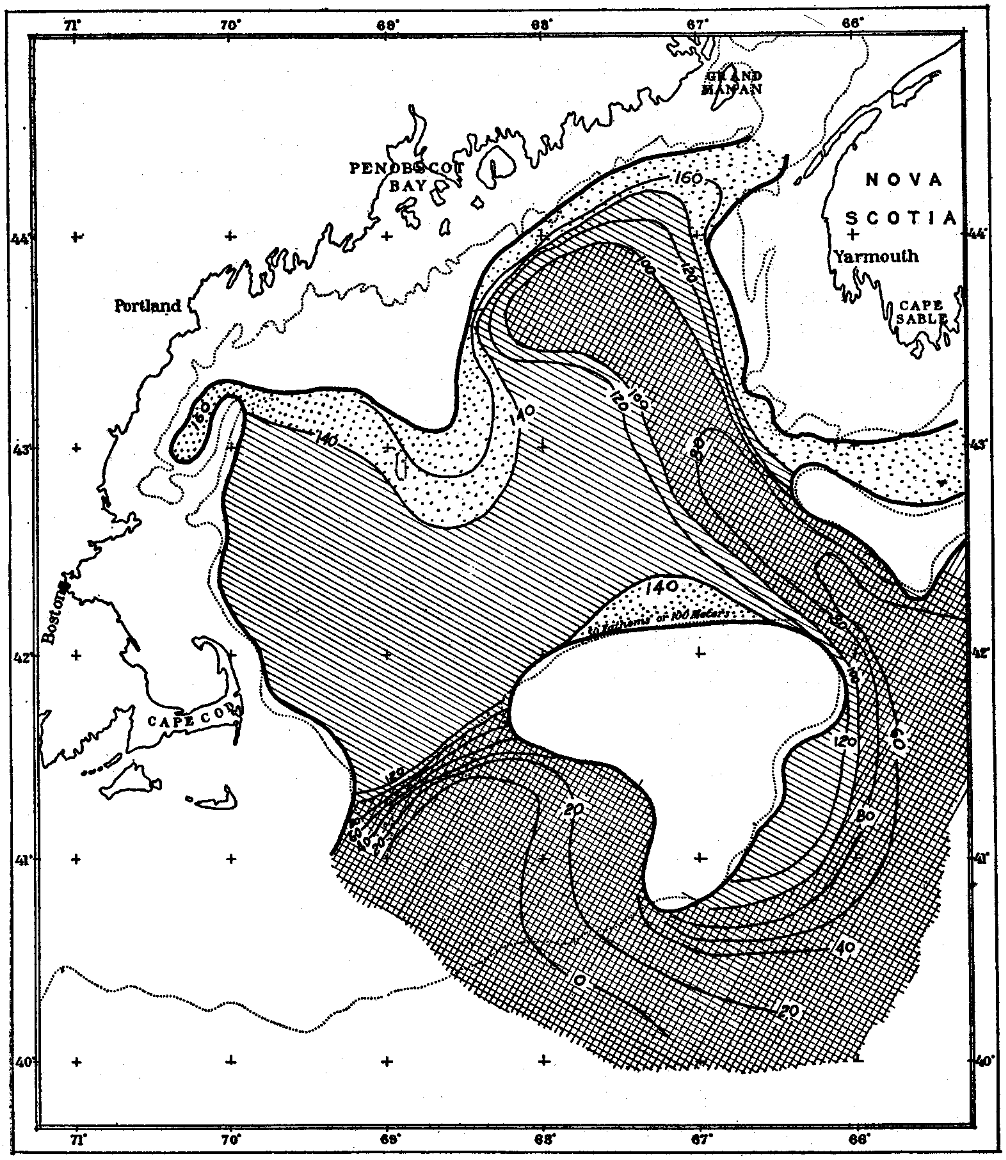

Fig. 20.—Depth below the surface of the isothermobath for 4°, February-March, 1920

A similar relationship obtained between the years 1920 and 1921 at the mouth of the Bay off Gloucester (fig. 21), the following readings taken there in the first week of March pointing to a minimum of 1.5° to 2° for the winter of 1920 and about 3° for 1921.

Meters	Mar. 1, 1920, station 20050	Mar. 5, 1921, station 10511	Meters	Mar. 1, 1920, station 20050	Mar. 5, 1921, station 10511
	Degrees	*Degrees*		*Degrees*	*Degrees*
0	2.5	3.61	100	1.52	3.85
20	1.95	---	150	1.68	3.86
40	1.89	3.84			

The winter of 1913 (Bigelow, 1914a, p. 391) was intermediate between 1920 and 1921 in temperature at this locality, with readings of 2.83° on the surface and 3.11° on bottom in 82 meters at a near-by location on February 13 (station 10053), when the minimum temperature for the winter was recorded.

An equally interesting annual difference is that the temperatures of late February and early March were lowest at the surface in 1913 and 1921, whereas in 1920 vernal warming already had raised the temperature of the surface fractionally above that of the underlying water by March 4. On February 24 to 28, 1925, the bottom was fractionally the warmest level at one deep station (*Fish Hawk* station 18a), while the surface was warmest at another (station 2), with the mid-stratum fractionally the coldest at both. Thus, the date at which the vernal warming of the surface begins to be appreciable does not necessarily mirror the state of the preceding winter, whether a cold one or a warm one in this part of the gulf (1920 was a very cold winter), but depends more on the degree of cloudiness, the precise condition of air, the direction of the wind, the temperature of the air, and on the snowfall from the middle of February on.

Turning now to the coastal belt just north of Cape Ann we find very little difference in actual temperature between readings of 2.4° to 3.7° at the *Fish Hawk* stations (Nos. 20 to 28) for March 10, 1925, and Welsh's records of 3.8° to 3.9° on March 19, 1913; but with the surface about 1° warmer than the 30-meter level at all these *Fish Hawk* stations, but the whole column virtually uniform in temperature down to 120 meters in 1913, it is evident that the vernal warming of the surface commenced at least two weeks earlier there in 1925 than in 1913. The year 1920 was certainly colder at this general locality than either 1913 or 1925, because the surface had warmed only to 3.05° there by the 6th of April (station 20092).

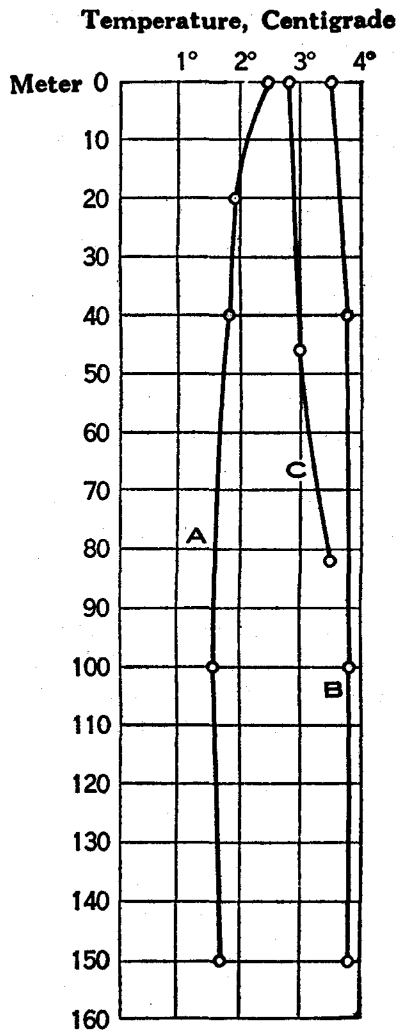

FIG. 21.—Vertical distribution of temperature off Gloucester during the first week of March of the years 1913, 1920, and 1921, to show the annual variation. A, March 1, 1920 (station 20050); B, March 5, 1921 (station 10511); C, March 4, 1913 (station 10054)

The temperature of the upper 100 meters was 2° to 3° lower in the sink off the Isles of Shoals on March 5, 1920, than on that same date in 1921, and while the bottom readings for the two years differ by only about 0.1° in 175 meters, the bottom water was certainly slightly colder there in 1915 than in either 1920 or in 1921, a temperature of only 3.7° at 175 meters as late in the season as May 14 of that year contrasting with about 4° early in March of 1920 and 1921.

Essentially this same relationship between the early March temperatures for 1920 and for 1921 was recorded off Cape Elizabeth and off Seguin Island, 1920 being from 0.2° to 2.4° the colder year at all levels down to the bottom in 45 to 100 meters.

The temperatures of the western basin some 35 miles off Cape Ann for February 22 and March 24, 1920 (stations 20049 and 20087), and for March 5, 1921, did not differ by more than 1.2° at any level; in all cases the highest reading was at about 170 meters, with the upper 40 meters coldest, and 2.74° (on March 24, 1920) as the absolute minimum. On the whole, however, the readings for 1921 are slightly higher and the maximum for the month was recorded on that date (6.45° at 175 meters).

Thus 1920 may be described definitely as a cold winter in the coastal zone out to the 50-meter contour; 1921 and 1925 as warm ones. There was much less annual difference in temperature in the neighboring basin and almost none below the 200-meter level. A regional difference of this sort is just what might be expected if the winter chilling of the gulf is due chiefly to the severe climate of the neighboring land mass to the west (as there is every reason to believe it is), because the icy northwest winds, as they blow out over the adjacent sea, necessarily have most effect on the temperature of the water near the land.

