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.

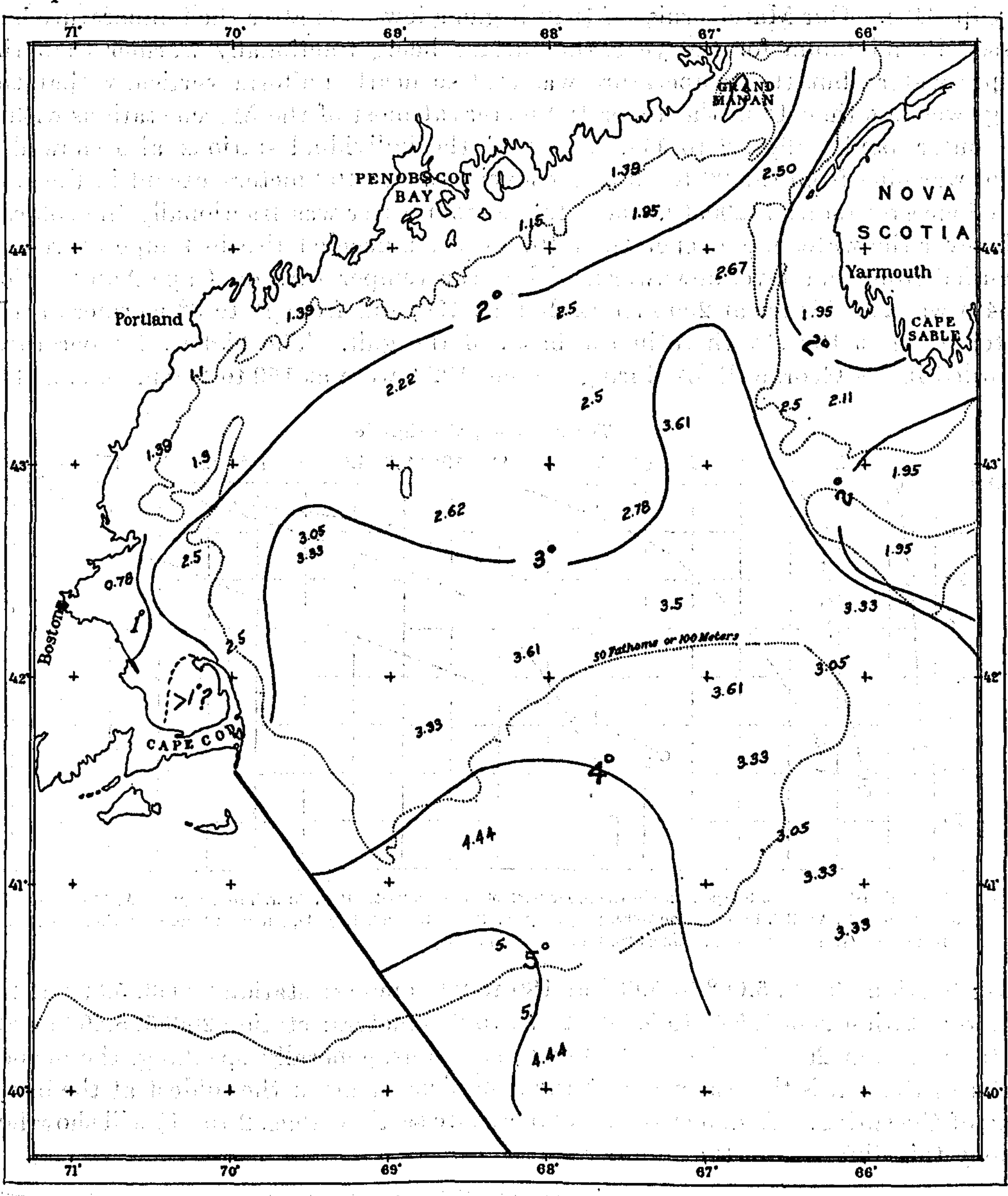

Fig. 1.—Temperature at the surface, February–March, 1920

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-

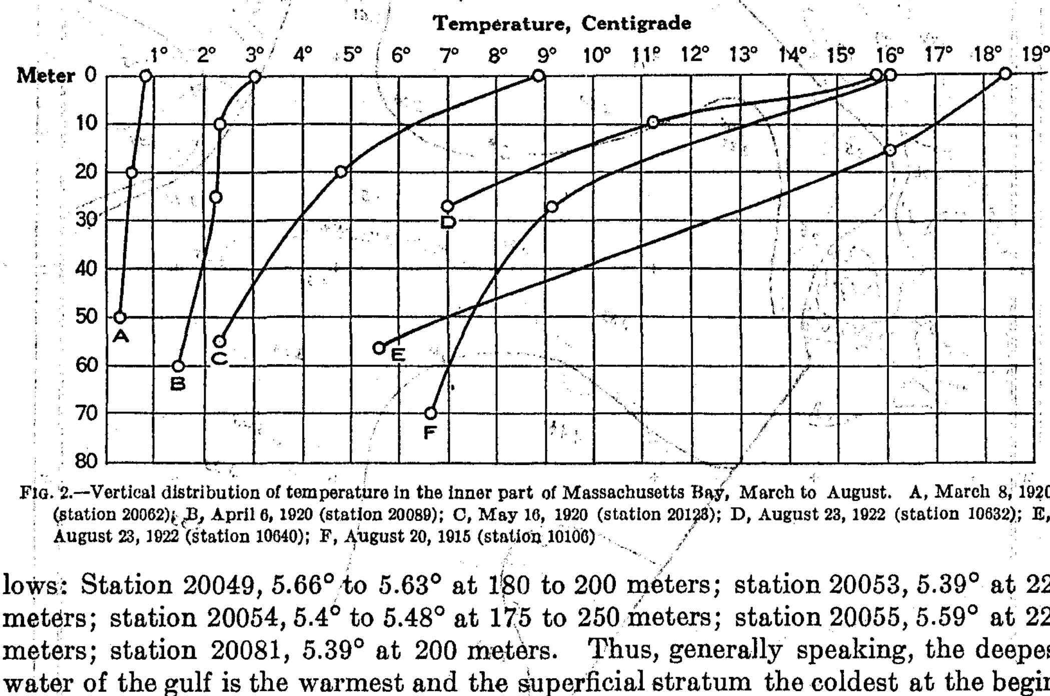

FIG. 2.—Vertical distribution of temperature in the inner part of Massachusetts Bay, March to August. A, March 8, 1920 (station 20062); B, April 6, 1920 (station 20089); C, May 16, 1920 (station 20128); D, August 23, 1922 (station 10632); E, August 23, 1922 (station 10640); F, August 20, 1915 (station 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,

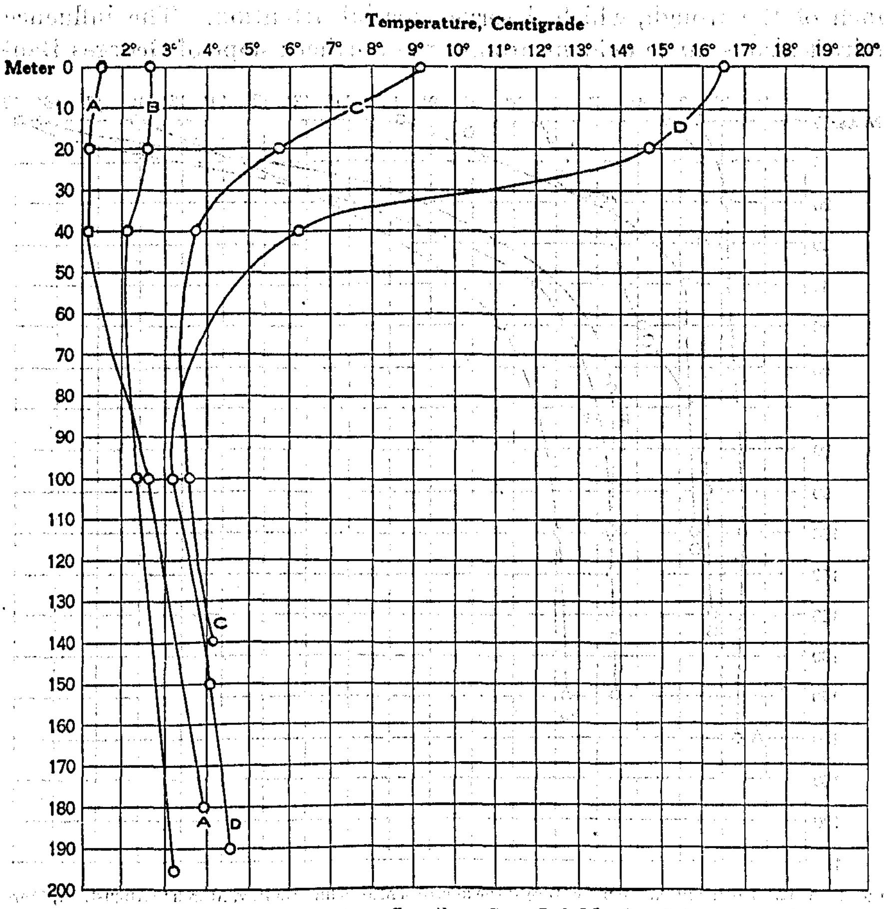

FIG. 3.—Vertical distribution of temperature off northern Cape Cod, March to July. A, March 24, 1920 (station 20088); B, April 18, 1920 (station 20116); C, May 16, 1920 (station 20125); D, July 19, 1914 (station 10214)

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-

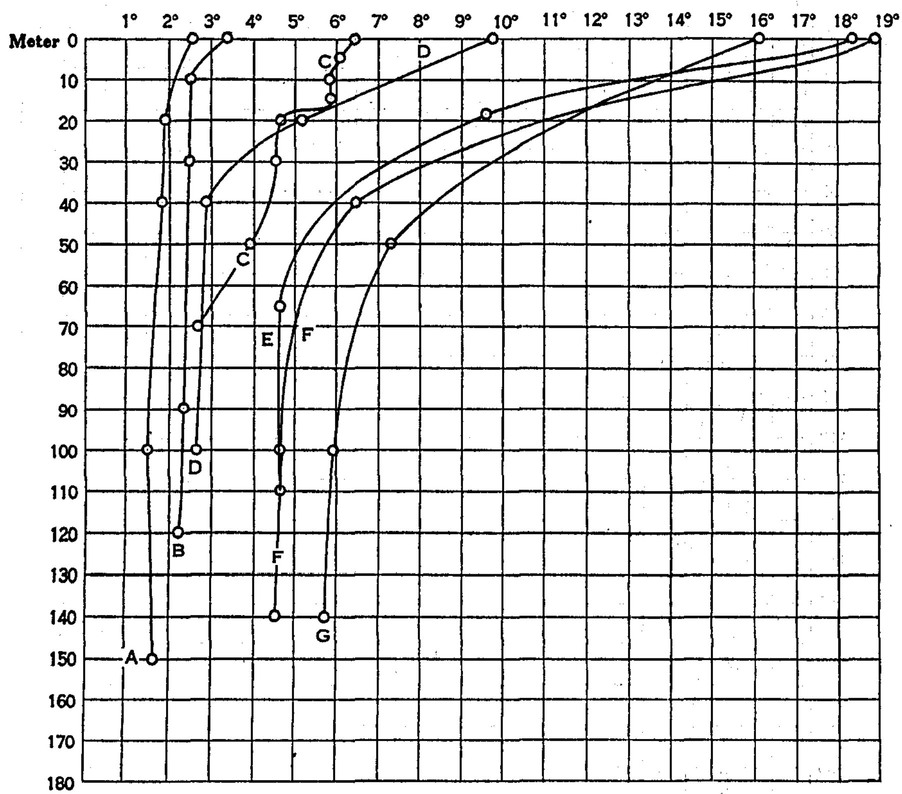

FIG. 4.—Vertical distribution of temperature at the mouth of Massachusetts Bay, March to August. A, March 1, 1920 (station 20050); B, April 9, 1920 (station 20090); C, May 4, 1920 (station 20120); D, May 16, 1920 (station 20124); E, July 20, 1912 (station 10002); F, August 22, 1914; G, August 31, 1915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

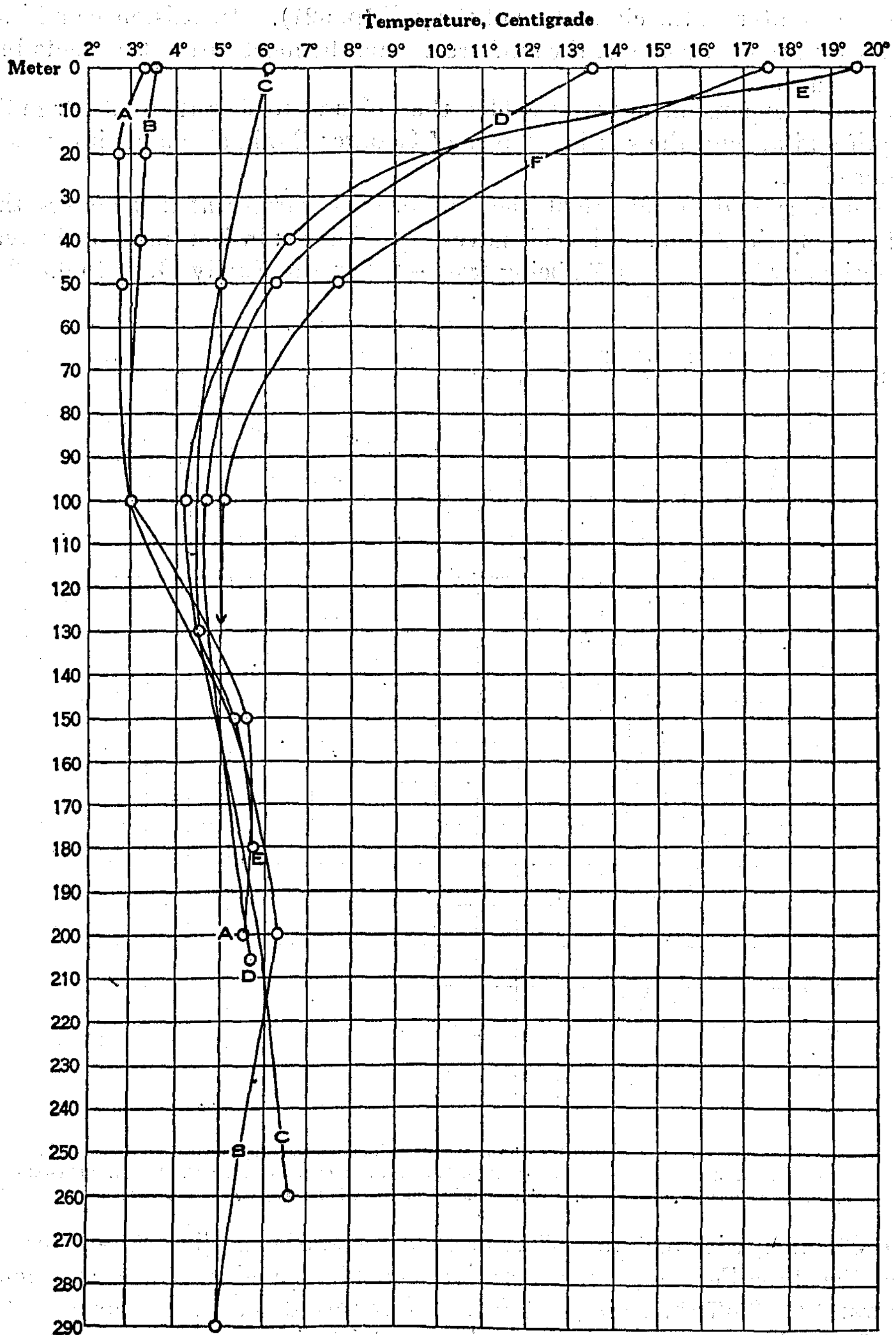

FIG. 5.—Vertical distribution of temperature in the western arm of the basin, off Cape Ann, March to August. A, February 23, 1920 (station 20049); B, April 18, 1920 (station 20115); C, May 4, 1915 (station 10267); D, June 26, 1915 (station 10299); E, August, 31, 1915 (station 10307)

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

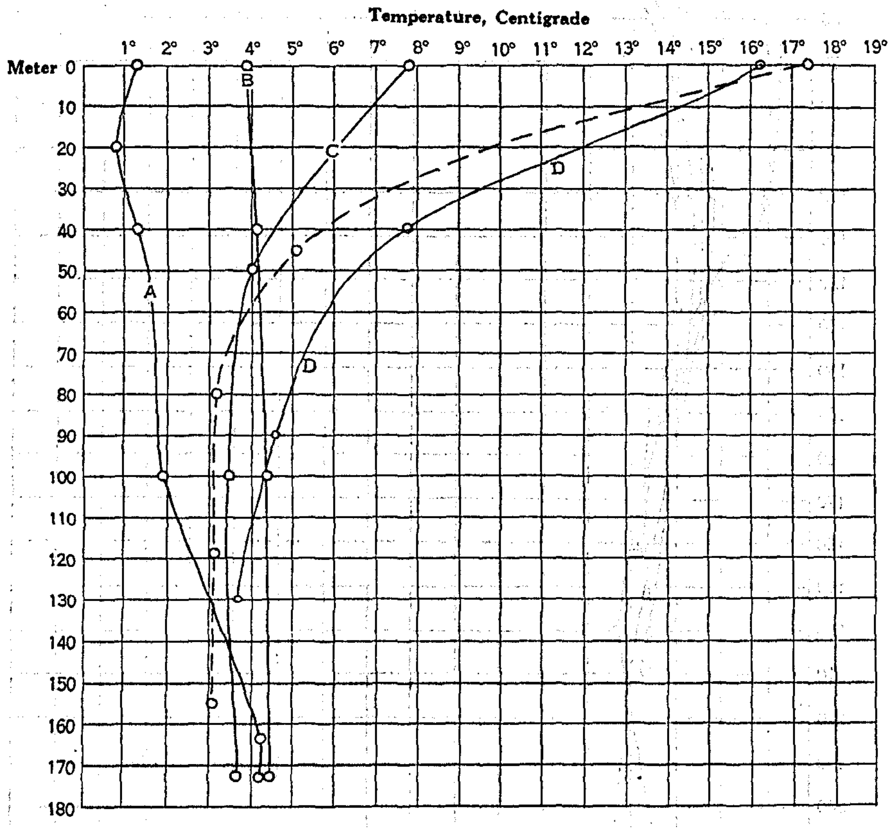

FIG. 6.—Vertical distribution of temperature in the deep trough between Jeffreys Ledge and the coast, March to August. A, March 5, 1920 (station 20061); B, March 5, 1921 (station 10509); C, May 14, 1914 (station 10278); D, August 22, 1914 (station 10252). The broken curve is for August 9 of the cold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

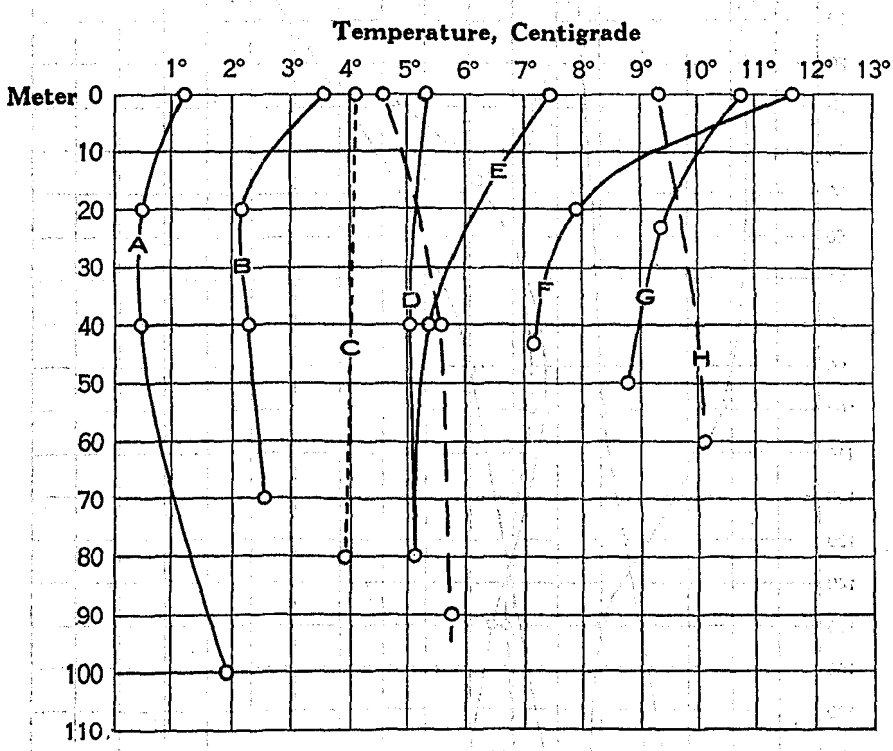

FIG. 7.—Vertical distribution of temperature near Mount Desert Island in various months. A, March 3, 1920 (station 20056); B, April 12, 1920 (station 20099); C, May 10, 1915 (station 10274); D, June 11, 1915 (station 10284); E, June 14, 1915 (station 10286); F, July 19, 1915 (station 10302); G, August 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-