VERNAL WARMING

After the middle or end of February the temperature of the western and northern parts of the gulf slowly rises as the heat given to the surface layers by the increasing strength of the sun is propagated downward by the vertical circulation of the water, but at different rates in different parts of the gulf, depending on the local activity of tidal stirring.

Were solar warming alone responsible for the warming of the gulf in spring, the change would, for the first month or two, be confined to the superficial stratum where this vertical mixing is most active, except where a deeper column is kept stirred by strong tides—the Bay of Fundy, for example, and parts of Georges Bank. Actually, however, the gulf also warms from below during the early spring as the slope water, comparatively high in temperature and which enters through the trough of the Eastern Channel (p. 526), is incorporated by mixture with the colder stratum above, any increase in the amount of this from season to season being betrayed by an increase in salinity as well as in temperature. During the first weeks of March the warming effected from below by this source raises the temperature of the deep waters of the inner part of the gulf as rapidly as solar heat warms the surface stratum.

It is interesting to trace the change that vernal warming effects in the level at which the gulf is coldest. Probably the inner parts are invariably coldest in the upper 40 meters by the end of winter, a state that persisted into the first week of

March in the years 1913 and 1921, as just noted (p. 524). In 1925, too, the superficial 10 meters of Massachusetts Bay did not become definitely and consistently warmer than the underlying water until the end of March (locally even later); and although the whole column had been warming slowly at all the stations there since the middle of February (p. 660), this change was at first so slow that the mean surface temperature of the southern side of the bay was only about 0.3° higher on March 10 (2° at stations 2, 10, 13a, 15, and 18a) than it had been on February 24 to 28, the mean bottom temperature for these same stations remaining virtually unchanged. This probably applies also to the whole area of Massachusetts Bay, for the surface had warmed by only about 0.56° just outside Gloucester Harbor, and not at all within the latter.

In Ipswich Bay, however, the surface had become definitely warmer than the underlying water by the first week of March, and this was the case over the gulf as a whole in 1920, as just described.

From early March onward the progressive warming from above lowers the coldest plane in the western side of the basin to a depth of about 100 meters by the middle or end of April. At the same time warming by slope water from below *raises* the coldest plane in the northeastern part of the basin (the latter itself now slightly warmer than in March) to within 15 to 20 meters of the surface. In the southeastern part of the basin, however, the temperature was lowest at the 100-meter level on April 17 (station 20112), instead of at 20 to 40 meters, as it had been on March 11 (station 20064). The minimum temperatures were recorded at about the same depth (20 to 40 meters) for the two months in the Northern Channel, the Eastern Channel, and on the southeastern continental slope of Georges Bank. On Browns Bank, however, where the upper 20 meters had been considerably coldest on March 13 (station 20072), the bottom (80 meters) was slightly coldest on April 16 (station 20106), and the whole column, top to bottom, had become nearly homogeneous in temperature during the interval.

Vernal warming, the normal event in boreal seas, is retarded—may even be reversed temporarily—in the eastern side of the Gulf of Maine when the intermittent Nova Scotian current floods past Cape Sable, as described in a later chapter (p. 832). The cold water from this source affects a greater displacement of the isotherms within the gulf and produces lower temperatures there in some springs than in others, depending on the volume and temperature of the flow past the cape, on the date at which this reaches its maximum, and on the duration of the period during which this Nova Scotian water enters the gulf in amount sufficient to appreciably affect the temperature of the latter.

In describing the spring cycle vernal warming must be carried along hand in hand with this chilling from the east. In 1913 the vernal warming of Massachusetts Bay and of the Isles of Shoals–Boon Island region to the north was at first most rapid on the bottom. Thus, the 82-meter temperature rose from 3.11° off Gloucester on February 13 (station 10053) to 3.61° on March 4 (station 10054), whereas the two surface readings were less than 0.1° apart (both 2.83° to 2.89°). Mr. Welsh found the surface still continuing fractionally colder (3.6°) than the deeper levels near Boon Island on the 29th of the month also, although, judging by the date, the superficial stratum almost certainly had experienced some increase in temperature by then.

It is probable that vernal warming followed a similar course, at first, in the coastal zone in 1921, with the indraft of warmer and salter water from offshore maintaining the winter status of cold surface stratum and warmer bottom water into the first week of March. In 1925, however (p. 1004), warming from above and from below raised the temperature of the whole column in Massachusetts Bay at a more nearly equal rate from the middle of February until late in March, whereas in Ipswich Bay the surface warmed the more rapidly from the beginning. In 1920, however, the surface was already fractionally warmer than the 20 to 40 meter stratum as early as March 4 (p. 524), and it may be that in any year when an extremely severe winter chills the upper 100 meters or so of the gulf to an abnormal degree the surface at once commences to warm after the grip of winter is released, whereas in more normal years the surface temperature may be expected to remain almost stationary for a brief period during late February and early March. In 1924, when a foot or so of snow fell on March 11 and 12, followed by several days of freezing weather, the surface had warmed to only 2.2° at a station 8 miles off Gloucester (*Halcyon* station 10652) by March 19, with about 1.8° at depths of 40 and 70 meters.

The progressive warming of Massachusetts Bay is illustrated for a warm April by the *Fish Hawk* stations for 1925, when the mean surface temperature rose from 2° on March 10 to about 4.6° on April 4 to 8. A definite regional differentiation also had developed, with the surface warmest (5° to 5.4°) in Cape Cod Bay, where it had been coldest during the preceding months. Thus, the relationship characteristic of winter (coldest next the land) was now definitely reversed, so to continue through the spring (fig. 22) and summer. At the 40-meter level, however, the bay still continued slightly warmer at its mouth (3.2° to 3.9°, *Fish Hawk* stations 30 to 33 and 34) than in Cape Cod Bay or near the Plymouth shore (2.9° and 2.6°, stations 6a and 10), evidence that the indraft of offshore water continued to exert more influence on the temperature of the deeper strata (up to the 7th or 8th of April in that year) than did solar warming from above. This was not the case in Ipswich Bay, however, where the 40-meter temperature was almost precisely the same on April 7 (2.4° to 2.8°) as it had been on March 10 (2.5° to 2.7°), though the surface had warmed from 3.35°–3.6° to 4.2°–4.9° during the interval.

By April 21 to 23 the mean temperature of the surface of Massachusetts Bay had risen to 5.2° (4° to 6.8° at the individual stations, fig. 22) and the 40-meter temperature to a mean value of about 3.8°, but virtually no change had yet taken place in the temperature of the bottom water at depths greater than 60 meters, a constancy illustrated by the following table. In 1920, also, the inner part of the bay was actually slightly colder at 40 meters on April 20 (1.58°) than it had been on April 6 to 9 (2.2°–2.4° at stations 20089 and 20090), evidence of some upwelling of the colder water from below.

Fish Hawk stations	Apr. 7 and 8, 1925		Apr. 21 to 23, 1925	
	Meters	*Degrees*	*Meters*	*Degrees*
No. 33	80	2.91	60	3.06
No. 30	84	3.11	80	2.92
No. 31	112	2.9	84	2.7

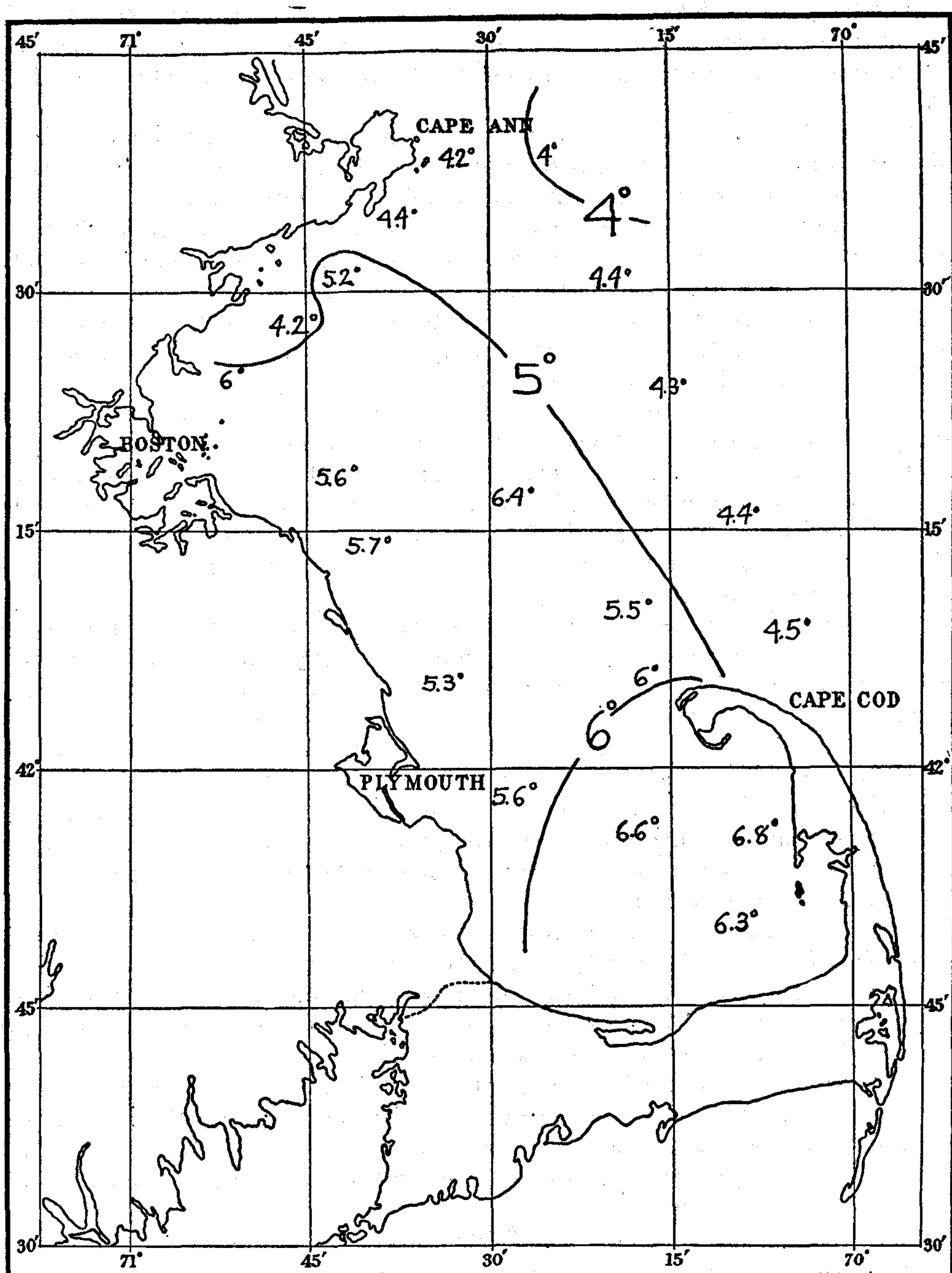

FIG. 22.—Surface temperature of Massachusetts Bay, April 21 to 23, 1925

The temperature followed a similar cycle in 1913, when the surface warmed to 5.56° near Gloucester by April 14, though no appreciable change had taken place at 25 meters during the preceding two weeks (about 4° to 4.1°; stations 10055 and 10056).

In 1923, following a very severe winter, the surface of the central part of the bay had warmed to only 2.8° by April 18, with 1.6° at 40 meters and 0.4° at the bottom in 80 meters. The bay continued nearly as cold as this until the end of April in 1920 (also following a cold winter) with readings of 3.6° at the surface, 2.87° at 20 meters, 1.58° at 40 meters, and 1.78° at 90 meters in its central part on the 20th (station 20119), but with the regional distribution (warmest, 4.4° in Cape Cod Bay, station 20118) essentially the same as in 1925. Probably the records for 1925, on the one hand, and 1920 and 1923, on the other, cover the extremes to be expected in the bay in April, except in very exceptional years.

Seasonal progression in the coastwise belt north of Cape Ann is illustrated for a warm year by serial observations taken by W. W. Welsh near the Isles of shoals and near Boon Island at intervals during the spring of 1913 (p. 980). Here the winter state prevailed until the end of March (fig. 23). On April 5 the temperature was equalized, surface to bottom, and after the middle of the month the surface was warmer than the underlying layers, warming progressively thereafter as illustrated by the graph (see also Bigelow, 1914a, p. 394).

The rate at which the surface warms along this part of the shore during April is irregular, often interrupted or even temporarily reversed by climatic conditions. During the winter, when the column of water is of nearly uniform temperature from the surface downward, the upwellings that follow offshore winds have little effect on the surface temperature; but as soon as the surface becomes appreciably warmer than the underlying water, any upwelling of the latter, or vertical mixing, is at once made evident by a decided, if temporary, chilling of the surface. Northwest winds are a frequent cause of such upwellings along the western shores of the gulf in early spring, and a blow from any quarter causes a more or less active stirring of the uppermost stratum by wave action.

During the spring of 1913 a northwesterly gale cooled the surface from 5° near the Isles of Shoals on April 13 to 4.6° on the 14th and 15th. The water then warmed to 7.9° by April 26, under the influence of unseasonably warm weather, when a northeasterly gale, with rain, followed by high northwest winds, once more chilled the surface to 6.7°. This was followed by another rise in surface temperature to 9.78° by May 6, when a third northwest gale, of several days duration, once more reduced it to about 7.2°. The wind then changed to the south, and by the 14th of May, when the latest observation was made, the surface temperature had risen to 8.11°.[10] Temporary upwellings of this sort are as clearly evidenced by a rise in salinity (p. 729) as by a fall in temperature.

APRIL

It is necessary to turn to the station data for 1920, combined with odd records for 1913 (p. 980) and 1925 (p. 1012), for a general picture of the temperature of the offshore waters of the gulf in April, remembering that after a mild winter readings 1° to 2° higher than those pictured (fig. 24) are to be expected in the coastal belt.

[10] For further details see Bigelow, 1914a, p. 395, fig. 7.

In 1920 the entire surface of the open gulf ranged between 3° and 4° by April 9 to 20, including the eastern part of Georges Bank, the Eastern Channel, and Browns Bank; except for one station on Platts Bank (20094), where active vertical circulation caused a fractionally lower surface reading (2.78°), and off the Kennebec River (station 20096, 2.78°), where a very low surface salinity (29.94 per mille, p. 1001) was

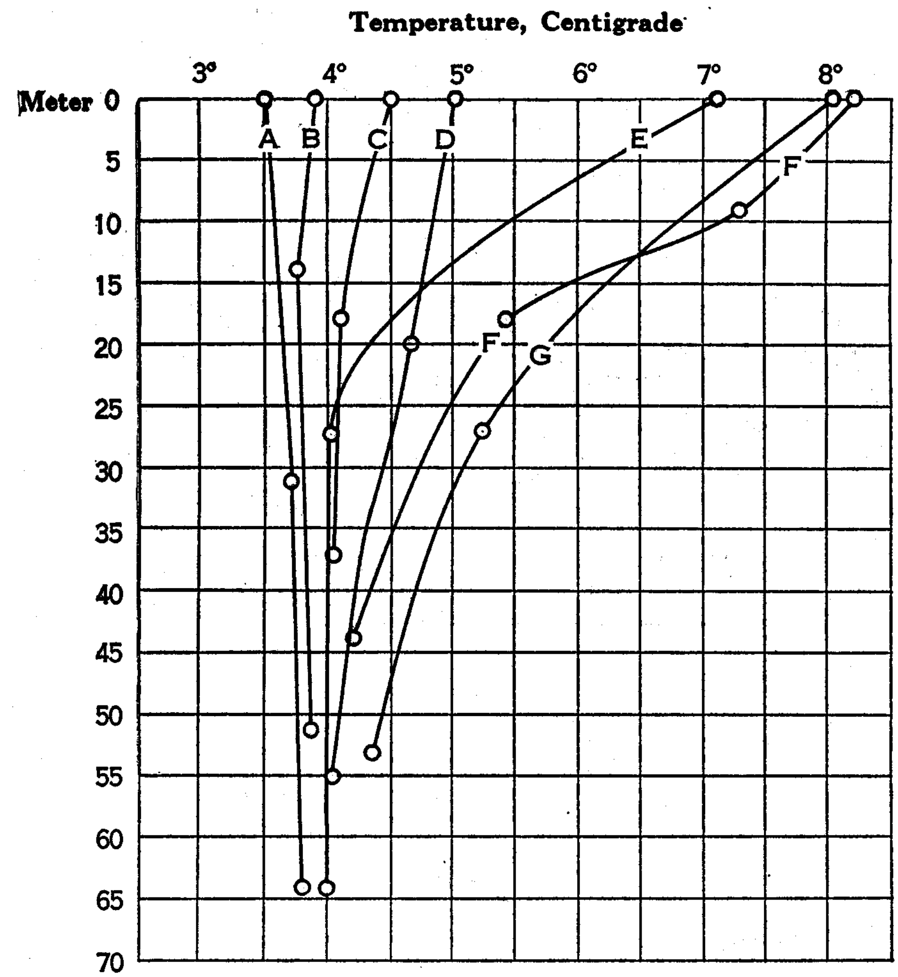

FIG. 23.—Vertical distribution of temperature near the Isles of Shoals and Boone Island at successive dates of the year 1913, to show the progress of vernal warming. A, March 29, 1913; B, April 5 (both near Boone Island); C, April 13; D, April 16; E, April 29; F, May 8; G, May 14 (C and F are near the Isles of Shoals)

unmistakable evidence of freshet water. In 1925 the surface of the coastal belt (Cape Ann to Mount Desert) was about 1 degree warmer at this season (*Halcyon* records, p. 1012), grading (south to north) from 5.5° to 2.5°–3.8°, though with the water to the eastward of Cape Elizabeth still continuing coldest next the land.[11]

[11] Close in to Boothbay 3.3°, but 4.4° near Seguin Island; 1.9° in Southwest Harbor, but 3 to 3.8° near Duck Island, off Mount Desert Island.