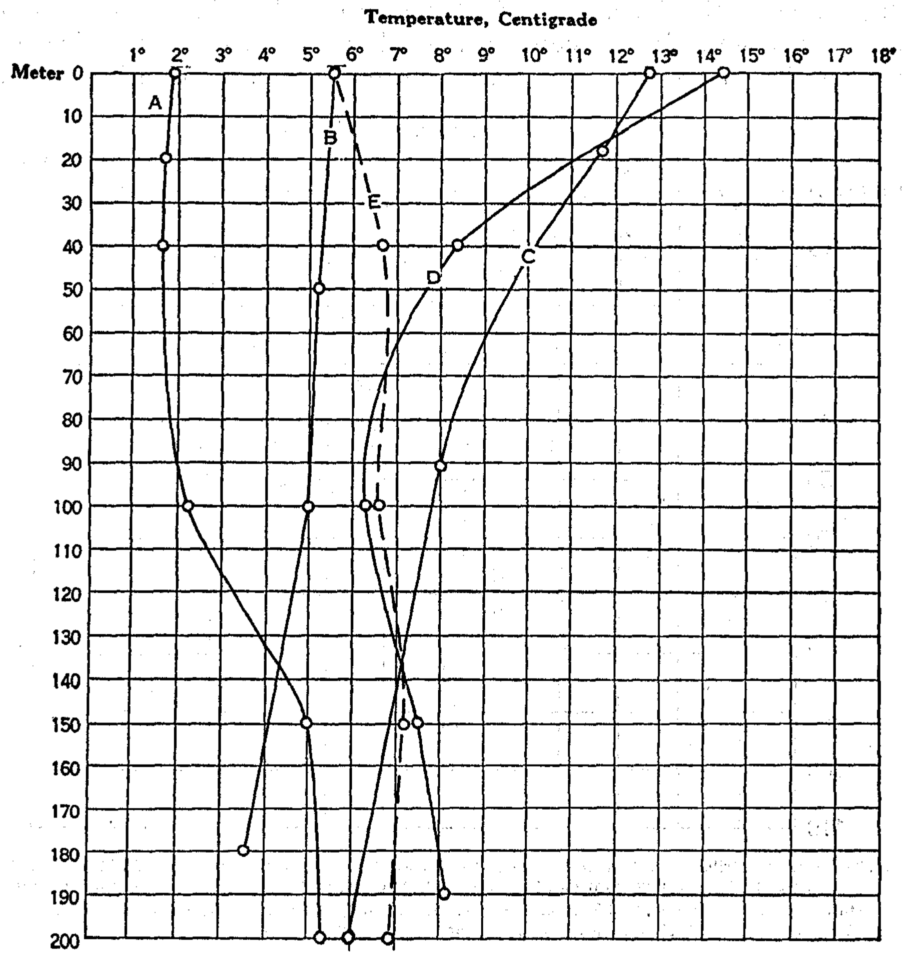

FIG. 8.—Vertical distribution of temperature in the northeastern corner of the Gulf of Maine. A, March 22, 1920 (station 20081); B, June 10, 1915 (station 10283); C, August 12, 1913 (station 10097); D, August 12, 1914 (station 10246); E (broken curve), January 5, 1921 (station 10502)

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

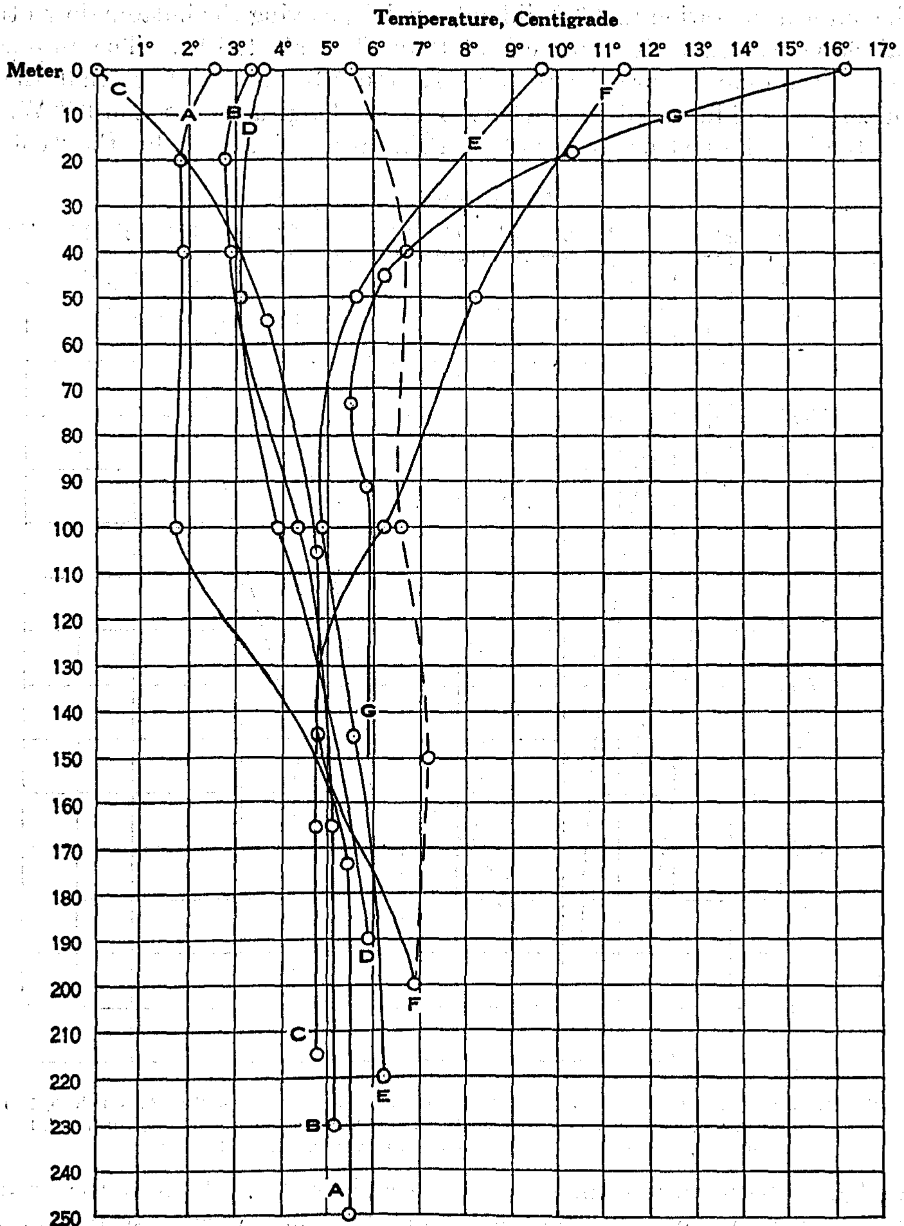

FIG. 9.—Vertical distribution of temperature in the eastern side of the basin of the Gulf of Maine. A, March 3, 1920 (station 20054); B, April 17, 1920 (station 20113); C, March 28, 1919 (Ice Patrol Station No. 3); D, May 6, 1915 (station 10270); E, June 19, 1915 (station 10286); F, August 7, 1915 (station 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"

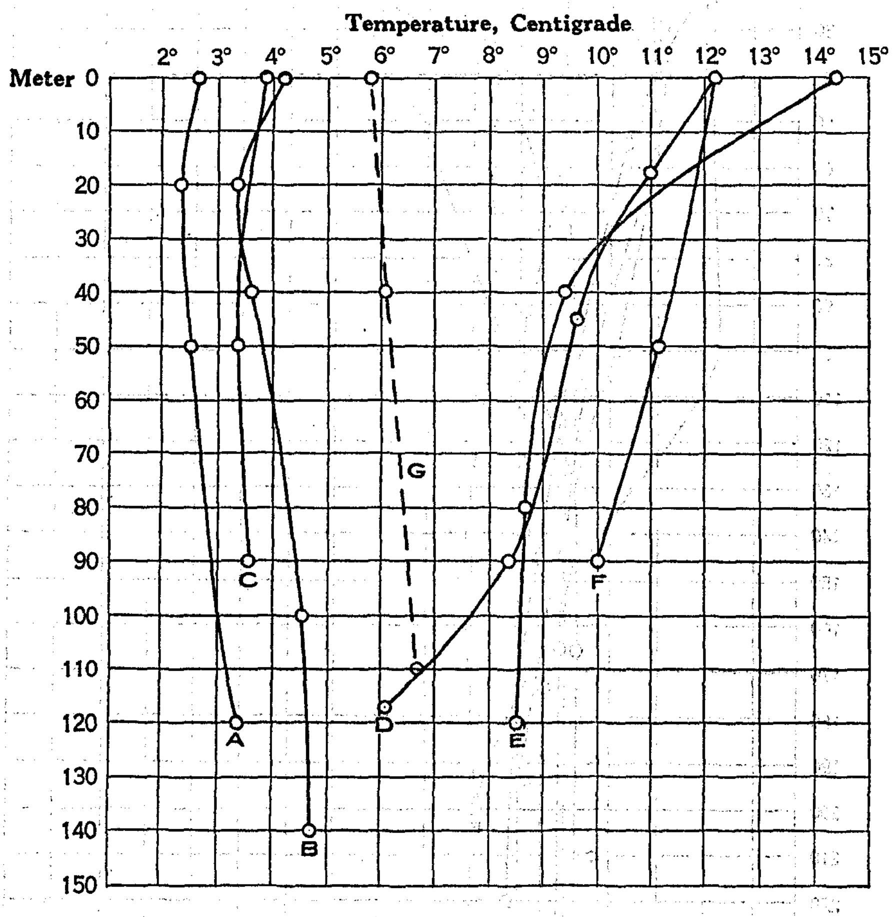

FIG. 10.—Vertical distribution of temperature near Lurcher Shoal in various months. A, March 23, 1920 (station 20082); B, April 12, 1920 (station 20101); C, May 10, 1915 (station 10272); D, August 12, 1913 (station 10096); F, August 12, 1914 (station 10245); G, January 4, 1921 (station 10500)

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

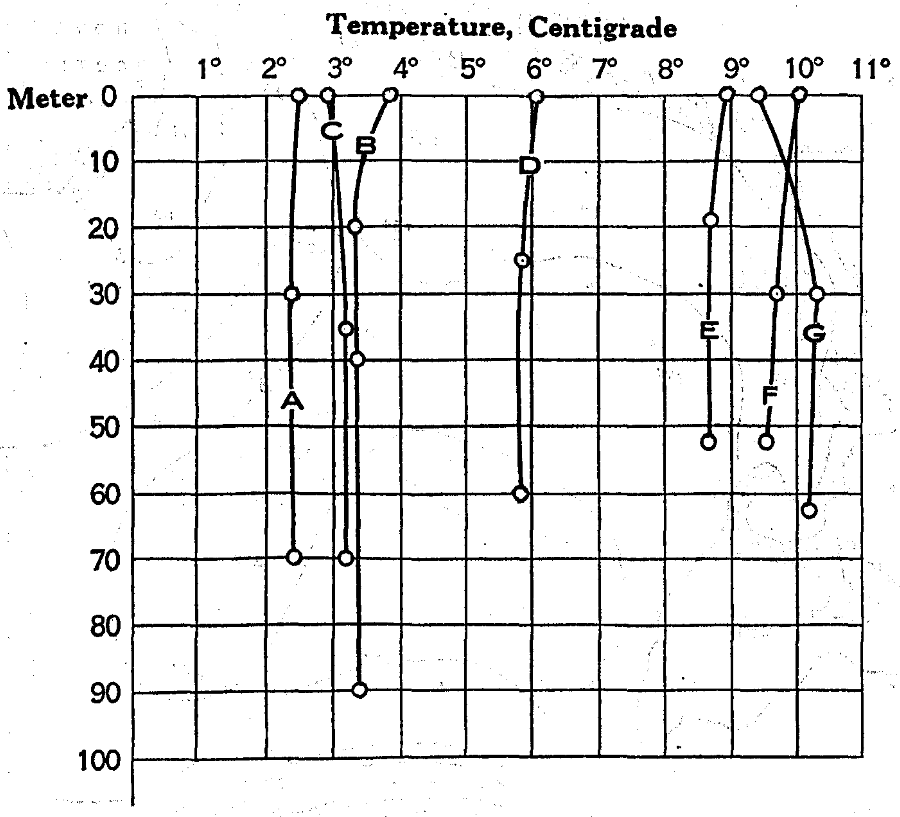

FIG. 11.—Vertical distribution of temperature on German Bank, March to September. A, March 23, 1920 (station 20085); B, April 15, 1920 (station 20103); C, May 7, 1915 (station 10271); D, June 19, 1915 (station 10290); E, August 12, 1913 (station 10095); F, August 12, 1914 (station 10244); G, September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

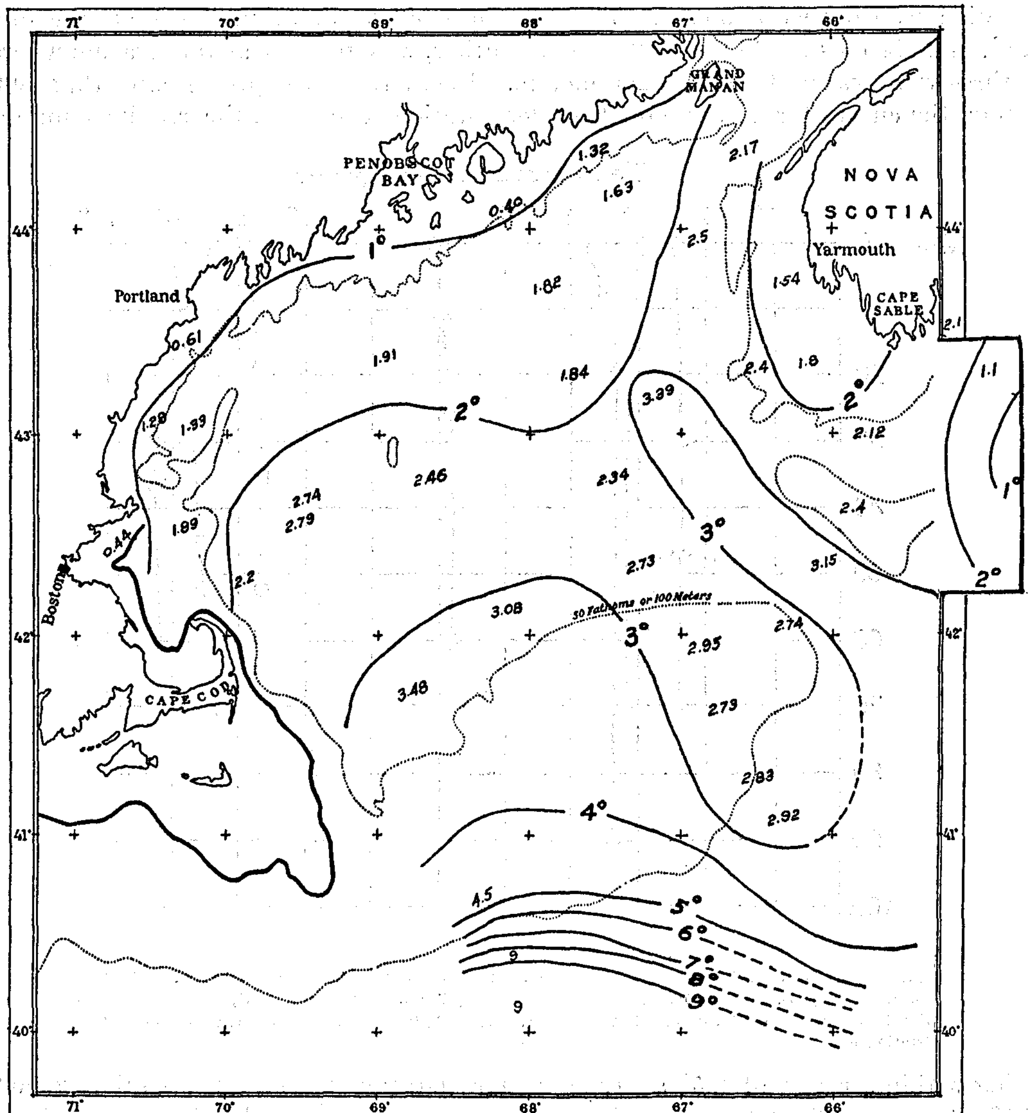

FIG. 12.—Temperature at a depth of 40 meters, Febuary-March, 1920

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.

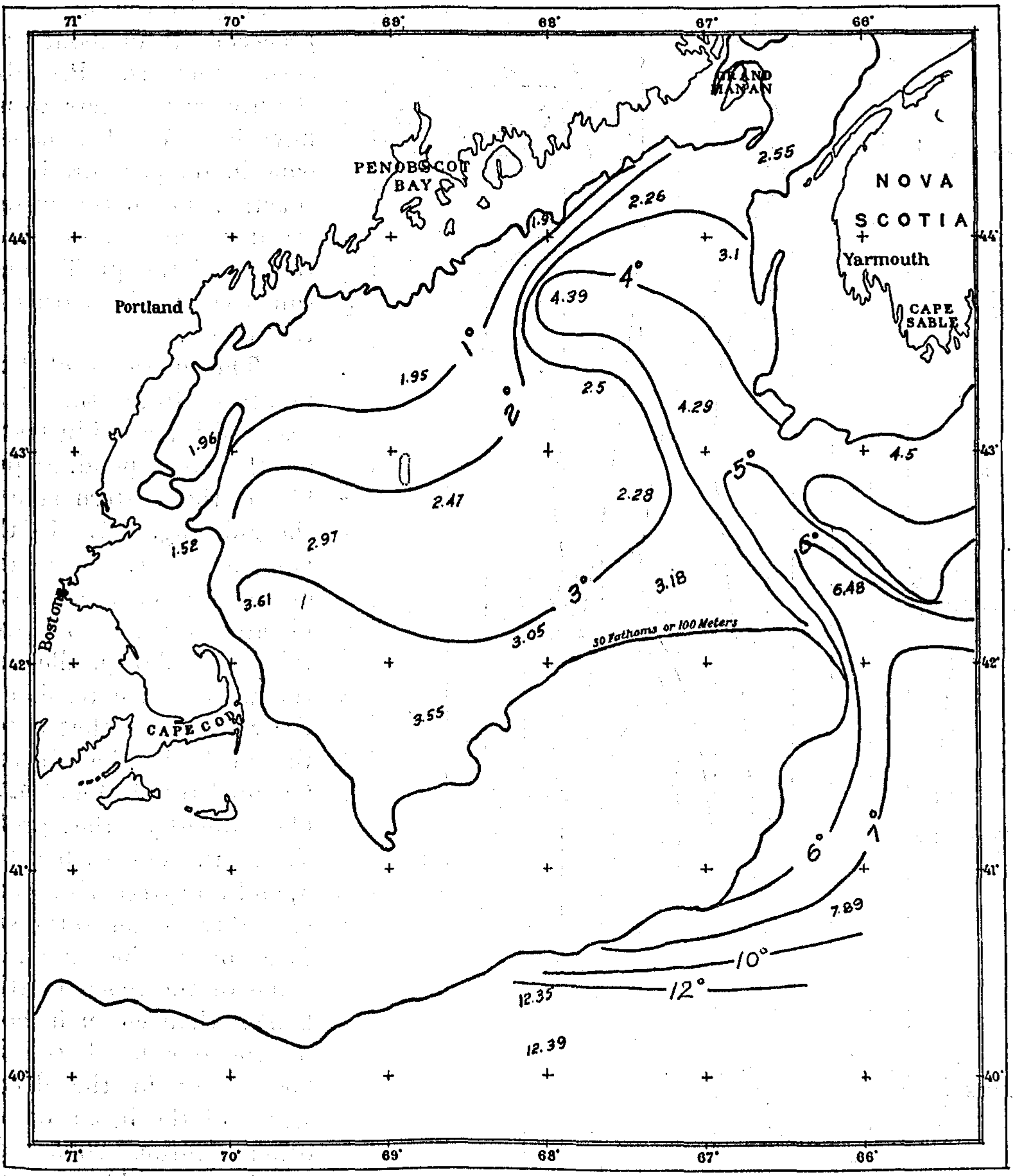

FIG. 13.—Temperature at a depth of 100 meters, Febuary–March, 1920

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

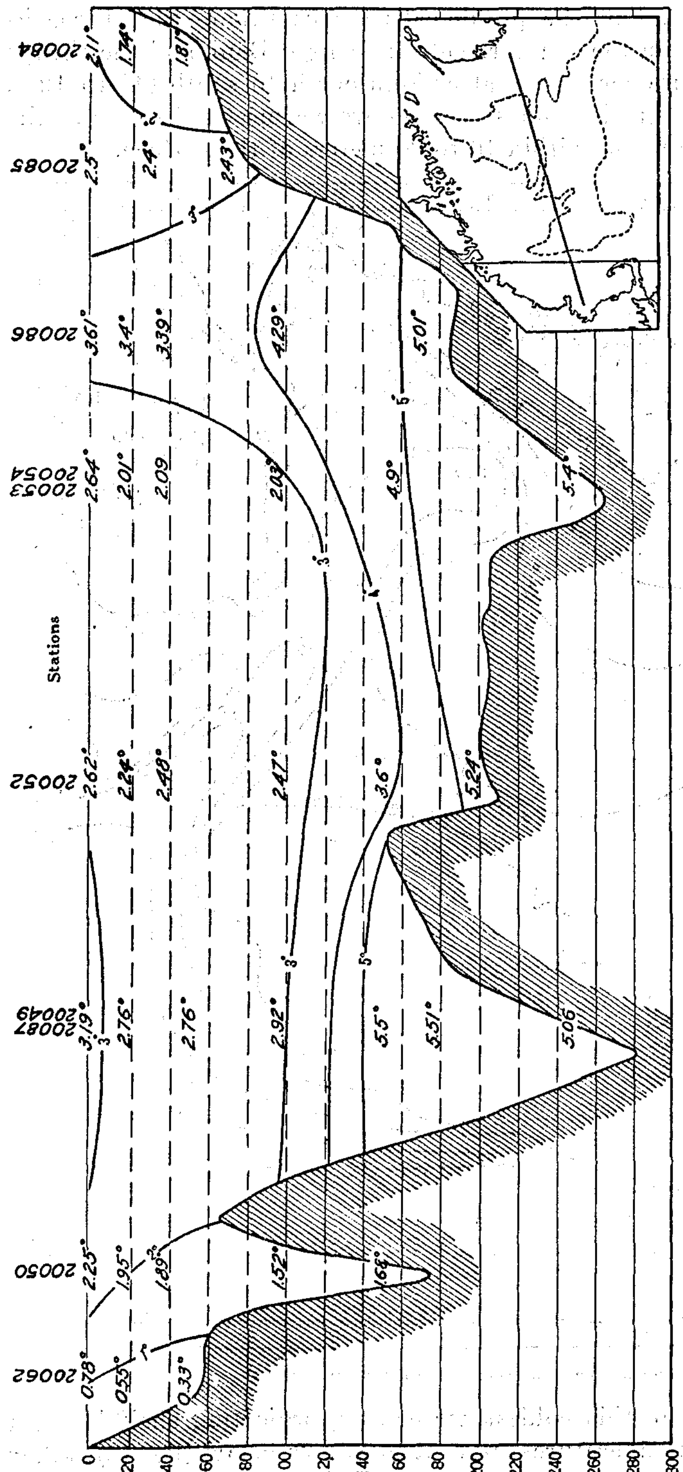

FIG. 14.—Temperature profile crossing the gulf from Massachusetts Bay to the vicinity of Cape Sable, March 5 to 23, 1920

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 below. Readings taken at a depth of 40 to 50 meters

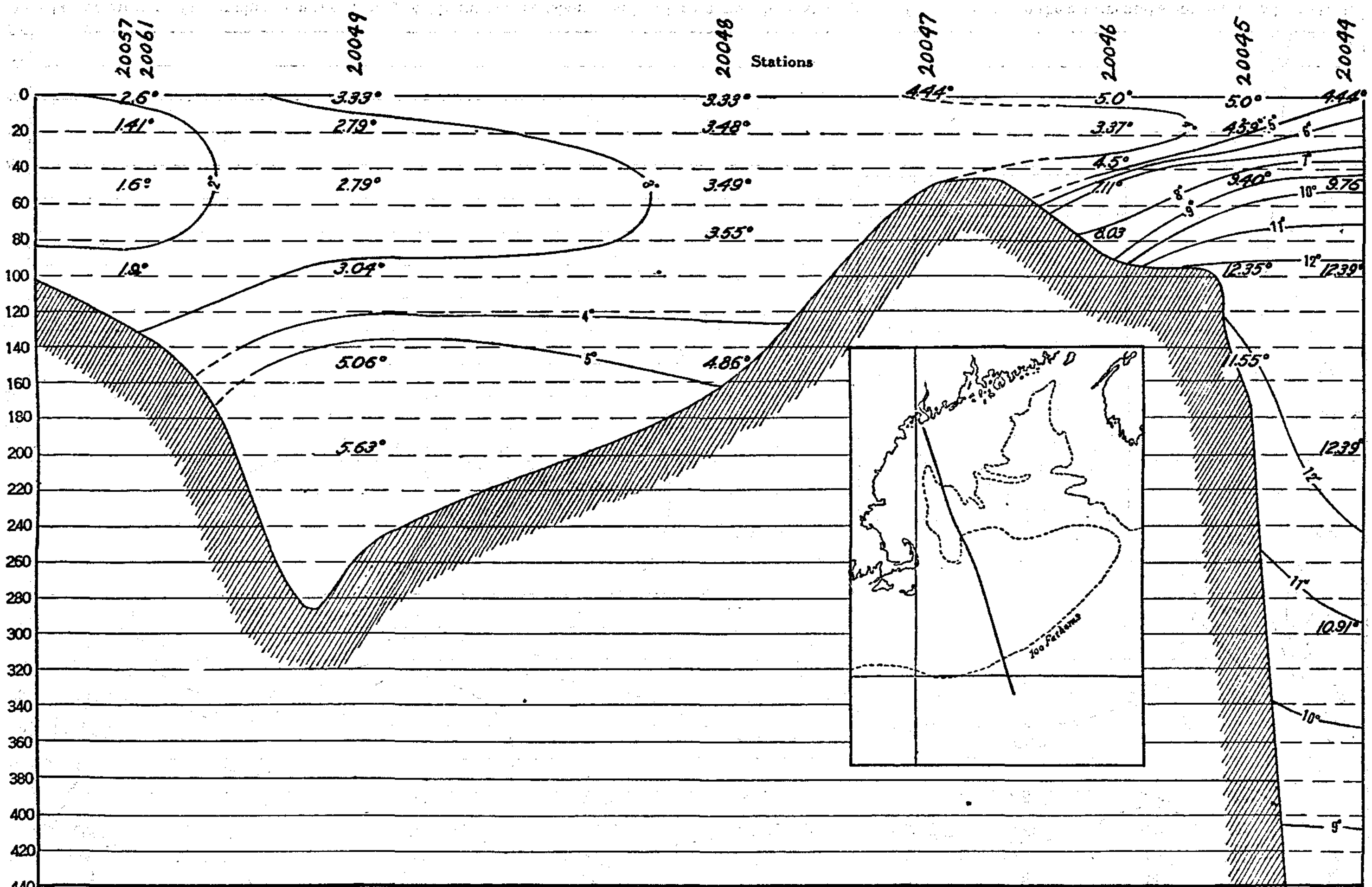

FIG. 15.—Temperature profile running southeasterly from the northwestern part of the gulf, off Cape Elizabeth, across Georges Bank to the continental slope, February 22 to March 4, 1920

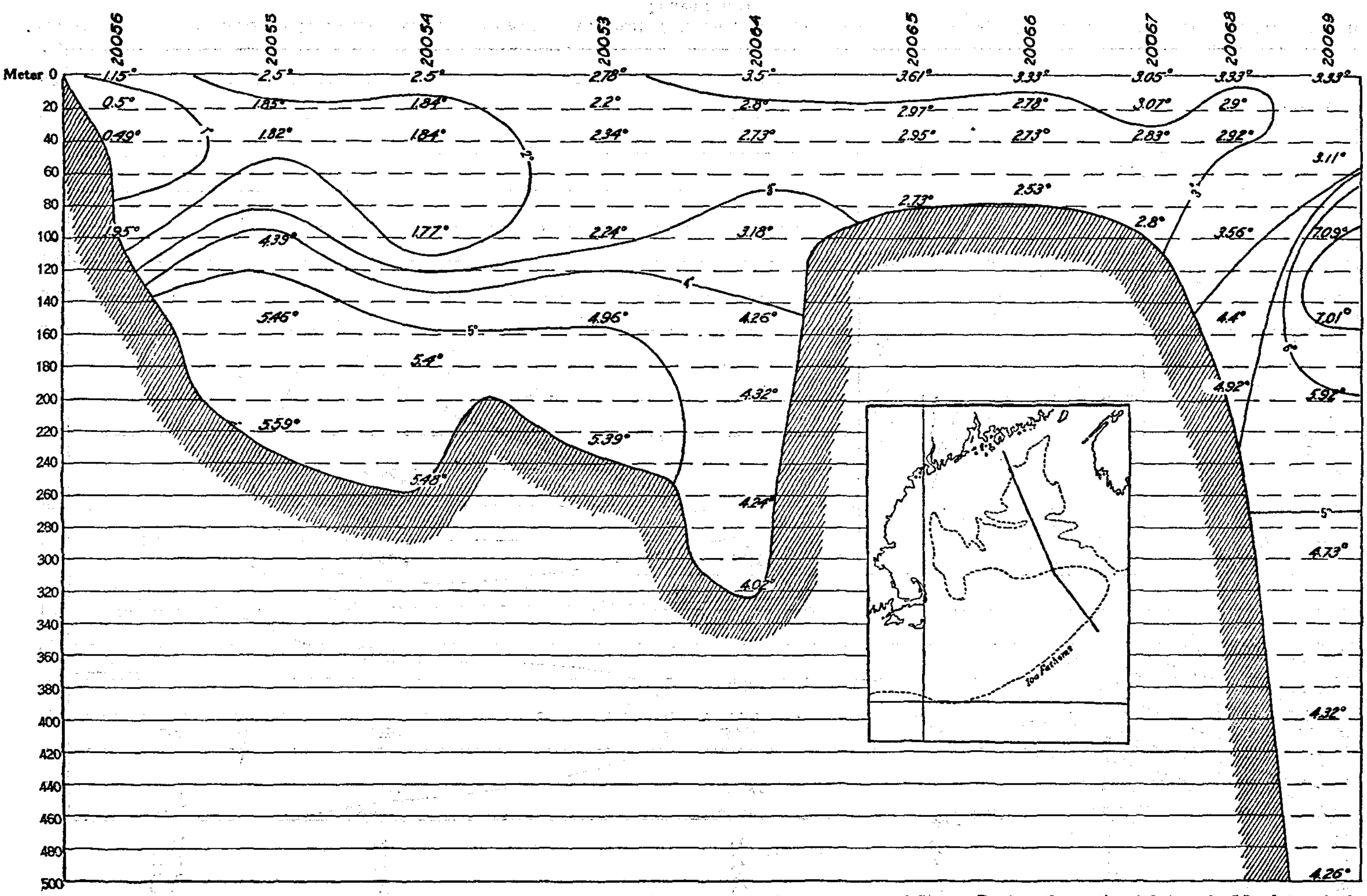

FIG. 16.—Temperature profile running from the vicinity of Mount Desert Island, southeasterly across the eastern part of Georges Bank to the continental slope, for March 3 to 12, 1920

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

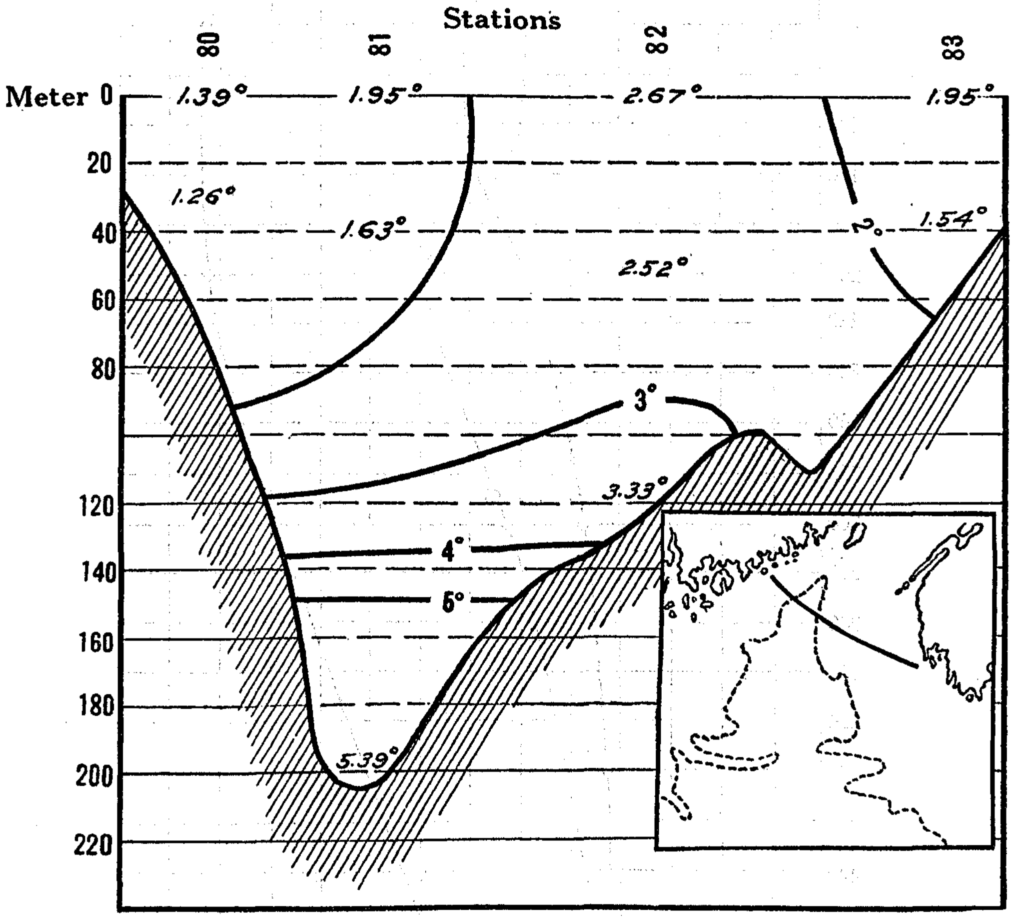

FIG. 17.—Temperature profile crossing the northeastern part of the gulf, off the mouth of the Bay of Fundy, for March 22 and 23, 1920 (stations 20080 to 20083)

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

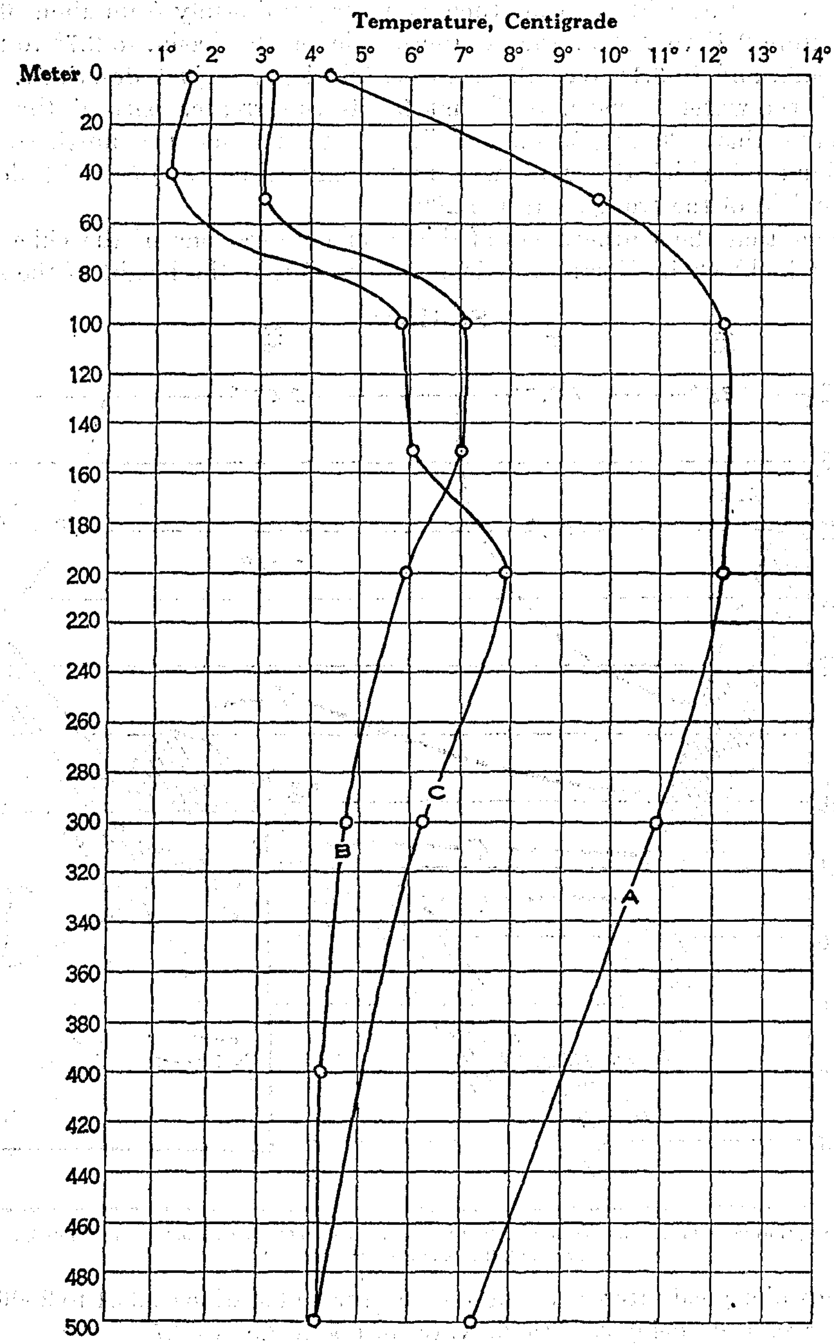

FIG. 18.—Vertical distribution of temperature along the continental slope. A, off the western part of Georges Bank (station 20044); B, off the eastern end of Georges Bank (station 20069); C, off Shelburne, Nova Scotia (station 20077), February-March, 1920.

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 stirring 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

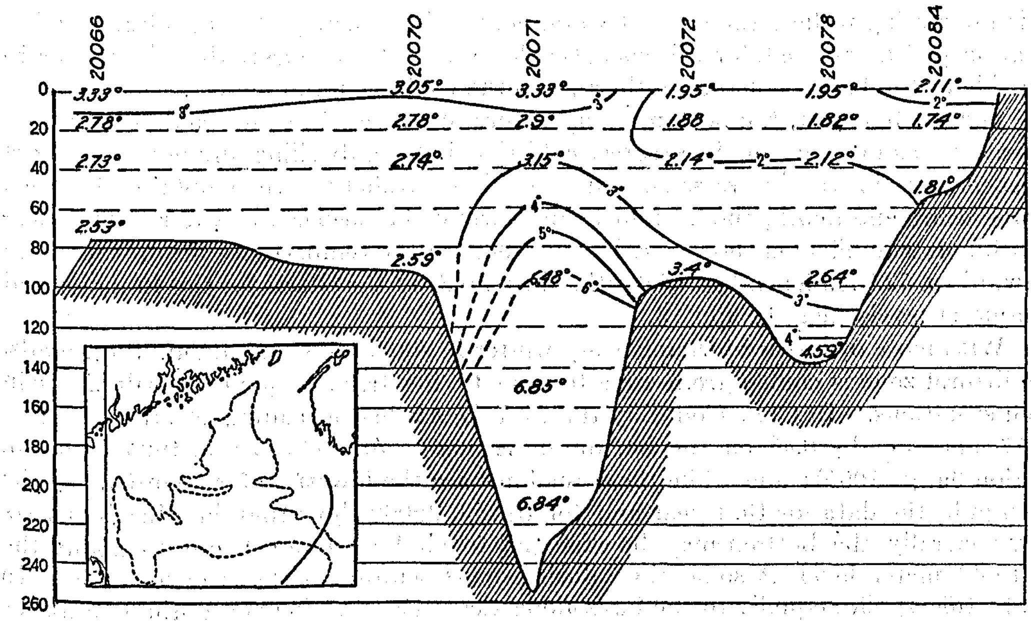

FIG. 19.—Temperature profile running from the eastern part of Georges Bank, across the Eastern Channel, Brown's Bank, and the Northern Channel, March 11 to 23, 1920

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 1920, 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.