No temperatures were taken on the western part of Georges Bank or on Nantucket Shoals during April, 1920. In 1913 Mr. Douthart had surface readings of 6.6° on the northern part of Georges Bank on April 11 and 15, with 7.7° on its western side

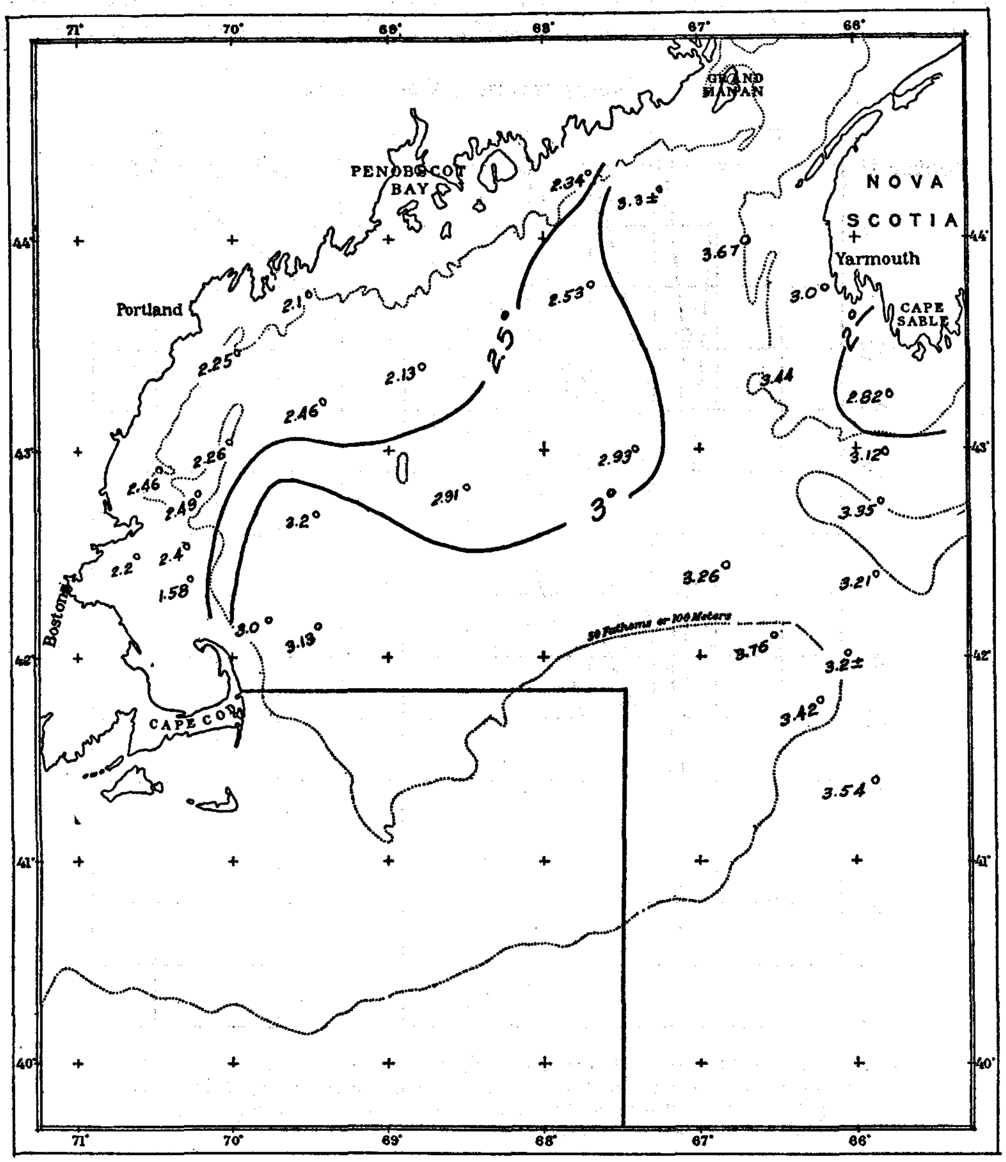

FIG. 24.—Temperature at a depth of 40 meters, April 6 to 20, 1920

on the 27th (p. 980). Taking into account the annual differences between early and tardy springs, temperatures about 2° lower might have been expected at these stations and dates in 1920. A surface reading of 3.3° on Rose and Crown Shoal near Nantucket Island on April 27, 1923 (p. 996) suggests that the surface has about the same temperature over Nantucket Shoals as that of the western and southwestern parts of the gulf generally at this season.

In 1920 the surface warmed by about 2° all along the belt from Massachusetts Bay to the Bay of Fundy from mid-March to mid-April; by less than 2° over the basin generally and along western Nova Scotia; by less than 1° on the eastern part of Georges Bank; and there had been no measurable change in surface temperature in the Eastern Channel (stations 20071 and 20107, 3.33°). In other words, where the surface is most chilled in winter it warms most rapidly in early spring.

The fact that the surface temperature increased over the German Bank–Cape Sable area and out across Browns Bank from March to April, 1920, is proof that the westward flow of Nova Scotian water, chilled by ice melting far to the eastward (p. 832), did not impress the temperatures of the gulf until still later in that spring, marking 1920 as a "tardy" year in this respect as in others. The opposite extreme is illustrated by a surface reading of 0° in the eastern side of the basin (the lowest yet recorded for the open gulf)[12] on March 28, 1919,[13] explicable only by some movement of cold water from the east, though as so thin a surface layer that neither the temperature nor the salinity were appreciably affected by it more than 20 to 30 meters downward.

In 1920 the mean temperature of the 40-meter level proved about 0.8° warmer in mid-April (fig. 24) than in mid-March, with this change greatest (1° to 1.67°) in the eastern side of the basin and off western Nova Scotia, resulting in a general equalization at 2.2° to 3° for the whole western and northwestern parts of the gulf, with 3° to 3.7° over the southern and eastern parts. In the warmer spring of 1925 the *Halcyon* found the 40-meter level about half a degree warmer—namely, about 3.2°—four miles off Cape Ann whistle buoy on April 17; 2.8° close to little Duck Island (off Mount Desert) on the 19th; and 2.9° eight miles out from Duck Island on that same day.

The progressive change in temperature was not so regular from March to April at depths greater than 40 to 50 meters in 1920, and wherever warming took place in the deep strata during the interval, it was accompanied by a corresponding rise in salinity, proving the source of heat to be warmer bottom water, solar warming not having penetrated more than a few meters downward as yet.

Thus the inner parts of the gulf north of the Cape Cod–Cape Sable line warmed by about as much (about 1.7°) from mid-March to mid-April at 100 meters (fig. 25) as at the surface. Virtually no change took place meantime in the 100-meter readings in the southern part of the basin, while the 100-meter level had cooled by nearly 1° in the southeastern part of the area, a change accompanied by a corresponding decrease in salinity (p. 735). Thus, it seems that the middle of April is the coldest season of the year in this region at this depth. This regional difference in the rate and order of the seasonal change of temperature tended to equalize the mid-stratum over the gulf as a whole, so instead of the regional range of nearly 5° obtaining at 100 meters in March (fig. 13), the highest and lowest readings at this depth were only 3.56° apart in April (fig. 25). While the general distribution of temperature remained the same—lowest (3° to 3.5°) along

[12] This reading is corroborated by a correspondingly low salinity (p. 727). [13] Ice patrol stations 1 to 3, p. 997.

the western slope of the basin and in the sink off Cape Ann, highest (4° to 6°) in the eastern side and in the Eastern Channel—the isotherms for April (fig. 25) do not outline the warm indraft into the eastern side as clearly as do those for March (fig. 13).