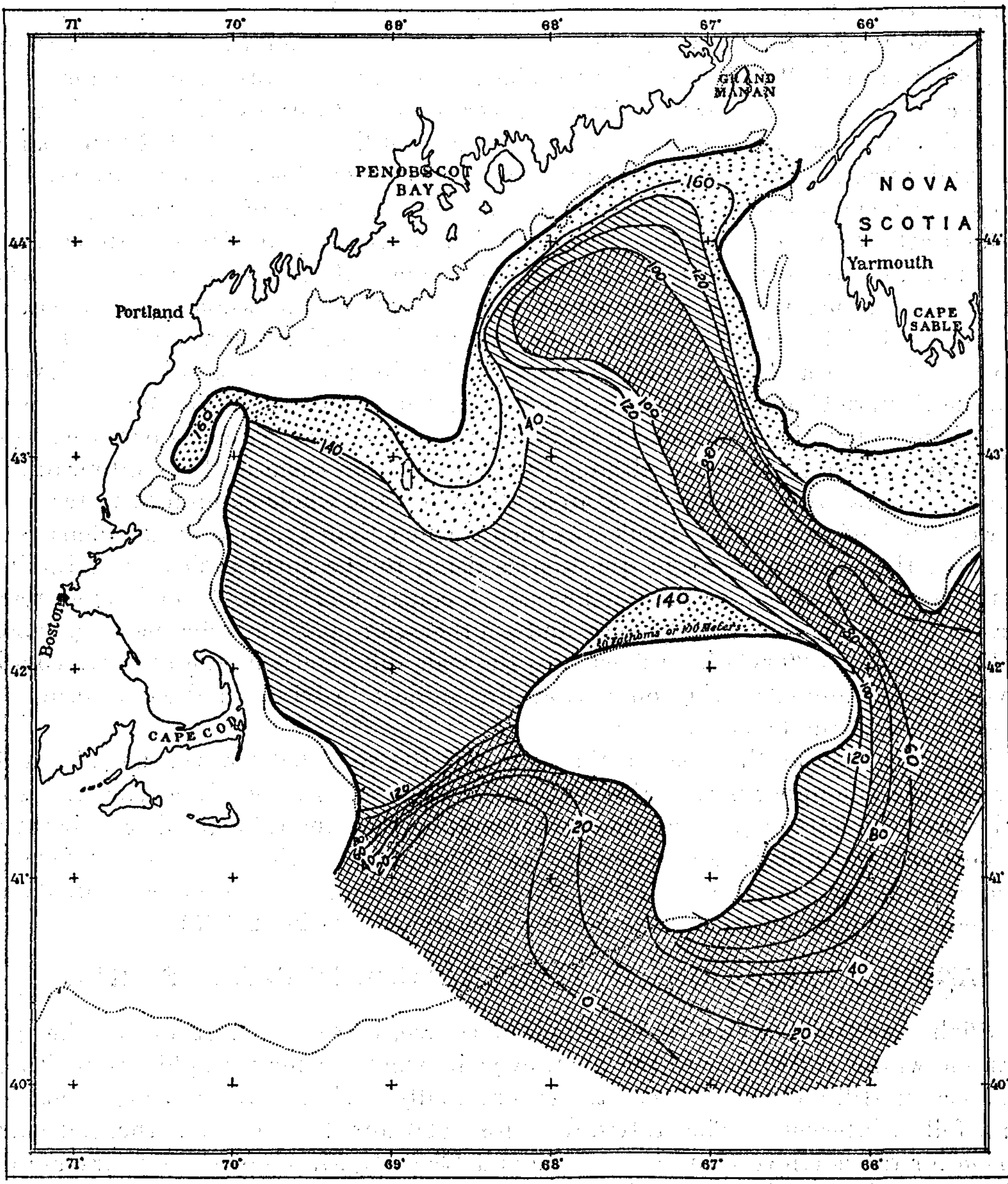

FIG. 20.—Depth below the surface of the isothermobath for 4°, February-March, 1920

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).

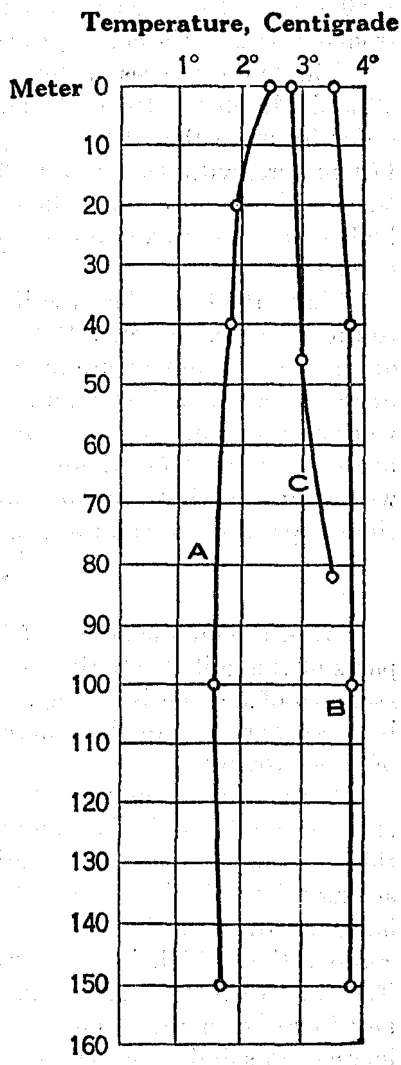

FIG. 21.—Vertical distribution of temperature off Gloucester during the first week of March of the years 1913, 1920, and 1921, to show the annual variation. A, March 1, 1920 (station 20050); B, March 5, 1921 (station 10511); C, March 4, 1913 (station 10054)

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

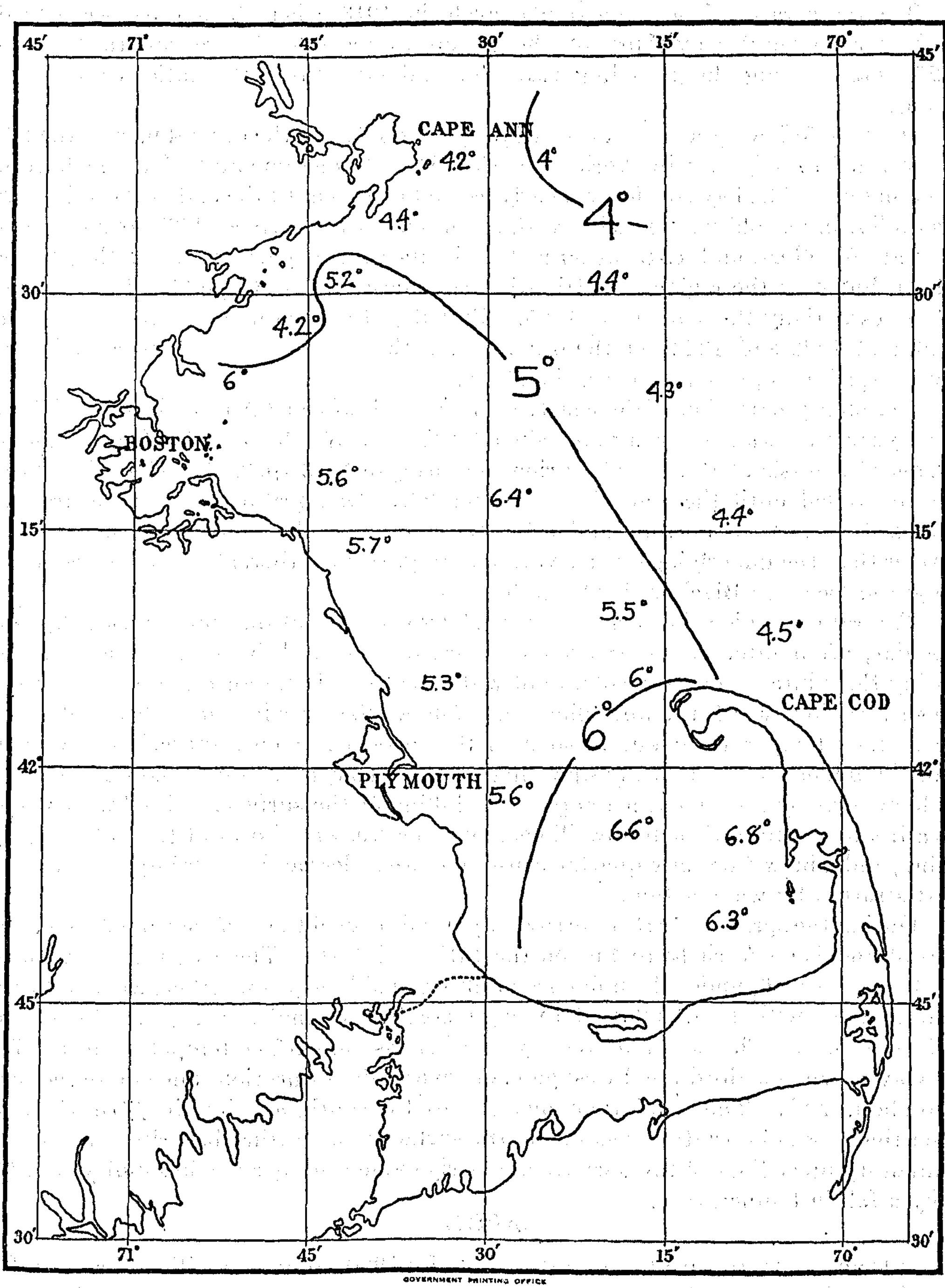

FIG. 22.—Surface temperature of Massachusetts Bay, April 21 to 23, 1925

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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

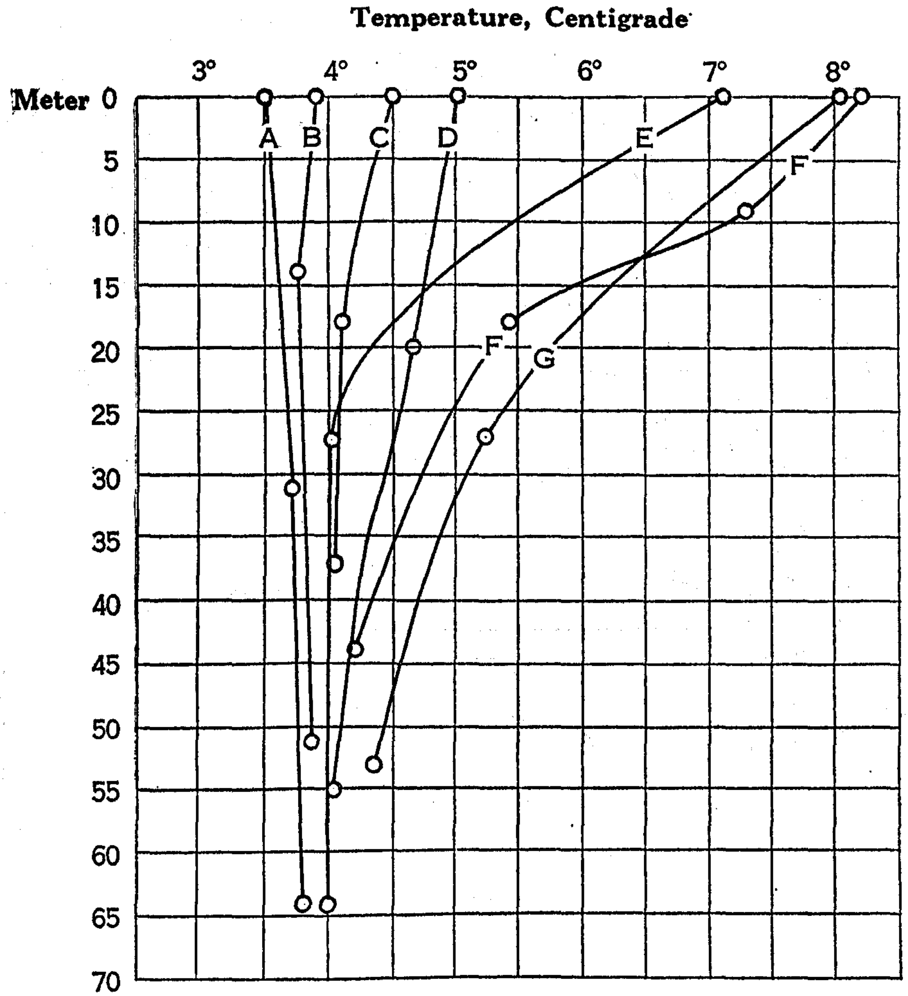

FIG. 23.—Vertical distribution of temperature near the Isles of Shoals and Boone Island at successive dates of the year 1913, to show the progress of vernal warming. A, March 29, 1913; B, April 5 (both near Boone Island); C, April 13; D, April 16; E, April 29; F, May 8; G, May 14 (C and F are near the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

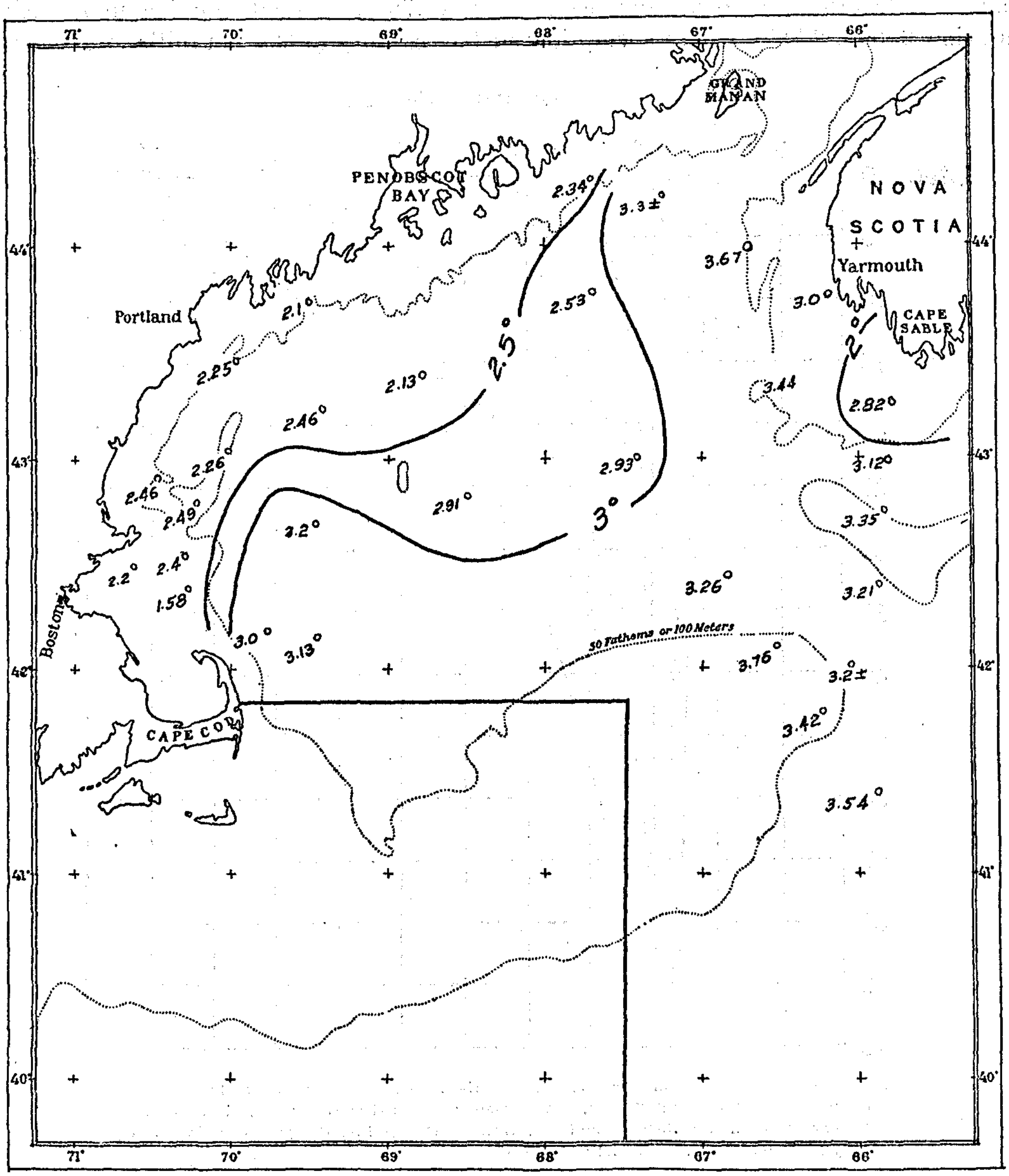

FIG. 24.—Temperature at a depth of 40 meters, April 6 to 20, 1920

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).

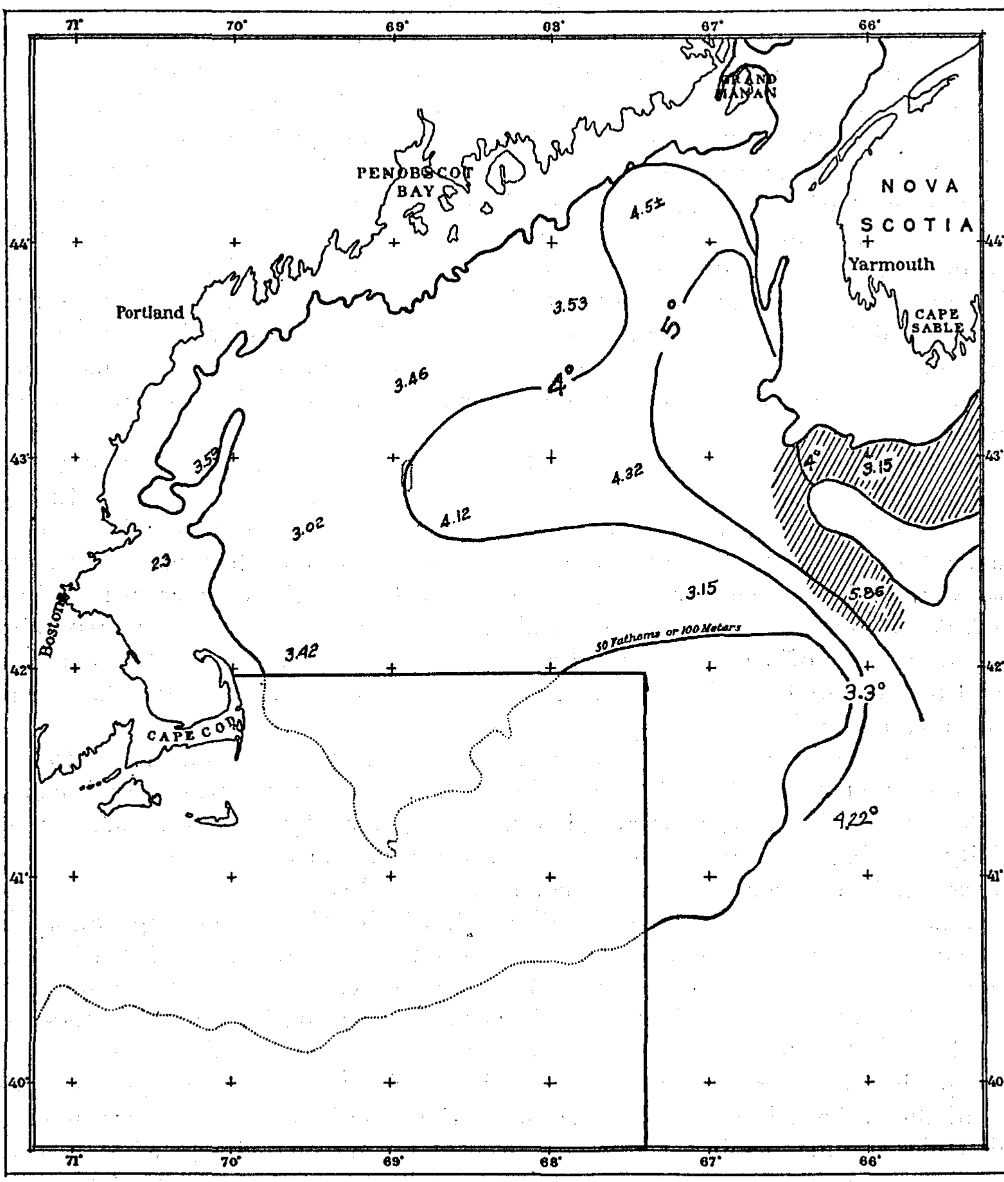

FIG. 25.—Temperature at a depth of 100 meters, April 6 to 20, 1920. The shaded area was colder in April than in March

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, 225, 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