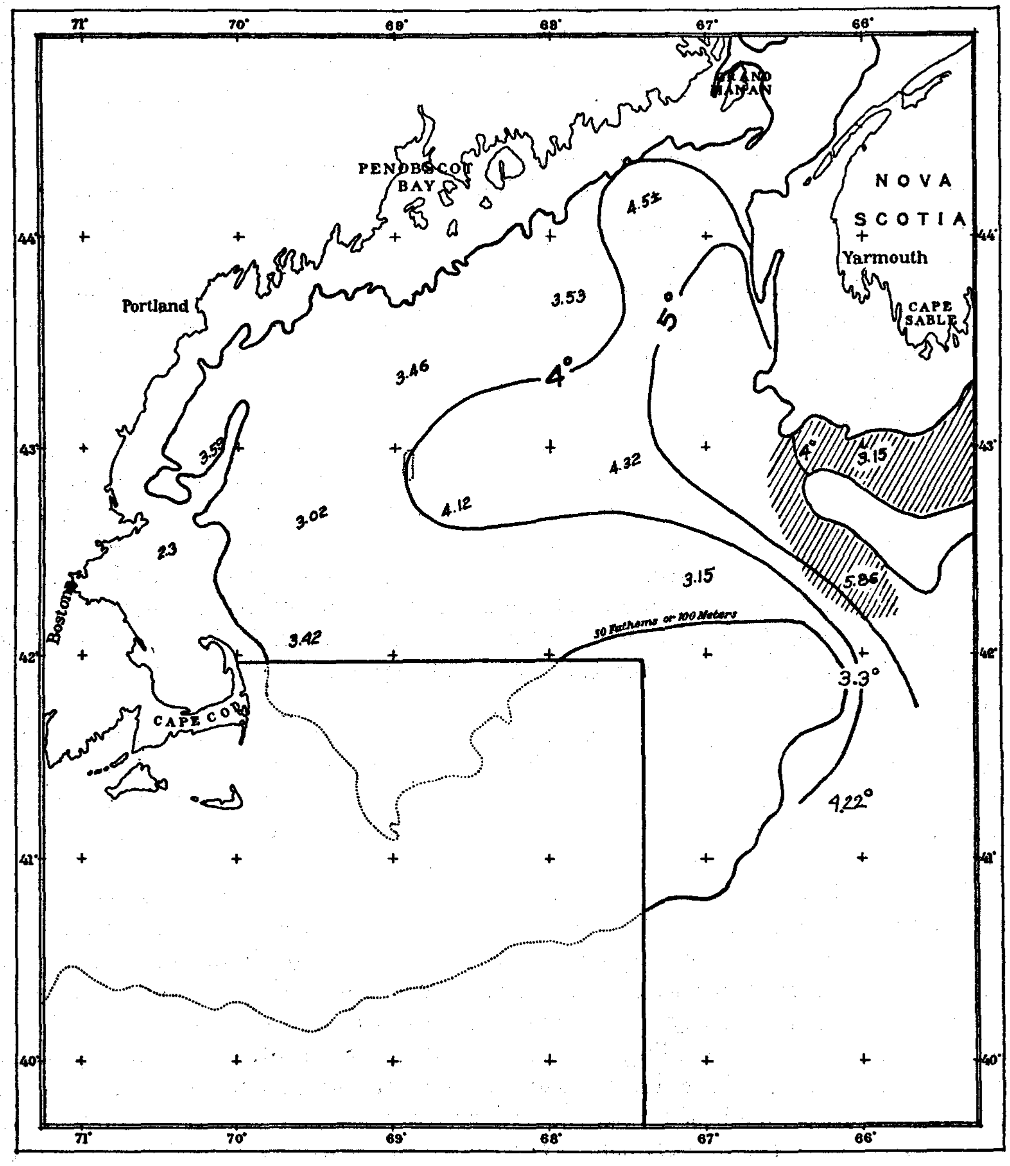

FIG. 25.—Temperature at a depth of 100 meters, April 6 to 20, 1920. The shaded area was colder in April than in March

Unfortunately the data do not afford an annual comparison for depths as great as this, no readings having been taken so deep in April, 1925; but temperatures of 2.7° to 2.9° at 80 to 84 meters in Massachusetts Bay on April 21 to 23 of that year, and of 2.9° at 91 meters at a station 8 miles off Little Duck Island (off Mount

Desert) on the 19th, are interesting as evidence that this general stratum was apparently no warmer in that spring than in the corresponding month of 1920, although the upper 40 meters of water was considerably so. Thus, as the depth increases, annual variations, like seasonal and regional variations, tend to diminish until a level is reached below which the temperature is governed chiefly by pulses in the bottom drift flowing in from the edge of the continent.

The bottom water at and below 200 meters was fractionally cooler in the eastern arm of the basin in April, 1920, than it had been in March, and fractionally warmer off the northern slope of Georges Bank and off Cape Ann (station 20115, 6.36° at 200 meters), with the deepest readings ranging only from 4.73° to 5.28° at 200 to 290 meters in the basin, rising to 6.07° in the Eastern Channel (station 20107). No observations were taken as deep as this on the continental slope in April, but a reading of 6.47° at 150 meters off the southeast face of Georges Bank on the 16th (station 20109) shows a rise of about 1.6° since March 12 (station 20068).

In March, 1920, it will be recalled (p. 541), the trough of the Eastern Channel below 100 meters was filled with water warmer than 6°, though no temperatures as high as this were encountered anywhere within the gulf. By mid-April, however, still warmer water (7.45° at 170 meters, fig. 26) had penetrated the channel, its effect (6 to 6.39°) spreading inward to the western side of the basin off Cape Ann (station 20115) as a thin stratum at 180 to 260 meters, but with slightly cooler (4.92°) water below it.[14]

Again, on March 5, 1921, there was a thin, warm stratum (6° to 6.4°) at 160 to 210 meters off Cape Ann. Evidently, therefore, temperatures as high as 6° may be expected below about 175 to 200 meters in the western arm of the basin of the gulf at any time from March to April (in summer, also), though not invariably. This warm stratum, when it occurs, may either be sandwiched in between lower temperatures in the bottom of the trough below, as well as above, or may extend right down to the bottom, with the vertical distribution of temperature following the curves shown in the accompanying graphs (figs. 3 and 5).

Temperature and salinity combined establish the Eastern Channel as the source of this indraft into the bottom of the gulf. Its course across the latter (unfortunately not chartable in detail from the data yet on hand) is discussed in a later chapter (p. 921). There is strong evidence that it takes the form of intermittent pulses, the 6°-water encountered off Cape Ann in April, 1920 (station 20115), being the result of such a pulse; for it seems to have been entirely cut off from the still warmer source in the Eastern Channel at the time by fractionally lower temperatures in the southeastern bowl of the gulf (stations 20112 and 20113).

These pulses are so important in the general circulatory system of the Gulf of Maine that an April profile along the arc of the banks (fig. 26) is introduced here for comparison with that of the preceding month (fig. 19). The most important seasonal alteration is the rise in temperature at 150 to 200 meters in the channel just mentioned, which could only result from the actual introduction of water of still higher temperature from offshore. On the other hand, vernal warming from above and a delay in the westward flood of Nova Scotian water until later in the

[14] No readings so high were obtained anywhere in the southern or eastern parts of the basin that April, the maxima being respectively, 5.28°, 5.14°, 5 28°, and 5.16° in depths of 210, 2 25, 175, and 165 to 230 meters at stations 20098, 20100, 20107, 20112, and 20113.

spring than this event is usually to be expected allowed a decided warming of the upper stratum to 2.8° to 3.5° from the Cape Sable slope out to Browns Bank, though with very little change from March to April on the Georges Bank side.

MAY

SURFACE

From late April, on, the temperature of the western side of the gulf constantly rises, most rapidly at the surface, progressively slower with increasing depth. Near Cape Sable, in the eastern side, however, the vernal cycle is dependent on the volume, temperature, and seasonal "time table" of the Nova Scotia current. Where

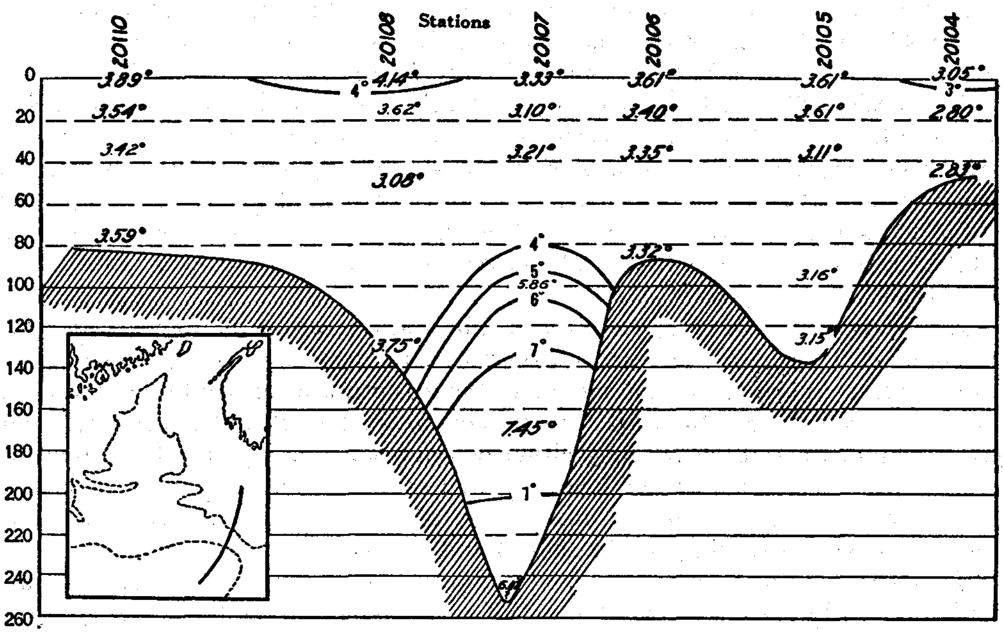

FIG. 26.—Temperature profile running from the eastern part of Georges Bank, across the Eastern Channel, Brown's Bank, and the Northern Channel, for April 15 and 16, 1920

this debouches into the gulf the surface stratum is at its coldest some time in April or even as early as the last of March in "early" years (1919, for instance), but not until May in "late" years, as probably happened in 1920. Unfortunately, neither of our May cruises (1915, 1920, or 1925), nor the ice patrols stations for 1919, has covered the gulf as a whole; hence I can offer only a composite picture for the month, based on years that certainly differed considerably in the rate of vernal warming and in the date at which the chilling effect of the Nova Scotian current reached its maximum.

On this basis the highest surface temperatures of early May (fig. 27) are to be expected in Massachusetts Bay, the lowest in the Cape Sable-German Bank region, with the whole area west of the longitude of Penobscot Bay warmer than 6° by the 10th, if not earlier, contrasted with surface readings of about 3° or lower off western Nova Scotia.[15]

15 Three degrees on German Bank, May 9, 1915 (station 10271); 2.7° there on Apr. 28, 1919 (ice patrol station No. 22)

In 1915 a west-east gradation in surface temperature was recorded along the coast of Maine from May 10 to 14, from 7.8° near the Isles of Shoals and off Casco Bay to 5° off Penobscot Bay and 4.2° to 4.8° near Mount Desert Island. No doubt the precise readings vary with the state of the weather, however, as well as with the date and exact locality and from year to year. I must also caution the reader that at this season the surface temperature is changing so rapidly in the western side of the gulf that a difference of a few days, one way or another, will make a considerable difference in the readings obtained; less so in the eastern side.

Although the precise surface temperatures at any given date vary from one May to the next, depending largely on the forwardness of the season on the land, probably

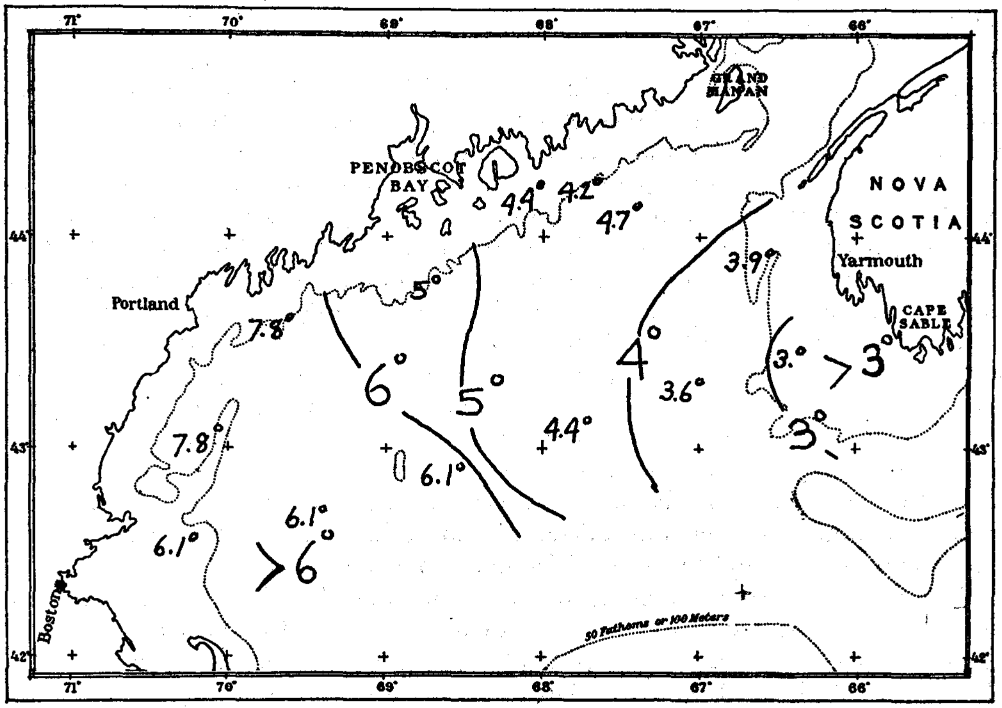

FIG. 27.—Surface temperature, first half of May, 1915

the comparative rates of vernal warming do not vary widely from year to year in different parts of the gulf.

It appears from combining the records for the three years 1913, 1915, and 1920, that this change is most rapid in the inner part of Massachusetts Bay, where the surface warmed from 3.05° on April 6 (station 20089) to 8.89° on May 16 (station 20123) in 1920. Similarly, temperatures taken by the *Fish Hawk* in 1925 show the surface of the southern side of the bay, generally, warming from 5.3° to 6.8° on April 21 to 23, to 7° to 11° on May 20 to 22.

At the mouth of the bay, where the surface does not chill to so low a figure at the end of the winter, a less rapid rate of vernal warming causes about the same

May temperatures. In 1925, for instance, the surface temperature at a line of stations from Cape Ann to Cape Cod rose from 4.3° to 4.4° on April 21 to 23 to 8.3° to 9.4° on May 20 to 22 (*Fish Hawk* cruise 13); and vernal warming proceeded at about this same rate there in 1920, when the surface reading rose from 2.5° off Gloucester on March 1 (station 20050) and 3.3° on April 9 (station 20090) to 6.39° on May 4 (station 20120) and 9.72° on May 16 (station 20124).

This thermal change is accompanied by an alteration in the regional distribution of surface temperature over the bay. Cape Cod Bay continues to be its warmest center, the immediate vicinity of its northern coast line its coldest, reflecting local stirring by the tide or some upwelling, as is the case in April (fig. 22). In 1925, however, the summer state was foreshadowed, as early as the last week in May, by slightly higher surface readings (9°) at the outer stations than between Stellwagen Bank and the shore (fig. 28).

The surface of Ipswich Bay, just north of Cape Ann, warms as rapidly from April through May as does Massachusetts Bay, judging from readings of 3.05° on April 9, 1920 (station 20092) and 7.22° on May 7 and 8 (station 20122).

Similarly, the surface temperature of the basin abreast of northern Cape Cod rose from 3.61° on April 19 (station 20116) to 9.17° on May 16 (station 20125); the surface of Gloucester and Boothbay Harbors rose from about 4° to about 9° between April 15 and May 15, and Lubec Channel from about 2° to about 5° during this same interval (figs. 29 to 31). As Doctor McMurrich[16] records a rise from about −1.67° at St. Andrews, on March 3, to about 5° to 6° in mid-May after the very cold and snowy winter of 1916, when the water was about 1° colder there than it was in 1917 (Willey, 1921) or than it is likely to be again for some years to come, the surface may be expected to warm by about 5° to 6° between the middle of April and the middle of May all along the western and northern shores of the gulf and out over the southwestern part of the basin generally. This warming, however, is made irregular, no doubt, or even intermittent, by local fluctuations in the weather (e. g., belated snowstorms) and by the cold freshets from the rivers.

The rise in surface temperature proceeds somewhat less rapidly out across Georges Bank, on the southwestern side of which we found the surface only about 3° warmer on May 17, 1920 (stations 20128 and 20129), than it had been there on February 22 (stations 20045 and 20046). Vernal warming is also less and less rapid from west to east across the gulf (fig. 32), with readings only fractionally higher along the coast of Maine east of Mount Desert Island on May 10 and 11, 1915, than on April 12, 1920, or between Grand Manan and Nova Scotia in 1917.[17]

Whether the surface stratum is warmer or colder in May than in April, from southern Nova Scotia out across German Bank (where the Nova Scotian current from the eastward exerts its chief effect), depends on the date when this current reaches its maximum and slackens again, events that certainly fall several weeks earlier in some years than in others. In 1919, as noted above (p. 553), icy water from this source was pouring into the gulf as early as the last week of March in volume sufficient to chill the surface to 0° as far west as the eastern side of the basin; but

[16] Plankton lists (p. 513).

[17] Mavor (1923, p. 375) records the surface at *Prince* station 3 as 2.27° on Apr. 9, 1917, and 2.96° on May 4.