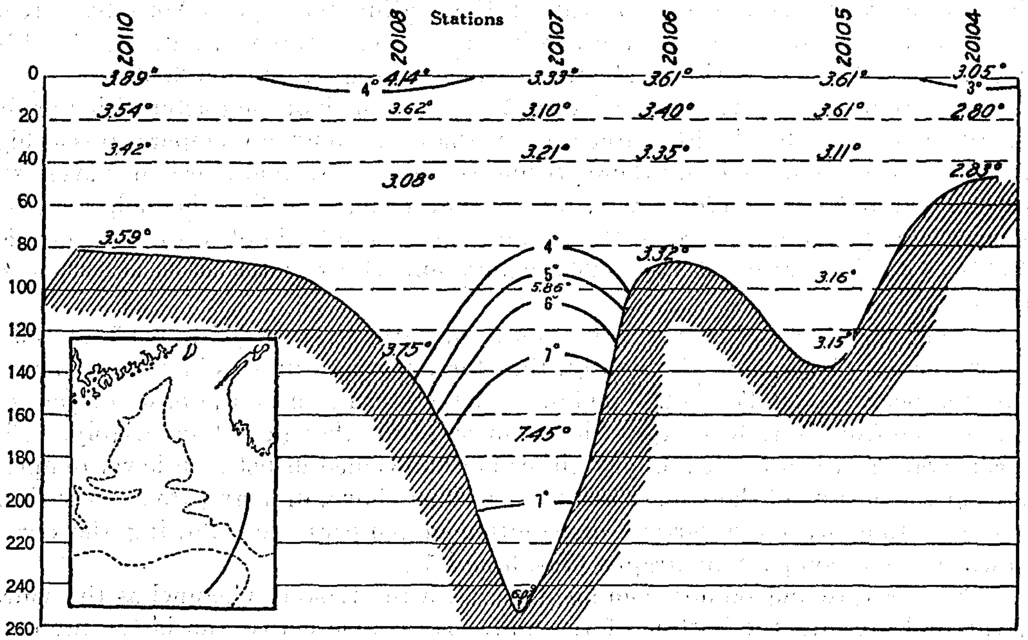

FIG. 26.—Temperature profile running from the eastern part of Georges Bank, across the Eastern Channel, Brown's Bank, and the Northern Channel, for April 15 and 16, 1920

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

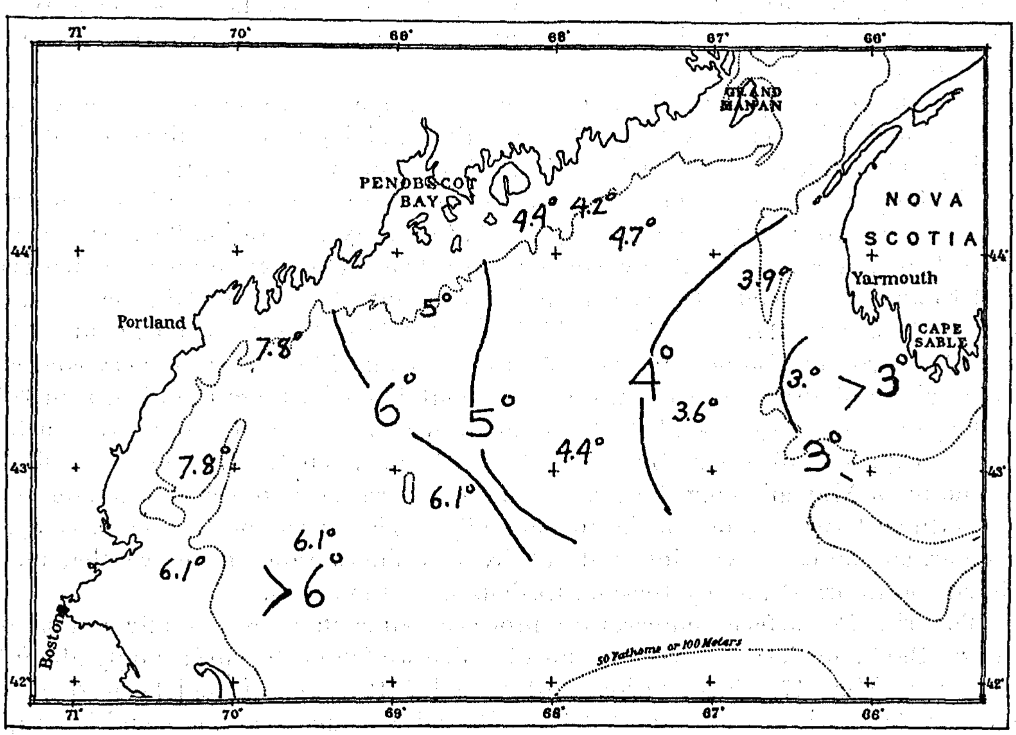

FIG. 27.—Surface temperature, first half of May, 1915

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.

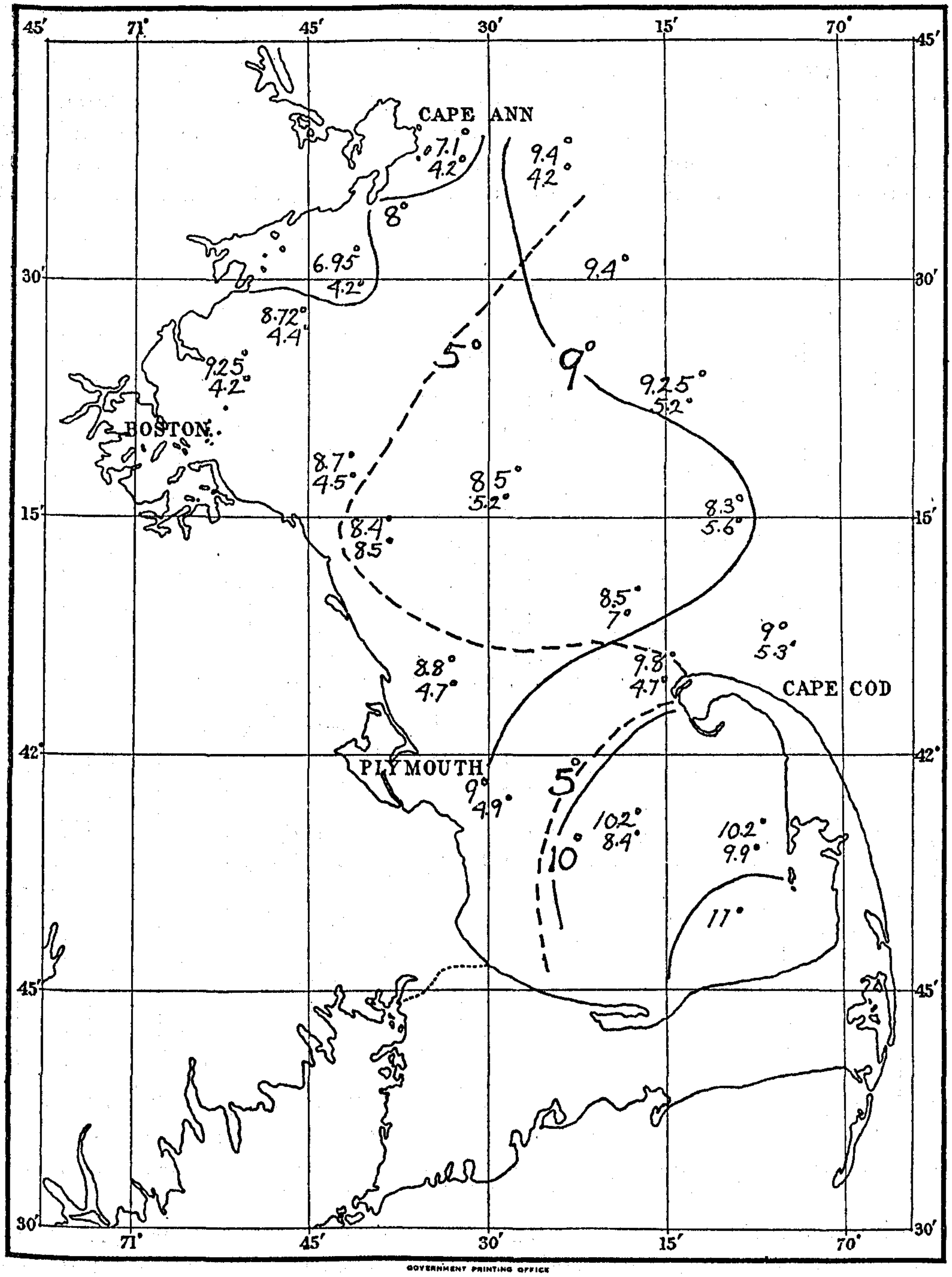

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FIG. 28.—Surface temperature of Massachusetts Bay at the surface (solid curves) and at 20 meters (broken curves), May 20 to 22, 1925

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

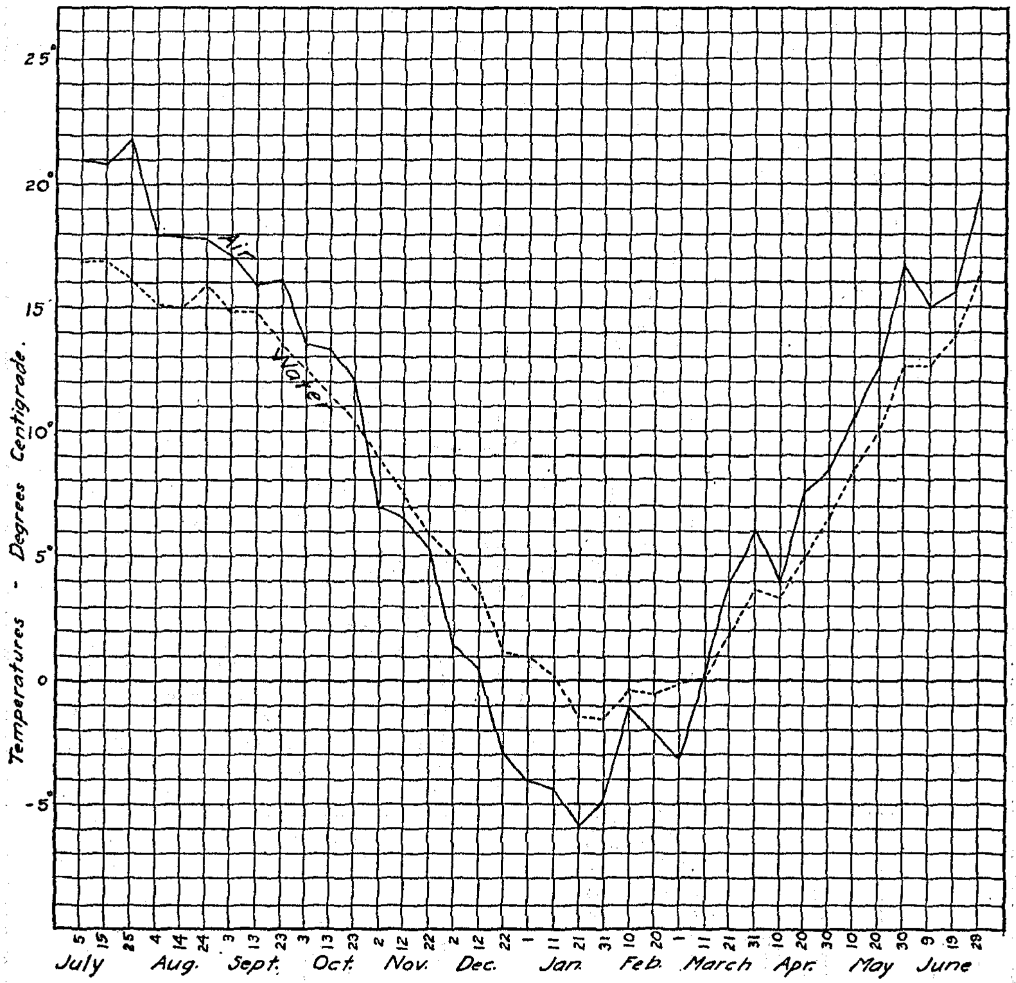

FIG. 20.—Mean air temperature (solid curve) and water temperature (broken curve) for 10-day intervals at Ten Pound Island, Gloucester Harbor, Mass., from July 1, 1919, to June 30, 1920

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.

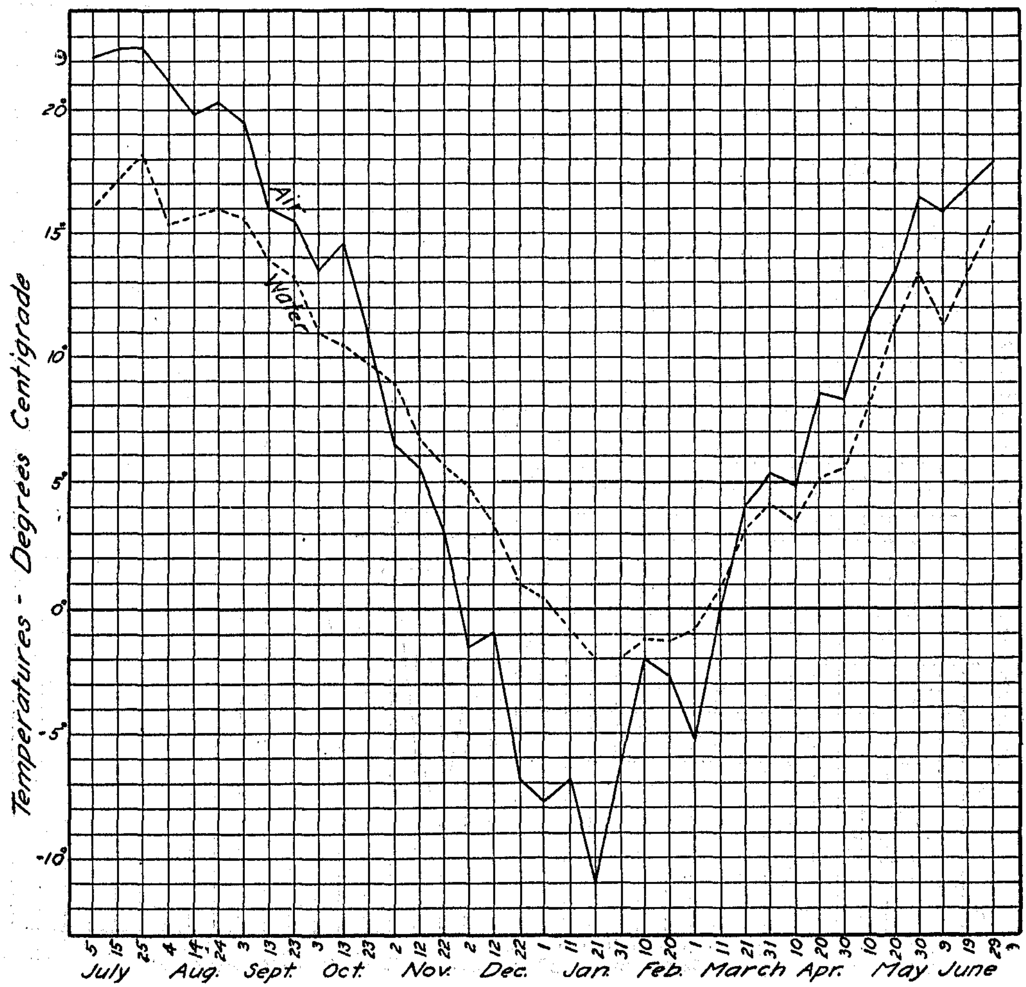

FIG. 30.—Mean air temperature (solid curve) and water temperature (broken curve) in Boothbay Harbor, Me., for 10-day intervals from July 1, 1919, to June 30, 1920

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.

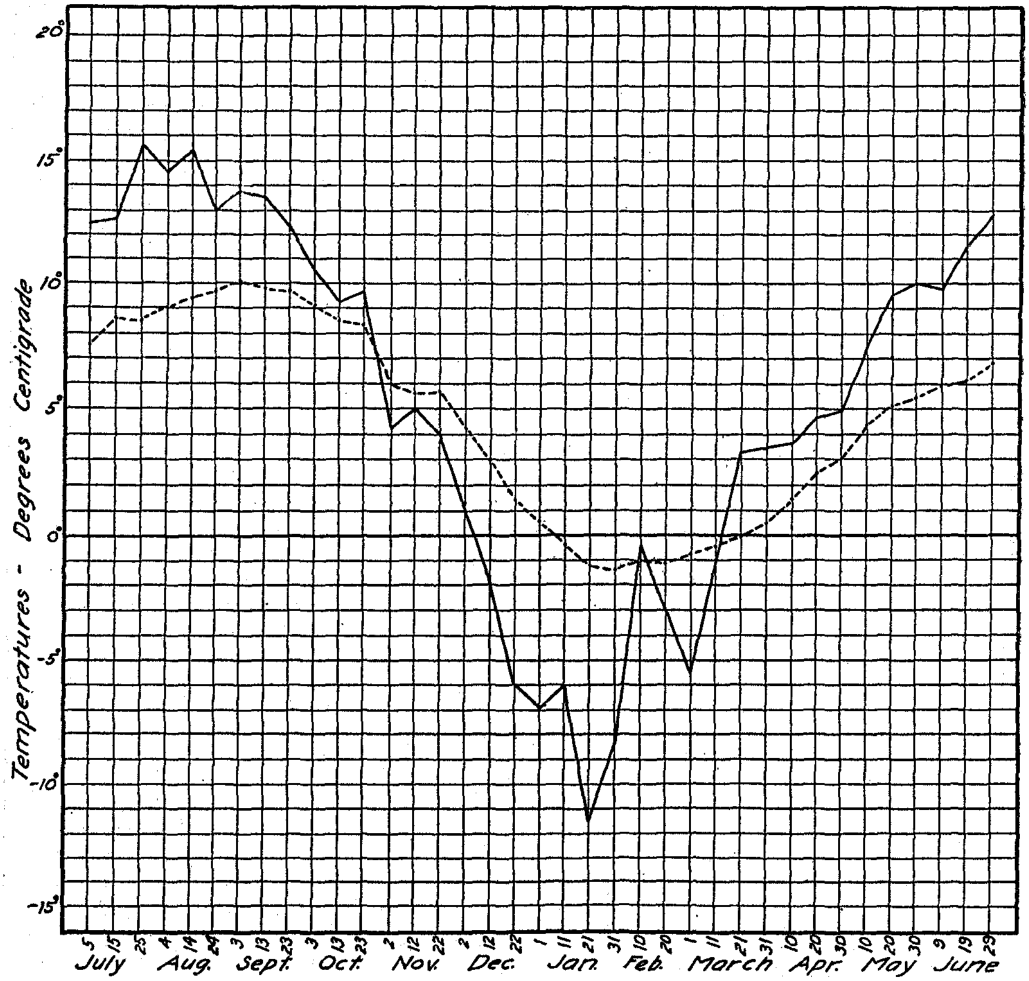

FIG. 31.—Mean air temperature (solid curve) and water temperature (broken curve) in Lubec Narrows, for 10-day intervals from July 1, 1919, to June 30, 1920

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

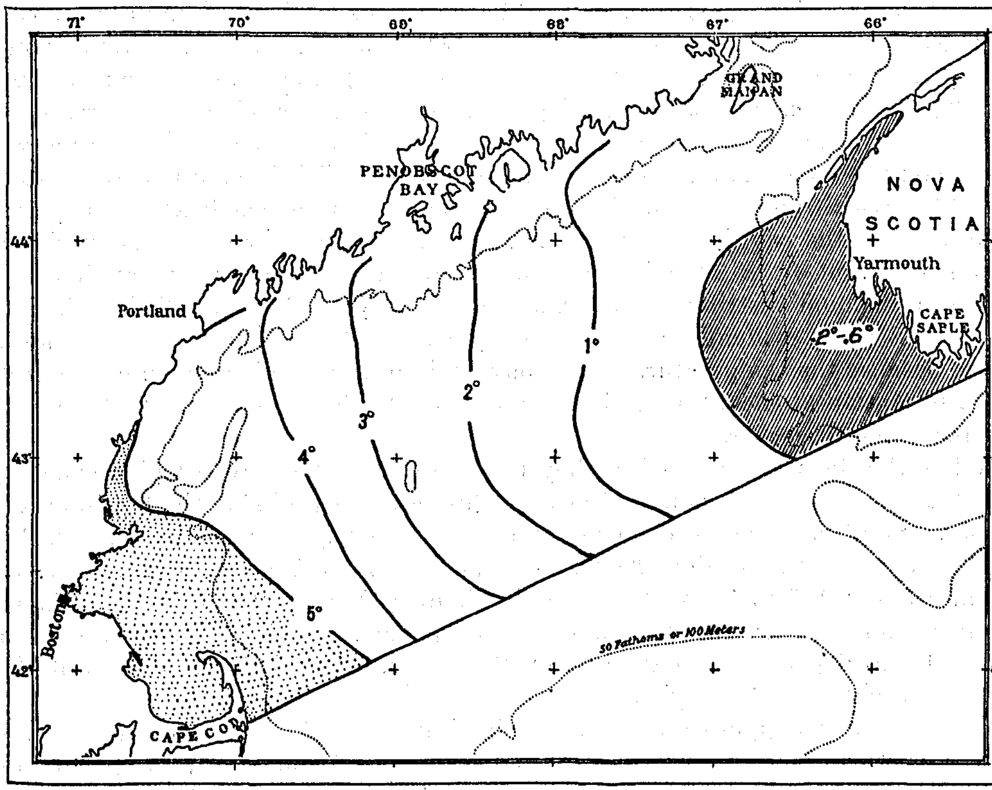

FIG. 32.—Normal rise in surface temperature from mid-April to mid-May. The hatched area experiences cooling

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.