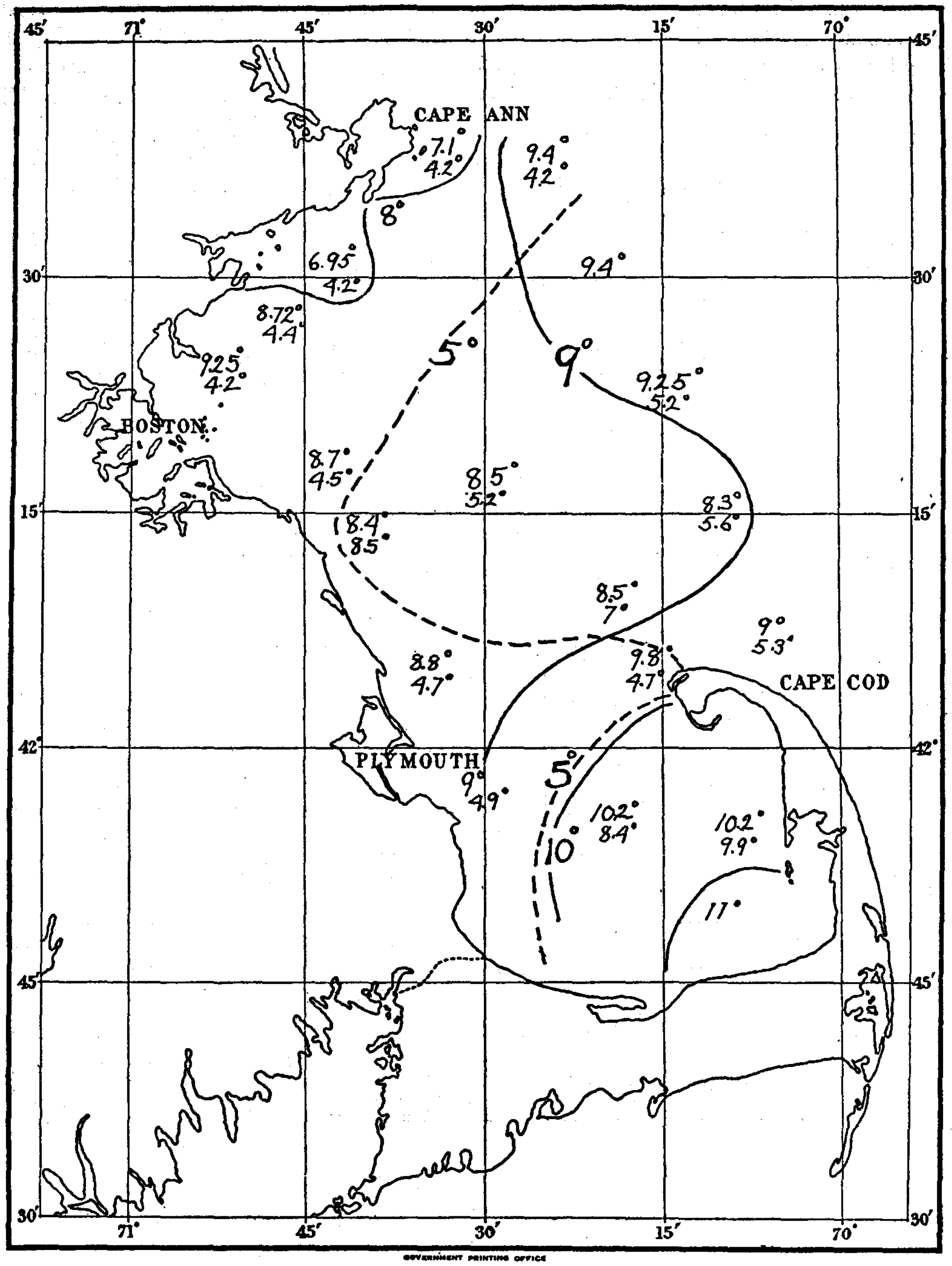

FIG. 28.—Surface temperature of Massachusetts Bay at the surface (solid curves) and at 20 meters (broken curves), May 20 to 22, 1925

its flow must then have slackened (or its temperature have risen), because the surface temperature of the critical locality rose to 4.6° by April 28 and to 7.8° on May 29, though the whole column of water on German Bank was still only 2.7° and 4.2°, respectively, on these dates (ice patrol stations 3, 21, 22, 37, and 38, p. 997). The seasonal time-table seems to have been about the same in 1915, when the cold Nova Scotian water was responsible for a temperature of about 3° from German Bank out across the eastern side of the basin on May 6 to 7 (fig. 27), suggesting that the

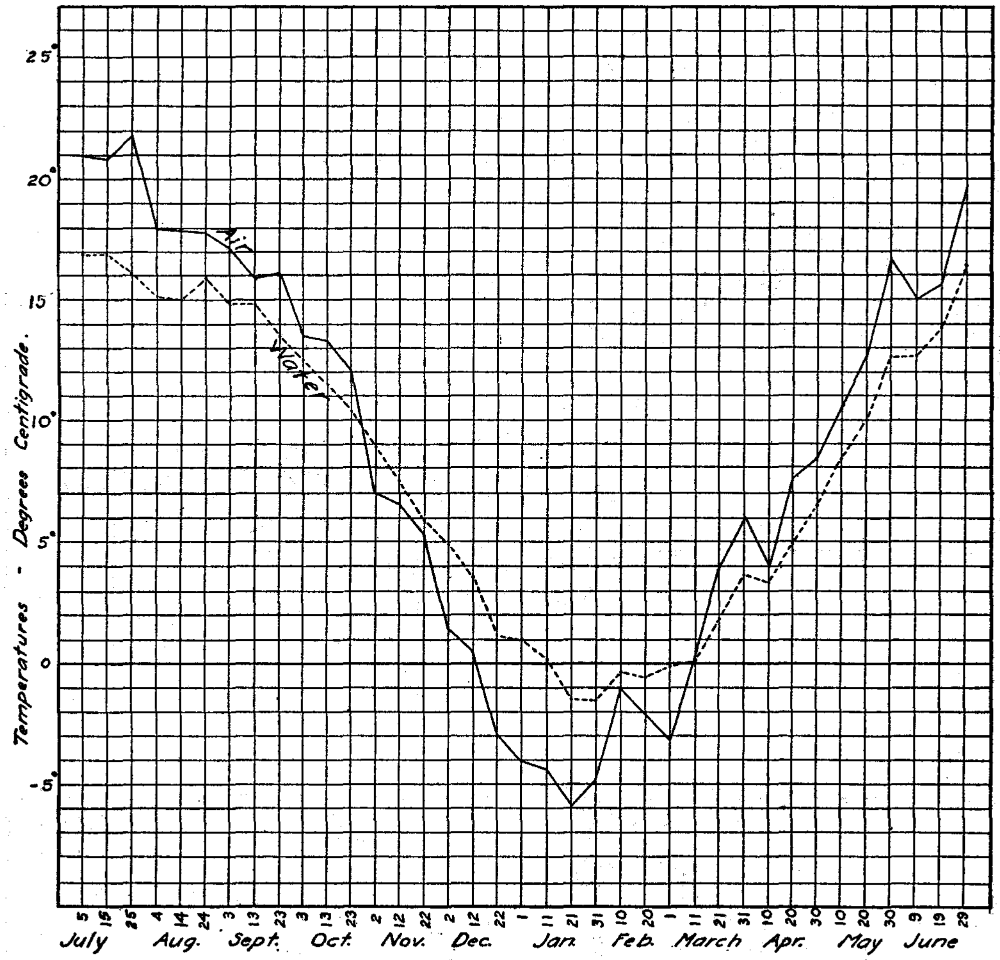

FIG. 29.—Mean air temperature (solid curve) and water temperature (broken curve) for 10-day intervals at Ten Pound Island, Gloucester Harbor, Mass., from July 1, 1919, to June 30, 1920

inrush into the gulf had reached its head some time in late March or April of that year. In 1920, however, it is certain that the cold current did not begin to flood past Cape Sable into the gulf in any considerable volume until after the middle of April.

Water as cold as 0.27° to 0.56° had, it is true, spread westward past La Have Bank to within a few miles of the longitude of Cape Sable as early as the 19th of March, 1920 (station 20075); but this seems to have constituted its western boundary during the next four weeks, because the whole column warmed by about 1° on German Bank and near the Cape between March 23 and April 15 (stations 20085 and 20103, 20084 and 20104), instead of chilling, or at least remaining stationary in temperature, as would have happened with any considerable flow of 0° to 1° water from the east. Nor did any extension of icy water develop to the southwestward along the offshore banks or continental slope during the interval.

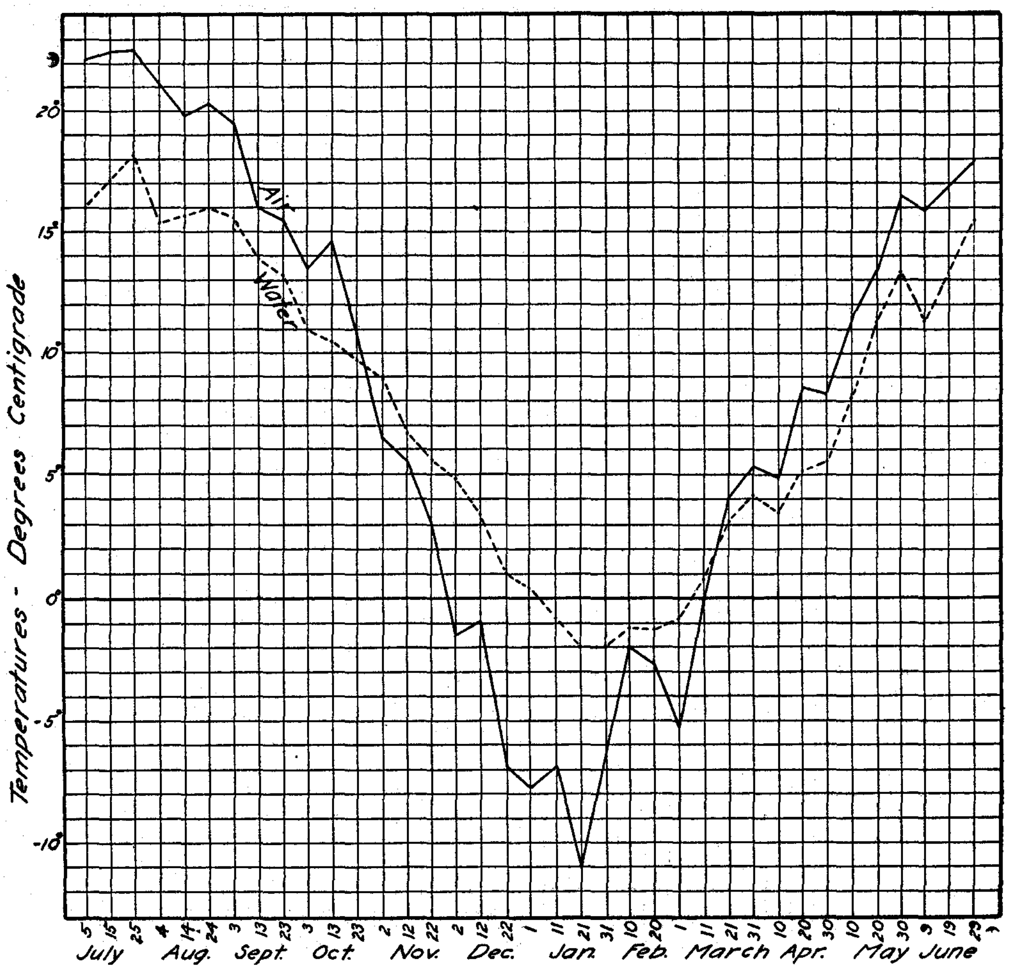

FIG. 30.—Mean air temperature (solid curve) and water temperature (broken curve) in Boothbay Harbor, Me., for 10-day intervals from July 1, 1919, to June 30, 1920

The greatest inflow of this cold water into the gulf may therefore be expected between the last week of March and the middle of April in "early" years, but not until the last of April or first part of May in "late" years. In spite of this annual variation in date, the close agreement between the late April–early May temperatures of 1915 and 1919 in the region most affected by it, and the uniformity in temperature in the eastern side of the gulf summer after summer, enlarged on below

(p. 626), suggests that it is not only a regular annual event but that the inflow from this source is comparatively uniform, both in volume and in temperature, from year to year. Its chilling effect on the surface temperature certainly extends northward along the Nova Scotian slope of the gulf as far as the neighborhood of Lurcher Shoal, where the whole column of water in 90 to 140 meters was about 0.4° colder on May 10, 1915 (station 10272), than on April 12, 1920 (station 20101)—just the reverse of the seasonal change to be expected.

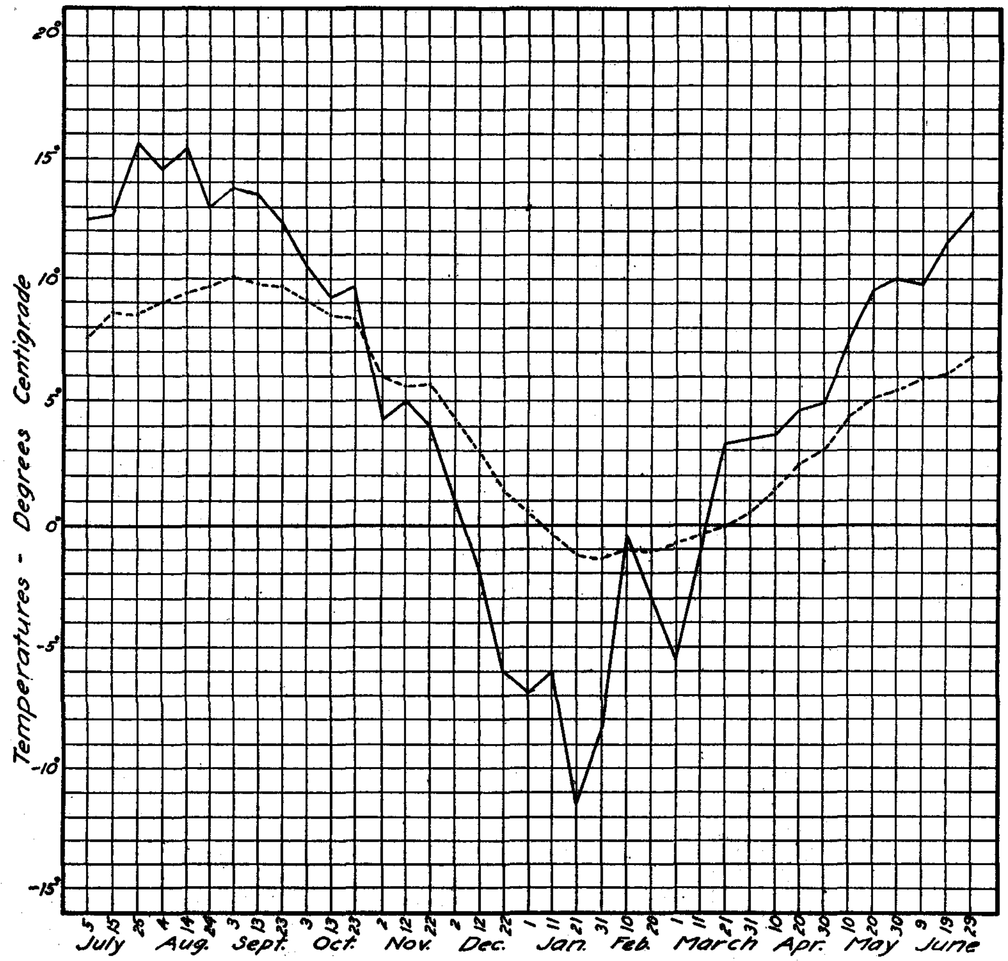

FIG. 31.—Mean air temperature (solid curve) and water temperature (broken curve) in Lubec Narrows, for 10-day intervals from July 1, 1919, to June 30, 1920.

It is much to be regretted that no data are available for May for the region from Cape Sable out across Browns Bank, the Eastern Channel, or the eastern end of Georges Bank. Lacking such, I can not outline the effect of the Nova Scotian current in this direction. Probably, however, icy water from this eastern source overflows Browns Bank at some time during April or May, perhaps the eastern end of

Georges Bank, also; and the presence of a band of water cooler than its immediate surroundings along the outer side of the latter bank and off Marthas Vineyard in summer (p. 608) suggests its influence.

It is still an open question how far westward into the gulf the vernal warming of the surface is retarded by this same agency. Even without its chilling effect, the surface probably would not warm as rapidly in the eastern side of the gulf as in the western, because the heat received there from the sun is more rapidly dispersed downward by more active vertical tidal stirring. Consequently, a slight west–east differential in surface temperatures, late in spring or early in summer, does not necessarily

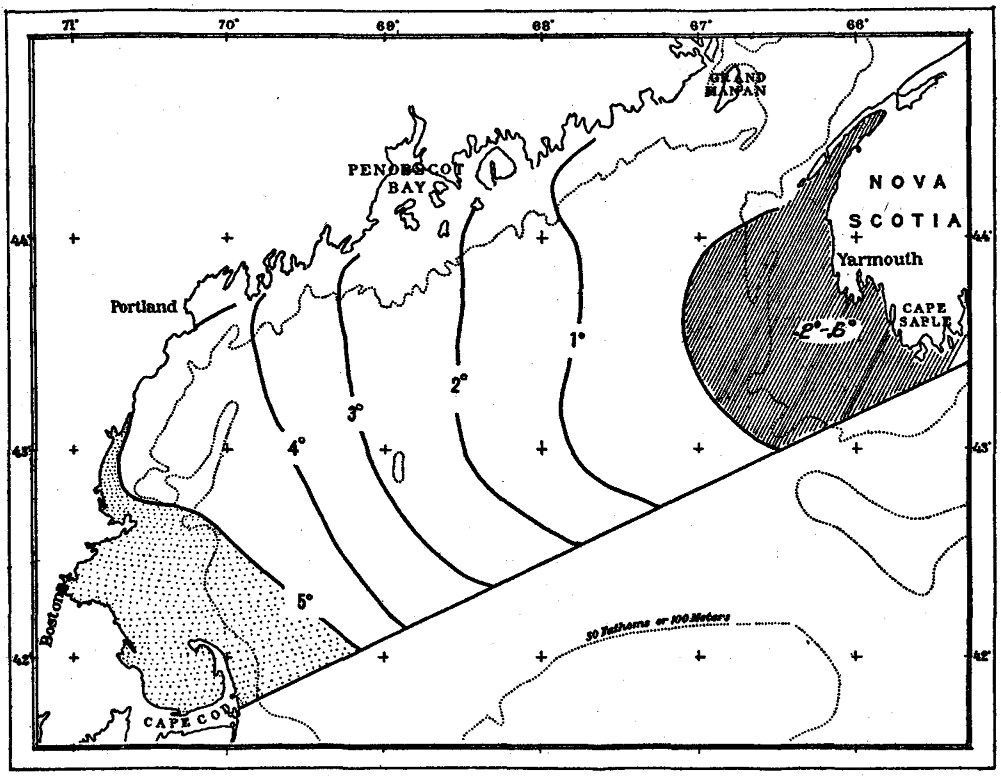

FIG. 32.—Normal rise in surface temperature from mid-April to mid-May. The hatched area experiences cooling

imply cold water from the eastward as its cause unless it reflects a corresponding difference in the mean temperature of the upper 40 to 60 meters.

Up to the present time we have found no positive thermal evidence of the Nova Scotian water beyond the eastern arm of the basin (the situation of ice patrol station No. 3, p. 997); and the temperature (salinity, too) of the gulf is so uniform from summer to summer that vernal chilling from this source is not to be expected farther west than this, unless an exceptional spring may see a much greater inflow of cold water from the east than usual past Cape Sable.