BELOW THE SURFACE

In the northern and western parts of the Gulf of Maine, to which the chilling effect of the cold Nova Scotian water does not reach and which are only indirectly affected by the shoreward and seaward oscillations of the warm oceanic water outside the edge of the continent, the superficial stratum, down to say 20 meters, is sensibly warmer by mid-May than in April. The surface, also, warms so much faster than the water only a few meters down that a temperature gradient of several degrees develops over all this part of the gulf by the end of May as the first step in the transformation from the homogeneous state that characterizes the upper 100 meters at the end of the winter (p. 523) to the very steep gradient of summer (p. 596).

Thus, the mean temperature of the 20-meter level of Massachusetts Bay was only about 1° higher on May 20 to 22, 1925 (about 5.5°), than it had been on April 21 to 23, the difference between this depth and the surface having now increased to about 3° to 5°, except around the shores of Cape Cod Bay, where tidal stirring was active enough to maintain a more homogeneous state (*Fish Hawk* cruise 13, stations 6 and 7). Local differences of this sort, in the rate at which heat is transferred downward into the bay during the spring, were responsible for a regional variation of about 6° (from 4° to 9.9°) in the temperature of its 20-meter level at this date, and for a regional distribution (warmest in Cape Cod Bay) paralleling the surface (fig. 28); but evidently they had not yet been effective much deeper than 20 meters, because the temperature of the bay still continued virtually uniform from station to station at the 40-meter level and at nearly the same values (3.3° to 3.8°) as it had a month earlier.

While the deepest water of the bay (at 70 to 80 meters level) had warmed by about 0.2° meantime, the source of heat in this case was probably the bottom water offshore. Similarly, the 40 to 60 meter level of the bay warmed by only 0.6° in 1920 between April 9 (station 20090, 2.3°) and May 16 (station 20124, 2.9°); the bottom water in 100 to 120 meters by only about 0.4° (from 2.3° to 2.7°), although the surface temperature rose by about 6.4° meantime. In short, seasonal warming is negligible at depths greater than 25 to 30 meters until after the third week of May in the Massachusetts Bay region.

This statement applies equally to Ipswich Bay north of Cape Ann, where the 20-meter level warmed from 1.94° to 4.18° between April 9 and May 7 to 8, 1920, and the 40-meter level only from 2.45° to about 3.1° (stations 20092 and 20122), with no appreciable change at depths greater than 60 meters, so that the vertical range of temperature between the surface and 40 meters increased from only about 1° to nearly 5° during the 4 weeks' interval (fig. 33).

In the basin off the northern part of Cape Cod, just outside the 100-meter contour, the 40-meter temperature rose from 2.2° on March 24 (station 20088) to 3.78° on May 16 (station 20125), while the temperature at 100 meters hardly changed appreciably during this interval of nearly 8 weeks. Below that depth the water, which had cooled slightly from March to April, then warmed fractionally, so that the curves for March and May fall close together (fig. 3) at 140 meters (about 3°–4°). In the southwestern part of the basin, where no observations were taken in April, a similar difference obtains between records for May 17 and February 23, 1920, showing a warming of about 4° at the surface (7.22° to 8.33° in May, according to the locality), but with very little change at 100 meters.

Turning now to the opposite side of the gulf, Mavor's (1923) tables show the central part of the Bay of Fundy warming only fractionally at any level from April 9 to May 4, 1917 (whole column then between 1.9° and 2.8°), but then more rapidly to 8.18° at the surface, 4.68° at 30 meters, and 3.92° at 100 meters on June 15.

Assuming, from the character of the winters preceding, that the mean temperature at 40 meters ranged about 1° lower at the beginning of spring in 1920 than in 1915, the difference between the April and May readings, just summarized, suggests that

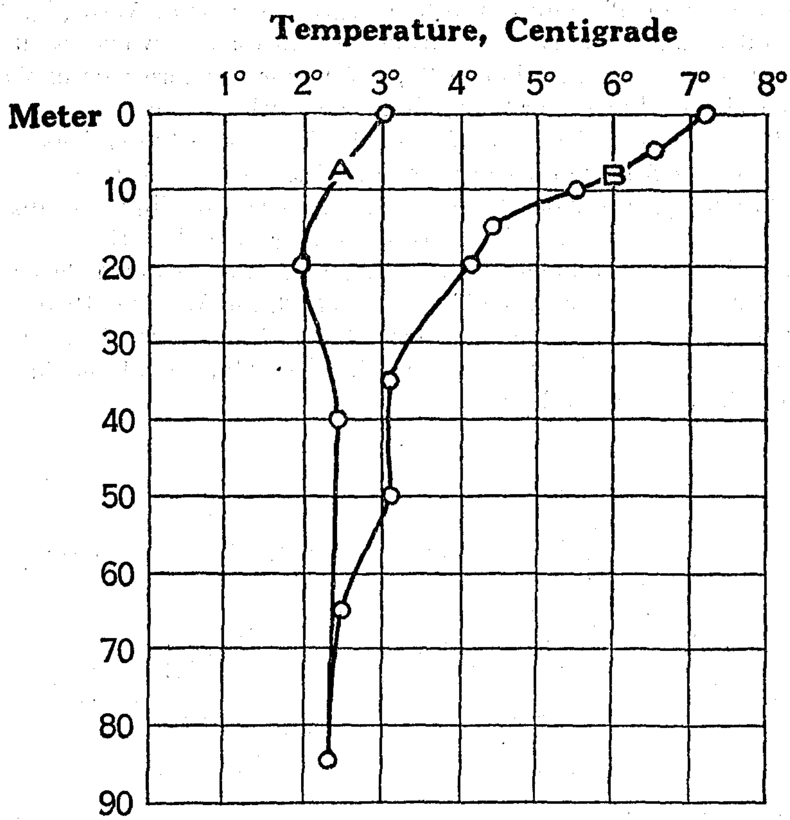

FIG. 33.—Vertical distribution of temperature in Ipswich Bay on April 9, 1920 (A, station 20092), and on May 7 and 8, 1920 (B, station 20122)

this level normally warms by about 1° during the interval from mid-April to mid-May in the parts of the gulf where the change is most rapid.

Taking the open gulf as a whole, the 100-meter readings for April, 1920 (a cold year), so closely reproduced the May readings for 1915 (a warm year)[18] that the temperature of the mid-depths may be described as virtually stationary during this part of the spring.

As the result of the two contrasting processes—vernal warming in the western side of the gulf and the inflow of cold water into the eastern—the regional distribution

[18] Maximum divergence at this level, for pairs of stations, was only from 3° in the western basin on Apr. 18, 1920, station 20115, to 4.8° on May 4, 1915, station 10267.

of temperature at the 40-meter level alters from April (fig. 24) to mid-May (fig. 34) by a shift of the coldest area (1.58° to 2.1° in April, 1920; 3° to 3.25° in May, 1915) from the western and northwestern sides of the gulf to the eastern side. Similarly, the warmest center shifts from the eastern arm of the basin, where the April readings were highest in 1920, to the western, with the coastal sector from Massachusetts Bay to Cape Elizabeth (4.5° to 5.1°, May 4 to 14, 1915), with about equal temperatures along the southwestern edge of Georges Bank (5.4° to 5.6° on May 17, 1920, stations 20128 and 20129).

The mid-stratum of the gulf, as illustrated by the 100-meter level, continues through May as regionally uniform in temperature as it is in April (fig. 25), with an extreme recorded range of only 2.45° within the gulf for the two years 1915 and 1920 (2.65°, Massachusetts Bay, station 20124, to 5.1° northeastern part of the basin, station 10273) and slightly warmer (7.5°) along the southwestern slope of Georges Bank (station 20129). Within the basin of the gulf the 100-meter readings for May have been highest (4.4° to 5.1°) in the central and northeastern parts, lowest in the western (2.6° to 3.5°) and eastern sides (about 4°). This last reading perhaps reflects the chilling effect of the Nova Scotian current from above; but there is no reason to suppose that the latter influences the spring temperature much deeper than this, because the 150-meter readings for March 2 and 23, for April 17, 1920, and for May 6, 1915, all fall within 0.2° of one another (about 5° in temperature) in the eastern side, and are nearly as uniform over the gulf, generally, for all the May cruises, as appears from the following table:

1915		1919		1920	
Station	Approximate temperature	Station	Temperature	Station	Temperature
	°C.		°C.		°C.
10267	5.2	Ice patrol 20[1]	4.35	20125[2]	4.04
10268	5	Ice patrol 21	4.4	20126	4
10269	5.1			20127[1]	3.8
10270	5				
10273	4.98				
10278	3.5				

[1] At 146 meters. [2] At 140 meters.

Thus the open basin of the gulf may be described as virtually uniform in temperature from side to side at the 150-meter level in May, though the precise readings may be a degree or so warmer or colder from one year to the next. The readings at the four deepest stations for May, 1915, also fall within 0.2° of one another at 185 to 190 meters (5.6° to 5.9° at stations 10267, 10268, 10269, and 10270).

The graphs for individual stations (figs. 3 to 11) show that in May (as is the case throughout the spring) the horizontal uniformity in temperature in the deep strata of the gulf usually is associated with a considerable rise in temperature with increasing depth, from the 50 to 100 meter level downward. As an example, I may cite a station off Cape Ann, occupied on May 4, 1915 (station 10267), when the 130-meter reading was 4.69°, with 6.59° at 260 meters depth. During the month the 200-meter level has averaged slightly warmer than the 100-meter level in the open basin of the gulf. In the Bay of Fundy, however, access to which for the inflowing bottom drift is hindered by the contour of the sea floor (p. 691), the temperature was virtually uniform from the 75-meter level downward on May 10, 1918 (about 2°), while in 1917 it was slightly lower (2.11°) at 175 meters than at 75 to 100 meters (2.2° to 2.8°) on the 4th of the month (Mavor, 1923). The deep sink inclosed by Jeffreys Ledge (recalling the Bay of Fundy in the contour of its floor, though smaller in area) was likewise nearly uniform in temperature from 100 meters (3.45°) down to 175 meters (3.7°) on May 14, 1915 (station 10278).

Whether the bottom water of the gulf basin cools or warms slightly from April through May, or whether the temperature remains virtually constant there, depends on the pulses just discussed (p. 555) and on the quantity and temperature of water

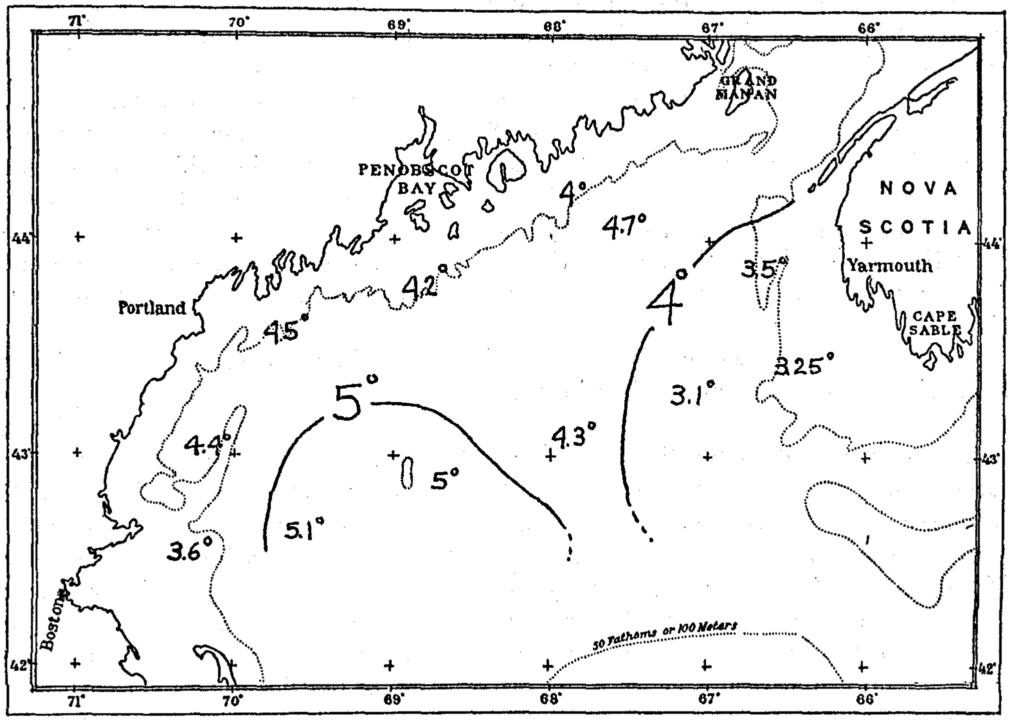

FIG. 34.—Temperature at a depth of 40 meters, May 4 to 14, 1915

brought in by them. If the inward drift over the bottom continues comparatively constant, little or no change is to be expected in the bottom temperature. If, however, the flow slackens or ceases, vertical circulation, from which no part of the gulf is free, will tend to equalize the temperature vertically; that is, to cool the deepest water while warming the overlying stata as they mix together. A pair of stations in the southwestern part of the basin for February and May, 1920, illustrate just this change, the slight rise in temperature with increasing depth from 100 meters downward to bottom in 150 meters, which was recorded for February 23 (station 20048), giving place to perfect vertical homogeneity by May (station 20127), while the 140 to 150 meter level cooled from 4.87° to 3·8° and the 100-meter level warmed from 3.54° to 3.8° during the interval.

The spacial distribution of temperature in May may be illustrated in a more connected way by three west–east profiles of the gulf—the first for April 28, 1919 (fig. 35), the second for May 4 to 7, 1915 (fig. 36), and the third for May 29 to 30, 1919 (fig. 37).

The first of these is interesting chiefly as it outlines the extension of the cold Nova Scotian current into the eastern side of the gulf, indenting like a shelf into the warmer water of the basin (isotherm for 4°, fig. 35). Water almost equally cold, washing the slope of Cape Cod at 60 to 120 meters in the opposite side of the profile, is reminiscent of the previous winter's cooling *in situ;* and the definite separation of these two cold masses by slightly higher temperatures in the central part of the basin deserves emphasis. Unfortunately no readings were taken deep enough in the basin to show what relationship the temperature of the bottom stratum bore to that of the mid depths at the time. So far as they go, however, they point to a homogeneous state at depths greater than 100 meters.

Although the May profile for 1915 (fig. 36) was run only a week later in date, the presence of a lenticular mass of 5° to 6° water over the western part of the basin, with maximum thickness of about 50 meters, illustrates a considerable advance in the seasonal cycle, reflecting the penetration of solar heat downward from the surface into the underlying water. Below it the cold coastal band that skirts the western side of the gulf earlier in the spring (the product of local chilling) is still represented at the mouth of Massachusetts Bay by temperatures of 3.5° to 4° at depths greater than 20 meters.

Whether the cold water of Nova Scotian origin in the eastern side of the gulf assumed a shelflike outline earlier in that particular spring, as it certainly did in 1919, is not known. If so, its tip had been eaten away by mixture with the surrounding water until its limiting isotherm (4°) had come to assume the more nearly vertical course shown on the profile (fig. 36). In actual temperature, however, this cold water mass was very nearly the same in 1915 as the ice patrol found it in 1919, one of the many illustrations that might be cited of the surprising constancy of the gulf in temperature from year to year. The presence of appreciably warmer (4° to 5°) water below it in both these years illustrates how strictly the inflow past Cape Sable into the gulf is confined to the upper stratum above the 100 to 120 meter level, a phenomenon resulting from the distribution of density in this side of the gulf (p. 946). As a consequence, the surface is the coldest level there in May, or at least the lowest readings will be had only a few meters down.

Figure 37 illustrates still a later stage in the thermal cycle, the Nova Scotian current having slackened and the two cold water masses that hug the two sides of the gulf earlier in the season having merged into the general stratum of minimum temperature (4° to 5°) at the 50 to 120 meter level. Vernal warming is illustrated further on this profile by a rise in the temperature of the upper 10 meters from about 5° at the end of April (5° to 6° on May 4 to 6, 1915) to 8° to 9°. In the deeps of the gulf a rise in temperature from about 4.5° to 5.6° to 6° during the preceding four weeks (cf. fig. 37 with fig. 35) is evidence of a considerable movement of slope water through the Eastern Channel into the gulf during the interval. However, the nearly horizontal course of the isotherm for 5 degrees across the basin on May 28 (fig. 37),

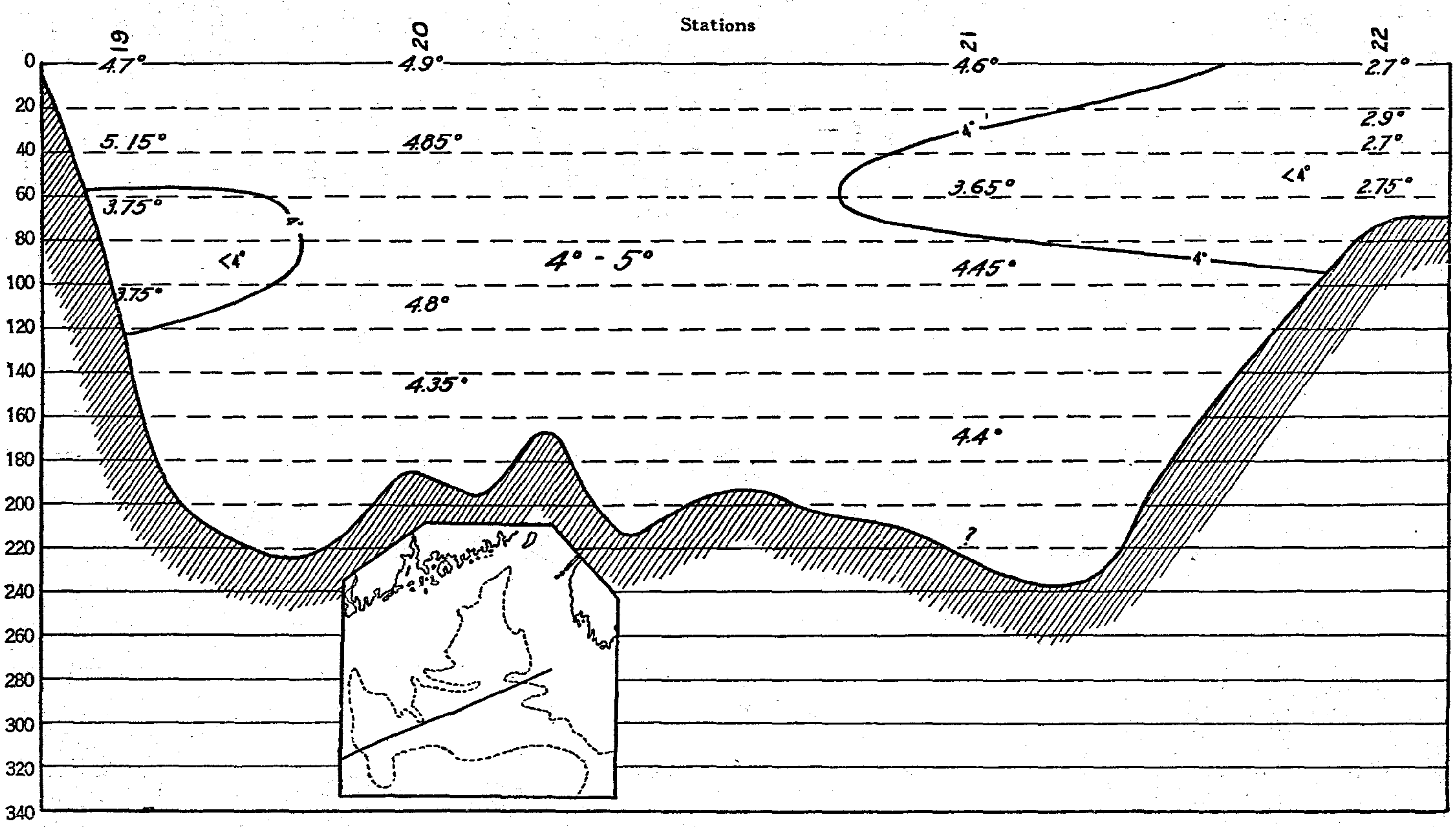

Fig. 35.—Temperature profile from a point a few miles off Cape Cod to German Bank, April 28, 1919 (ice patrol stations 19 to 22)

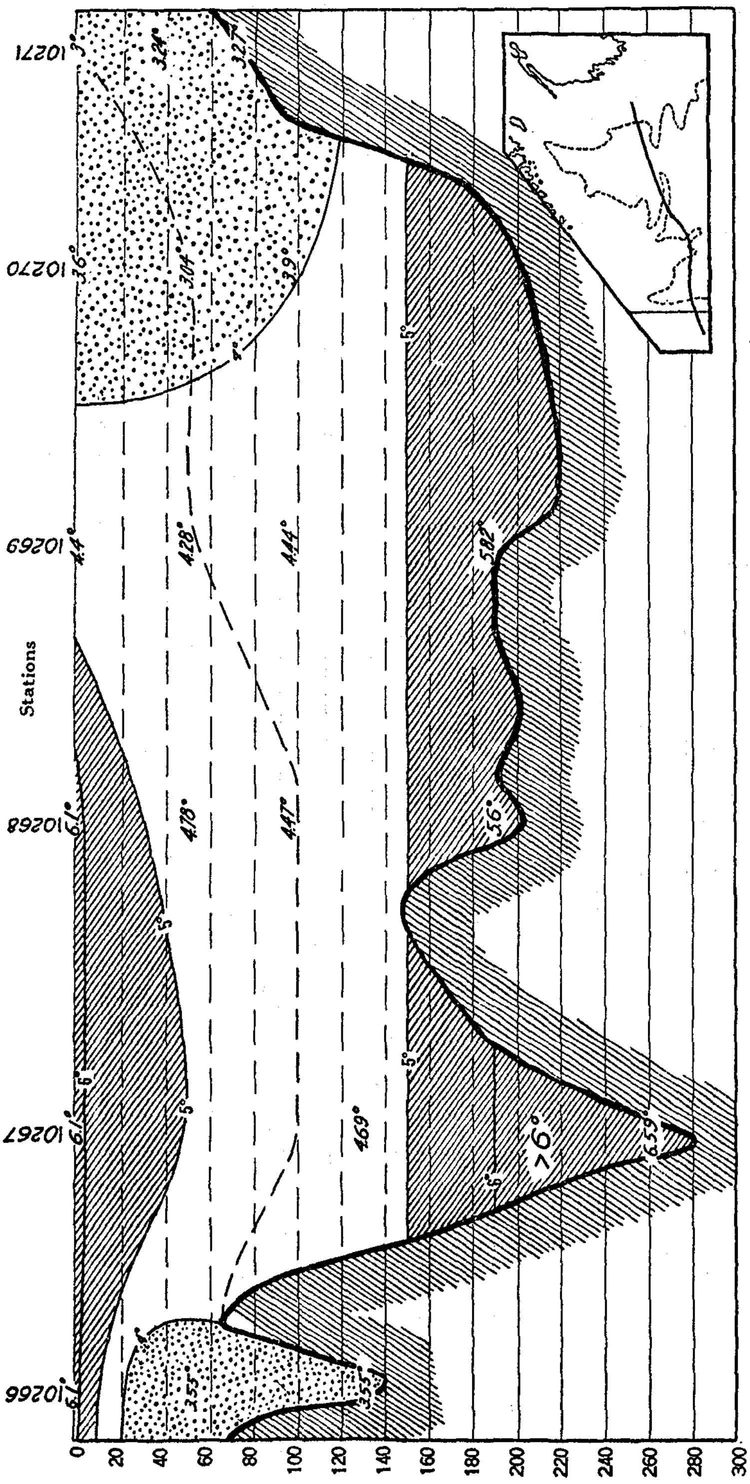

FIG. 36.—Temperature profile crossing the gulf from the mouth of Massachusetts Bay to German Bank for May 4 to 7, 1915

evidence of a static condition in the bottom water rather than one of active circulation, marks the precise date when this profile was run as falling between two of the pulses by which this indraft is believed to progress (p. 558), not as coinciding with one of them. Whether such a pulse annually succeeds the slackening of the Nova Scotian current remains to be learned, but this is not unlikely.

In 1920 the general increase in temperature that involves the gulf proper and the western part of its offshore rim from April to May, did not extend to the seaward slope of the latter. There, on the contrary, a change of the reverse order took place from about the 40-meter level right down to the bottom in 150 to 200 meters (fig. 38), illustrated by a decrease in the bottom temperature from 11.5° on February 22 (station 20045, 150 meters) to 8.28° on May 17 (station 20129, 160 meters). Accompanied, as it was, by a corresponding freshening at the bottom, this cooling is clear evidence that the warm, highly saline oceanic water that bathed this part of the slope in February, as it usually does in summer (p. 617), had receded offshore by May. Lacking data farther eastward along the slope for this season, it is impossible to state the precise cause of this event further than that it probably represented a dynamic alteration (p. 936) rather than a direct extension of Nova Scotian water in this direction (p. 825).

Whatever its cause, however, the fact that so great a chilling of the bottom water undoubtedly did occur in just this location in 1920 (and may, perhaps, every spring) is of great interest biologically, as events of this sort necessarily limit the permanent bottom dwellers of the eastern part of the so-called "warm zone" to such

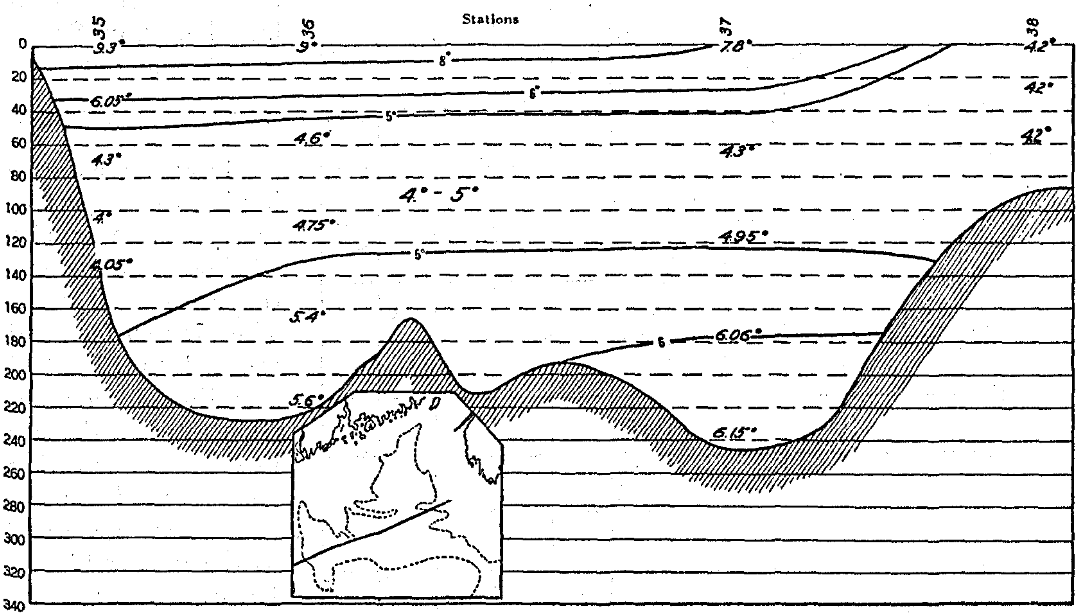

FIG. 37.—Temperature profile from a point a few miles off Cape Cod to German Bank, for May 29 and 30, 1919 (ice patrol stations 35 to 38)

animals as can survive temperatures as low as 7° to 8°. Unfortunately no readings were taken there during the only spring (that of 1884) when a serious mortality is known to have taken place among its inhabitants—invertebrates as well as fishes (notably the tilefish)—but in very cold years the temperature there may fall several degrees lower, perhaps, than happened in 1920. Tentatively, mid May may be set as the coldest season on bottom along this part of the continental slope—three months later than in the inner waters of the Gulf of Maine.

JUNE

I am not able to present as satisfactory a thermal picture of the gulf for June as for the spring, no measurements of temperature having been made in the western side of the basin, along shore between Cape Ann and Cape Elizabeth, nor on Georges Bank during that month. On the other hand, our June cruise of 1915 led far enough east past Cape Sable to cross-cut the Nova Scotian current before it passes that promontory. The *Fish Hawk*, also, made a general survey of Massachusetts and Cape Cod Bays on June 16 and 17 in 1925. A few temperatures were taken by the *Halcyon* near Gloucester on the 6th in 1924, in the Nantucket Shoals region during the first half of the month in 1925, and Dawson (1922) also took a considerable number of June readings along Nova Scotia in 1904 and 1907.

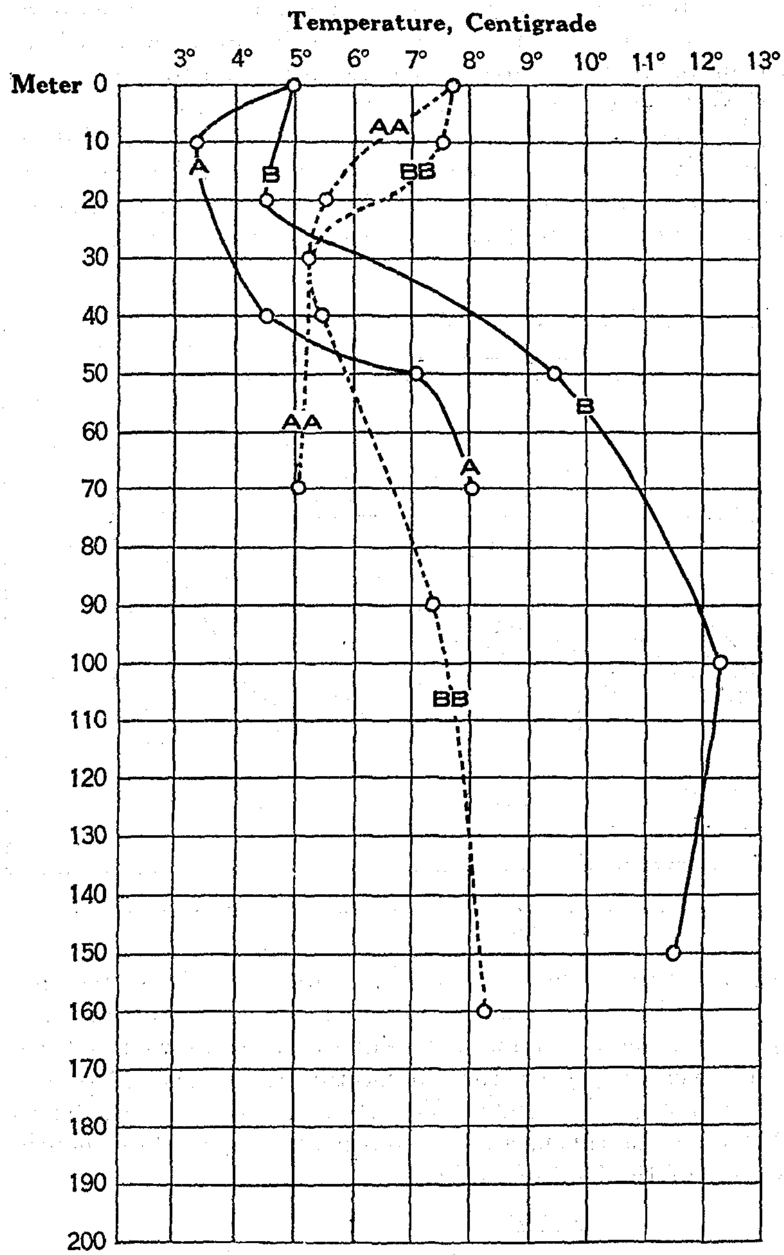

Fig. 38.—Vertical distribution of temperature on the southwestern slope of Georges Bank to show cooling of the bottom water, but warming at the surface, from February to May, 1920. A and B, February 22 (stations 20046 and 20045); AA and BB, May 17 (stations 20128 and 20129)

RATE OF WARMING

Progressive warming is to be expected, of course, over the whole area throughout the month of June. Thus, the surface had warmed to 10.56° at a station 8 miles off Gloucester on the 6th in 1924, and to 12.1°–15.2° over Massachusetts Bay generally by the 16th or 17th in 1925, an average change of about 5 degrees since May 20 to 22. At the 20-meter level these mid-June temperatures averaged about 7.8° (18 stations), contrasting with about 5.5° in May (p. 564), with the readings for June 6, 1924 (6.2°) intermediate, as the date would suggest. These Massachusetts Bay stations for 1925 also illustrate interesting regional differences in the rate at which heat penetrates downward into the water during the late spring and early days of summer, depending chiefly, it would seem, on differences in the extent to which the water is stirred by the tides and on the freedom of interchange of water between the coastal zone and offshore—perhaps to some degree on upwellings.

In midwinter the Plymouth shore and Cape Cod Bay to the southward see winter chilling more rapid than in any other part of the Massachusetts Bay region (fig. 81). With the advance of spring, however, the regional relationship is reversed, so that by May we find the surface water warmest in Cape Cod Bay (p. 557, fig. 28). During the last week of that month, however, and the first half of June, the western side of Massachusetts Bay had caught up with Cape Cod Bay in the progression of temperature, so that all this area (inclosed by the isotherm for 15° on fig. 39) was now nearly uniform (15 to 15.2°) in surface temperature, except for one station off Plymouth Harbor, where vertical circulation of some sort was responsible for a slightly lower reading (14.43°).

Considerably lower surface temperatures (12.1° to 13.3°), right across at the mouth of the bay, show that the offshore waters had lagged behind the coastal belt in warming; and still lower readings (12° to 13°), along the north shore of the bay deserve emphasis because the 20-meter level was warmest here, coldest at the mouth of the bay, and with a rather surprisingly wide range in temperature (12.03° to 4.56°) from station to station. Active vertical stirring is clearly responsible by bringing the upper 20 meters within the immediate effect of the sun's rays, to warm nearly uniformly along the northern shore. At the same time it is probable that the warming of the upper stratum in this particular region is forwarded during June by a more or less constant drift of the surface water—already warmed to 12° to 14° temperature—around Cape Ann and westward into the bay. Consequently, a somewhat higher mean temperature for the upper 20 meters may be expected to prevail along its northern shore than in its central parts in June, just as was actually recorded in that month in 1925 (*Fish Hawk* cruise 14, stations 35 to 37), instead of a lower mean temperature, as is the case later in the summer.

More rapid warming of the surface along the Plymouth shore and in Cape Cod Bay, but a slower rise in temperature at 20 meters, points to a less active overturning by the tides; and the fact that the surface and 20-meter readings both averaged 2° to 3° higher there than over the deep sink off Gloucester (*Fish Hawk* station 31) is evidence that the interchange of water between the open basin of the gulf, on the one hand, and the western and southern parts of Massachusetts and Cape Cod Bays, on the other, had been so slow for some weeks previous that the latter had acted as a more or less isolated center of local warming. On the other hand, the low temperatures (5 to 6°) at the 20-meter level along the eastern side of Stellwagen Bank, at the mouth of the bay, point to a certain amount of upwelling over the slope of the latter, bringing up cold water from greater depths offshore.

These regional differences in the June temperatures for 1925 are smoothed out over the Massachusetts Bay region with increasing depths. At 40 meters, for example, the extreme range of temperature was then only from about 3.5° to about 6.1°, with the mouth of the bay uniformly 4° to 4.5°, and the 40-meter temperature (about 3.6°) off Gloucester for the 6th of the month, for 1924 (station 10653), falls within this range. At 75 to 94 meters the temperatures of Massachusetts Bay were also about the same in 1924 (3.13°, station 10653) as in 1925 (3.97° and 4.04° at *Fish Hawk* stations 30 and 32).

Out in the open basin, off Cape Ann, the surface warmed from 6.1° on May 4, 1915 (station 10267), to 13.6° on June 26 (station 10299), or at about the same rate

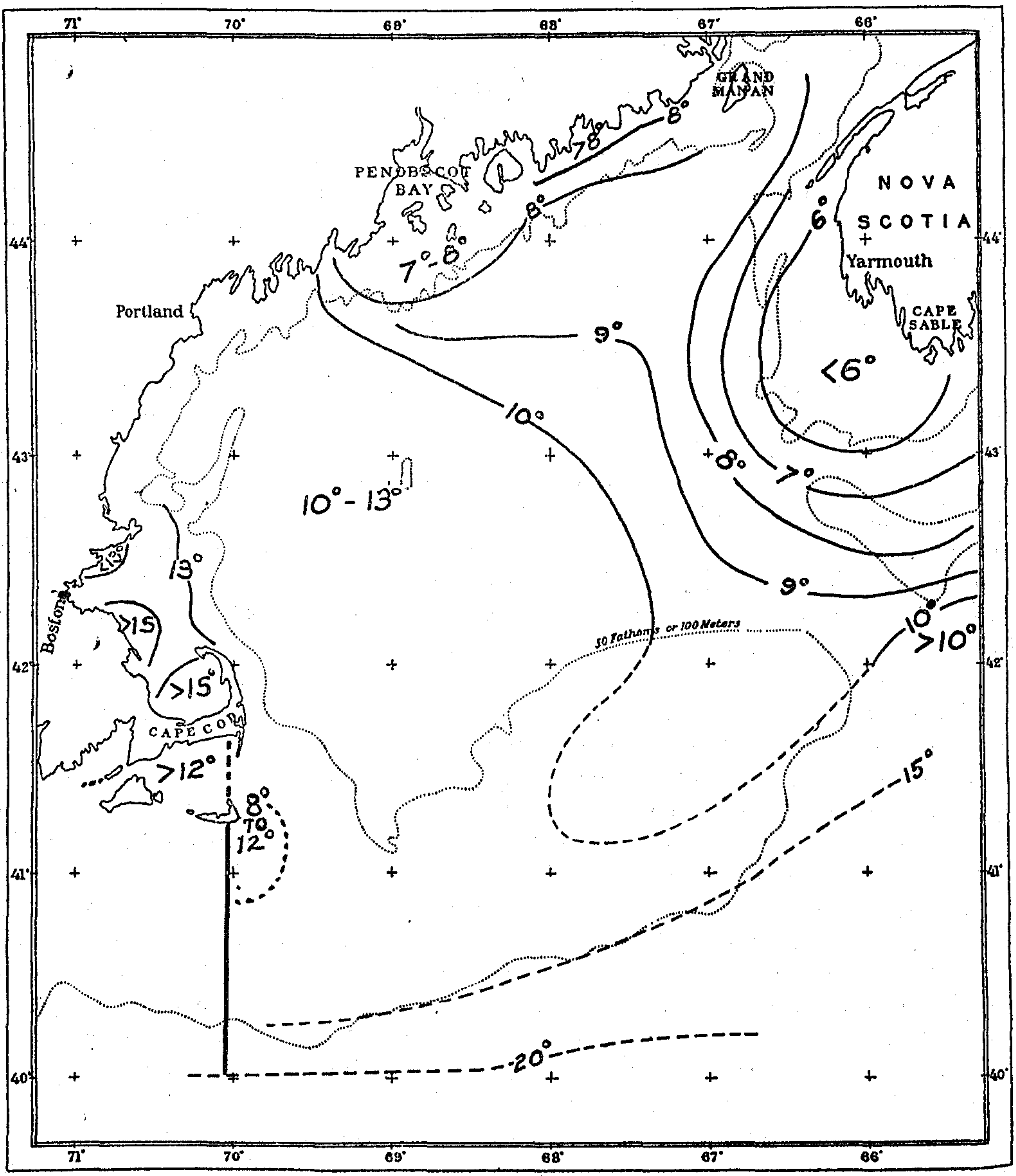

FIG. 39.—Surface temperature in mid-June from all available sources. The dotted curves are based on Dixon's (1901) tabulation

as in Massachusetts Bay in 1925. The 40-meter temperature, however, rose by only 1.5° during the interval (from about 5.2° to about 6.8°), while virtually no change took place at 90 meters or deeper (fig. 5). It is probable, also, that the seasonal succession illustrated by these two stations is characteristic of that side of the basin in general.

No observations have been taken in the western side of the gulf in June, or on Nantucket Shoals, on the cruises of the Bureau of Fisheries' vessels, except those just mentioned; but the daily data tabulated by Rathbun (1887) for several lighthouses and lightships partially fill the gap for the coast sector between Cape Ann and the Mount Desert region, and are consistent with the serials taken of late years in the northeastern part of the gulf, in the Bay of Fundy, and in Massachusetts Bay.

Approximate temperatures (°C.) at the surface on June 15, from Rathbun's (1887) tables[1]

Locality	1881	1882	1883	1884	1885	Average
Pollock Rip lightship	14.2	9.7	12.2	11.7	10.6	11.7
Thatchers Island (Cape Ann) light	13.2	------	12.2	------	------	12.7
Boon Island light	10	8.3	10.6	11.4	10.3	10.1
Seguin Island light	9.8	10.9	11.9	11.4	9.4	10.7
Matinicus Rock light	8.3	8.3	7.2	8.3	7.5	7.9
Petit Manan light	7.6	8.9	10.3	10.6	10.1	9.5

[1] Given only to nearest 0.1°.

The 10-day averages for Gloucester and Boothbay for 1920 (figs. 29 and 30) show that the water warms only slightly faster in inclosed locations of this sort than off the open coast (compare 13° at Gloucester and about 12° at Boothbay on June 15 with Rathbun's record of 12° to 13° at Thatchers Island, off Cape Ann, and of 9° to 11° at Seguin Island. A temperature about 3 degrees lower at Matinicus Rock, at the mouth of Penobscot Bay, than at Seguin Island, some 34 miles along the coast to the westward, probably reflects some local retardation of vernal warming by the spring freshets from the Penobscot River. Conversely, the comparatively high temperature at Petit Manan suggests that readings as warm as 10° are to be expected by June 15 after a few days of warm weather, in sheltered locations along shore in shallow water, to the east as well as west of Mount Desert. In fact, Doctor McMurrich records almost as high surface temperatures (9° to 9.5°) at St. Andrews by June 15 in 1916. Lubec Narrows, however, open to the Grand Manan Channel and with a great volume of water rushing through on every tide, had warmed to only about 6° by this date in 1920 (fig. 31).

Earlier in the season, and up to mid May, the vertical distribution of temperature in the upper 150 meters or so is of one type throughout the inner waters of the gulf, though the actual values differ slightly from station to station. During late May and June, however, very important differences develop between the state just described for the western side of the gulf (where the rapid warming of the upper stratum by the sun, coupled with the sudden establishment of a high degree of vertical stability, causes the development of a steep temperature gradient in the upper 40 to 50 meters, overlying water more nearly homogeneous) and the northeastern part of the gulf, where more active stirring by the tides spreads the warmth received from the sun through a thicker stratum of water. Furthermore, we find the rate of warming decreasing from west to east as we follow around the coast line of the gulf, even after this regional difference in the downward dispersal of the heat received has been allowed for. Thus, the surface had warmed only from 5° on May

12 (station 10276) to 7.8° on June 14 (station 10287) off Penobscot Bay; the 40-meter level from 4.2° to about 5.8°, while the courses of the curves suggest that no appreciable change in the temperature of the water is to be expected at or below 80 meters off this part of the coast during the month of June.

In the immediate vicinity of Mount Desert Island the surface temperature rose by about 1° from May 10 to 11 (stations 10274 and 10275, 4.2° and 4.4°) to June 10 to 11 (stations 10283 and 10284, both 5.4°); but four days later surface readings of 7.5° to 8° were had at three stations (10285 to 10287) a few miles to the westward. The graphs (fig. 7) for these stations, as compared with May 10 (station 10274), show that the whole column, down to the bottom in 80 meters, warmed at a nearly equal rate there up to June 10, instead of most rapidly at the surface, as happens off Penobscot Bay and in the Massachusetts Bay region, no doubt because of the stronger tidal currents to the east than to the west of Penobscot Bay (p. 678).

Near Mount Desert Island this vertical stirring is sufficiently active to bring the whole column of water uniformly under the effect of the sun's rays during the early spring, resulting in the uniform rate of warming from surface to bottom just noted. During June, however, the surface receives heat so rapidly there, coupled with a corresponding freshening (p. 747), that the column is stabilized vertically, though the deeper layers are never so insulated here as in the less actively stirred waters to the west of Penobscot Bay and to the south of Cape Elizabeth.

In 1915 this establishment of stability in the Mount Desert region evidently fell between June 10 and June 15, because the surface warmed more rapidly there between these two dates (a change of about 2°) than it had during the preceding month, though the 30-meter and deeper temperatures rose by only about 0.2° meantime.

Data are not available for a general survey of the temperature of the Bay of Fundy for the month of June, but very considerable local differences in the rate of vernal warning are to be expected there during the early summer to correspond with regional differences in the activity with which the water is stirred by the violent tidal currents. The Grand Manan Channel stands at the one extreme, with the whole column of water warming uniformly, or nearly so, through June down to 100 meters, and correspondingly slowly at all depths. Thus, on June 4, 1915, the whole column of water in the western end of the channel abreast the north end of Grand Manan (station 10281; 80 meters) was about 4.5° in temperature, pointing to a rise of about 2° at all levels from the minimum of the preceding winter, and the channel continues homogeneous in temperature from surface to bottom into August (p. 599).

In the central parts of the Bay of Fundy, however, vernal warming essentially parallels the account just given for the Mount Desert region, with a similar seasonal relationship between successive monthly curves (fig. 40) constructed from Mavor's (1923; *Prince* station 3) records for the spring of 1917, though the actual temperatures differ somewhat at the two localities. Thus, this Fundy station warmed from 2.96° to 8.18° at the surface between May 4 and June 15; from 2.01° to 4.13° at 50 meters; from 1.87° to 3.92° at the 100-meter level; and from 1.75° to 2.08° at 150 meters;

so that the temperature curves for the two dates recall those off Mount Desert for May 10 and June 14, 1915, in their mutual relationship. A similar seasonal relationship also obtains between serials taken in the Fundy Deep near by on March 22, 1920 (station 20079), and June 10, 1915 (station 10282).

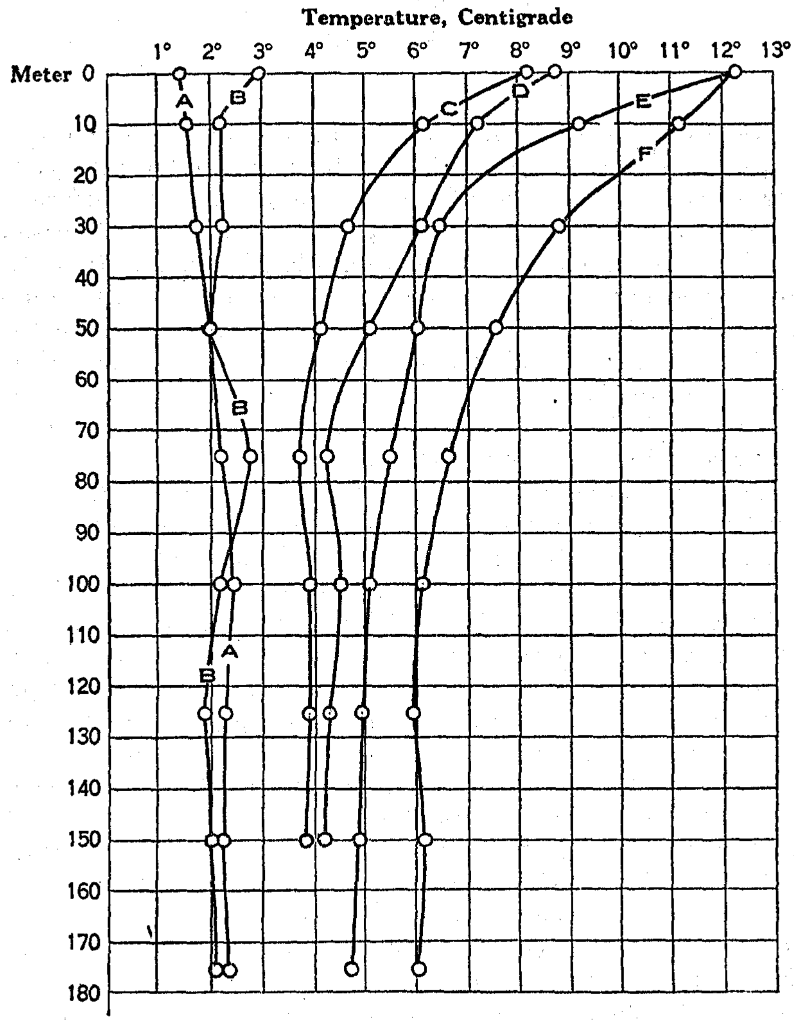

FIG. 40—Vertical distribution of temperature in the Bay of Fundy in 1917, from Mavor (1923, *Prince* station 3, 1916–17). A, February 28; B, May 4; C, June 15; D, July 4; E, July 31; F, September 4.

In 1917 the surface temperature had risen only to 8.68° at the *Prince* station by July 4 (Mavor, 1923, p. 375); the 50-meter level to 5.06°, the 100-meter level to 4.5°, and the 150-meter level to 4.21°; but warming either took place more rapidly in the Bay of Fundy in 1904, or the temperature did not fall so low there during the preceding winter, because Dawson (1922, p. 82, station F) found the deeper strata of the Fundy Deep about 2° warmer than this a week earlier in the season, as follows:

Serial temperatures (° C.) in Fundy Deep for June, 1904, after Dawson (1922)

Depth	June 23, 1904	June 29, 1904[1]	Depth	June 23, 1904	June 29, 1904[1]
Surface	8	11.1	27 meters	6.7	8.6
9 meters	7.5	9.7	55 meters	6.4	7.5
18 meters	7	9.4	91 meters	6.4	6.4

[1] Dawson's records are given to the nearest 0.5° F.

Surface water only about 4° warmer than the 50 to 60 meter level at these Bay of Fundy stations, as late as the last half of June, is an interesting contrast to the coastal sector between Cape Cod and Cape Elizabeth, where the surface temperature rises to 7° to 8° higher than 50 to 60 meter temperature by that season; nor does this regional divergence reach its maximum until late in summer (p. 596).

The most interesting phase of the June temperatures for 1915 is the light which they throw on the hydrographic cycle in the southeastern parts of the gulf. As stated above (p. 561), actual chilling takes place over the banks west of Nova Scotia, and out into the neighboring basin, from April to May, while the icy water of the Nova Scotian current is flowing into the gulf from the east past Cape Sable, although vernal warming is well under way elsewhere.

In 1915 this flow had become so weak during the last half of May (if it had not ceased altogether) that it no longer offset the normal tendency of the water to warm at this season. Consequently the temperature of the whole column of water on German Bank rose from about 3° on May 7 to about 6° on June 19 (station 10290). Unfortunately, the neighboring station in the basin (10270) was not revisited in June; but the surface a few miles northward also warmed from a temperature of 4° to 5° in mid May to 9.7° on June 19 (station 10288), though with a rate so rapidly decreasing with depth that the deep water, at 100 to 180 meters, was only 0.4° to 1° warmer on the later date than on the earlier one. As this rise of temperature in the deeps was accompanied by a corresponding rise in salinity (p. 755), it is to be credited to a renewed pulse in the inflow through the Eastern Channel, and 1919 seems to have been a still "earlier" season in this respect, as described above (p. 558).

Off Shelburne, only 25 to 30 miles to the eastward of Cape Sable, by contrast, the 50 to 75 meter stratum continued very cold next the coast (0.7° to 0.9°) until the last week of June in 1915 (Bigelow, 1917a, stations 10291 and 10292), and was only slightly warmer at the end of July of that year (Bjerkan, 1919) or in July, 1914 (station 10231). Consequently, it would not be surprising to find the water along western Nova Scotia temporarily chilled by a renewed pulse from this icy reservoir at any time during June, either at the surface or a few meters down. Serial readings taken off Yarmouth, also off Cape Sable, by Dawson in 1907 (1922, p. 82, stations M and S), show that some such event did take place that year, made evident by a drop in the bottom temperature (55 meters) in the offing of Yarmouth, Nova Scotia, from 4.7° on June 17 to 1.1° on June 25, although the surface water continued to rise in the normal seasonal advance.

Temperatures (°C.) 17 miles southwesterly from Cape Fourchu in 1907, from Dawson (1922, p. 82)

Depth	June 17	June 21	June 25
Surface	5.6	6.4	8.9
9 meters	5	6.1	6.9
18 meters	5	4.7	3.9
27 meters	4.7	4.7	2.8
55 meters	4.7	4.7	1.1

The source of this cold indraft is found near Cape Sable—by Dawson's records 10 miles south from Brazil Rock on the 26th and 27th, quoted below—which also shows an interesting variation in temperature at different stages of the tide.

Temperatures (°C.) 10 miles south of Brazil Rock (from Dawson)

Depth	June 26, high water	June 27, low water
Surface	8.6	7.8
9 meters	4.7	7.5
18 meters	2.8	4.7
27 meters	2.5	3.9
55 meters	1.4	1.9

It is probable that when belated overflows of the cold Nova Scotian water into the gulf do occur after early June they are of brief duration, for we have found no evidence of such an event later in the season on our recent cruises.

Dawson's June temperatures likewise afford an interesting illustration of the rate at which the surface water may be expected to warm along the Nova Scotian coast sector between Yarmouth and Cape Sable during the month of June. Thus, the surface there was 4.4° to 5° on the 7th of the month in 1904, though it had already risen to 6° at the mouth of Yarmouth Harbor by that date. In 1907 the surface was 5° to 6° in the offing of Yarmouth on the 11th to 15th; 6° to 7.8° on the 22d (warmest close in to the land); 6.5° to 8° to the eastward of Cape Sable by the end of that month; but the tide-swept region close to the cape was still only 4.2° to 5°, and this cold pool reappears on our charts for August (p. 592).

In 1915 the temperature of the surface water had risen to 10° over Browns Bank and the Eastern Channel (stations 10296 and 10297) by June 24 to 25, which is 3.5° cooler than the expectation for Massachusetts Bay at that date, and the water that filled the trough of the channel at depths greater than 100 meters was about 1 to 2 degrees warmer (7° to 8°) than on April 16, 1920 (station 20107). On Browns Bank, too, the temperature of the bottom water was about 4° higher at the June station than at the April station (stations 10296 and 20106), but the 40-meter reading was actually lower in June (2.8°)—colder, in fact, than any June reading in the inner parts of the Gulf of Maine. The presence of a cold mid stratum at this particular locality sandwiched between water of 7.36° on bottom at 80 meters, 10° at the surface, is unmistakable evidence of an extension of the cold Nova Scotian water from the eastward out over the bank, indenting into the higher temperatures that may be expected to prevail there earlier in the season. The profile run across the shelf abreast of Shelburne, Nova Scotia, the day before (stations 10291 to 10295, June 23 and 24, 1915) corroborates this apparent tendency for the cold Nova Scotian current to swing offshore abreast Cape Sable at the time, instead of flowing past the cape into the eastern side of the Gulf of Maine, as it does earlier in the season. This profile (fig. 41) lies outside the geographic limits of the present discussion; it will be enough, then, to point out that it cuts across a lenticular mass of water colder than 2°, occupying the whole breadth of the continental shelf at the 40 to 100 meter level, with a minimum reading of only 0.7° (station 10292, 50 and 75 meters) in the trough between the land and La Have Bank.

The high temperatures recorded for the Eastern Channel in June, 1915, prove Browns Bank the westerly boundary for the icy water at the time; but it may extend across the Eastern Channel to Georges Bank earlier in the month in some years, a question discussed below in connection with the July temperatures of the bank (p. 919).

Unfortunately, no temperatures have been taken below the surface on any part of Georges Bank in June. It is probable that the vernal expansion of the cold Nova Scotian current maintains temperatures lower than 10° on the eastern part of the bank until the first of the month, and Dickson (1901) so represents it on his chart of surface temperatures for June, 1897, contrasting with temperatures higher than 12° in the western side of the gulf, on the one hand, and outside the continental edge, on the other. July temperatures (p. 594), however, suggest that the surface on the western end of the bank may be expected to warm to 10° to 11° by mid June, except locally, where strong tidal currents and rips sweep around its shoalest portions. Considerable variations develop in the temperature gradient on Nantucket Shoals by that month, however, according to the local activity of the tidal stirring, for the *Halcyon* found the temperatures almost exactly the same on bottom in about 30 meters depth (8.3°) as at the surface near Round Shoal on June 7, 1925, but the bottom more than 5° colder than the surface[19] in water of about 40 meters depth only 6 miles to the eastward.

Judging from daily readings made at Nantucket lightship in the years 1881 to 1885 (Rathbun, 1887), and from the *Halcyon* temperatures just cited, surface temperatures of 10° to 12° (varying somewhat from year to year) are to be expected in the Nantucket Shoals region generally by the middle of June.

GENERAL DISTRIBUTION OF TEMPERATURE

A graphic picture of the June state for the gulf as a whole results from combining the June stations for the various years (fig. 39). Unfortunately, the observations not only include possible annual differences, but cover too long a space in time for this surface chart to be as satisfactory as might be wished at a season when the water is absorbing heat from the sun as rapidly as happens through June. It will serve, however, as an indication of the regional distribution and approximate values that may be expected in various parts of the gulf at the middle of the month. Its feature of chief interest is that the temperature is higher in the western side than

[19] Surface 11.7°; bottom 6.4°.

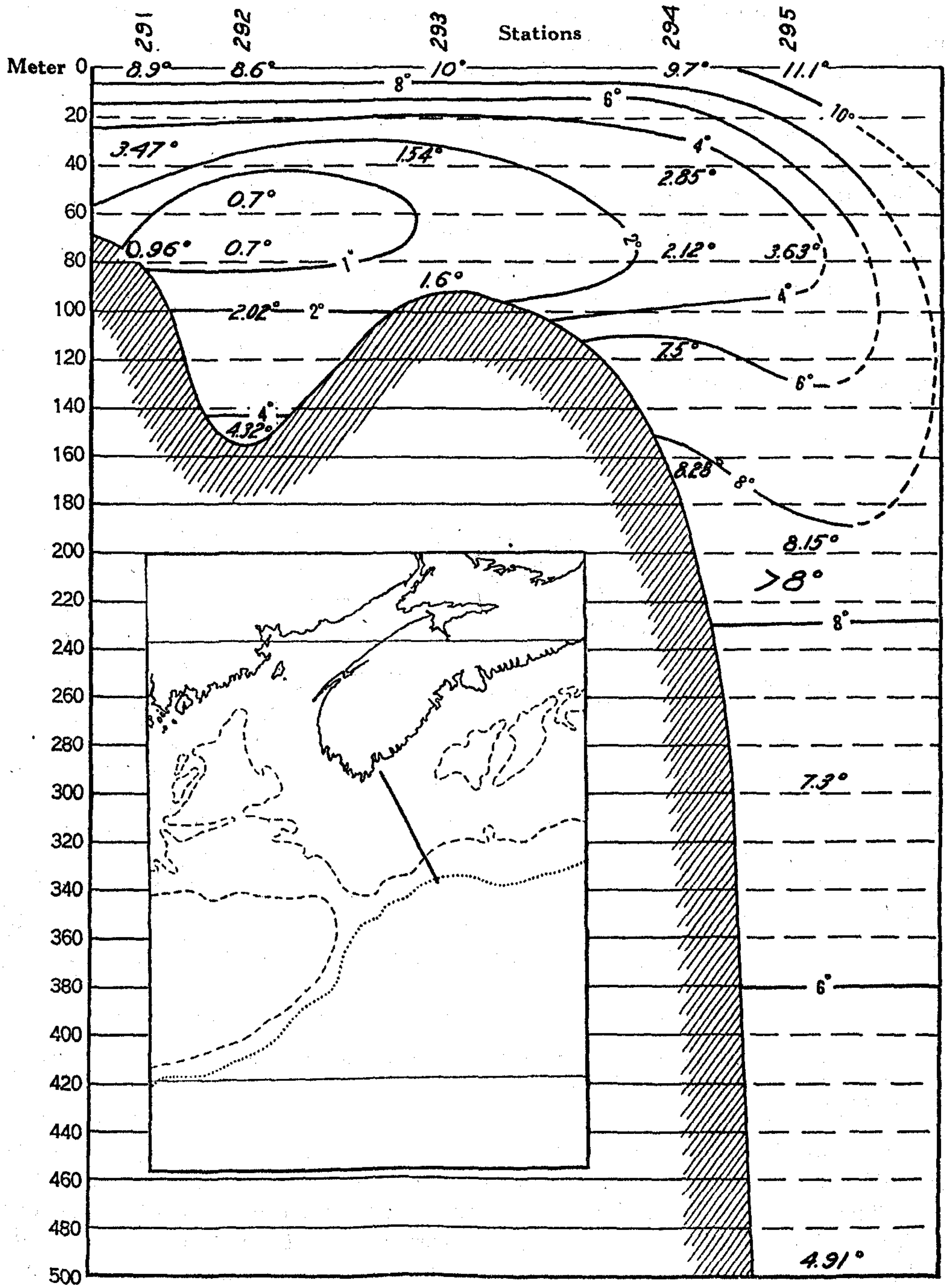

FIG. 41.—Temperature profile running southward from the vicinity of Shelburne, Nova Scotia, to the continental slope, for June 23 and 24, 1915

in the eastern side in June, just as it is in May (p. 556, fig. 27), and warmest in the inner part of Massachusetts Bay.

In June the surface of the gulf is coldest over the shallows west of Nova Scotia, with rather a sudden transition from surface temperatures of 8° to 9° and higher in the eastern side of the basin to readings lower than 7° to 8° next the land. The comparatively warm core (8° to 9°) extending up the deep trough of the Bay of Fundy, outlined by the curve for 8° on this surface chart, also deserves mention, as does the slightly cooler zone (7° to 8°) extending westward along the coast of Maine across the mouth of Penobscot Bay.

In the offshore side of the picture, Dickson's (1901) data for the years 1896 and 1897 locate the isotherm for 15° as following along the continental edge of Georges Bank, with surface water of 20° separated from the edge of the continent by a wedge of cooler water increasing in breadth from west to east.

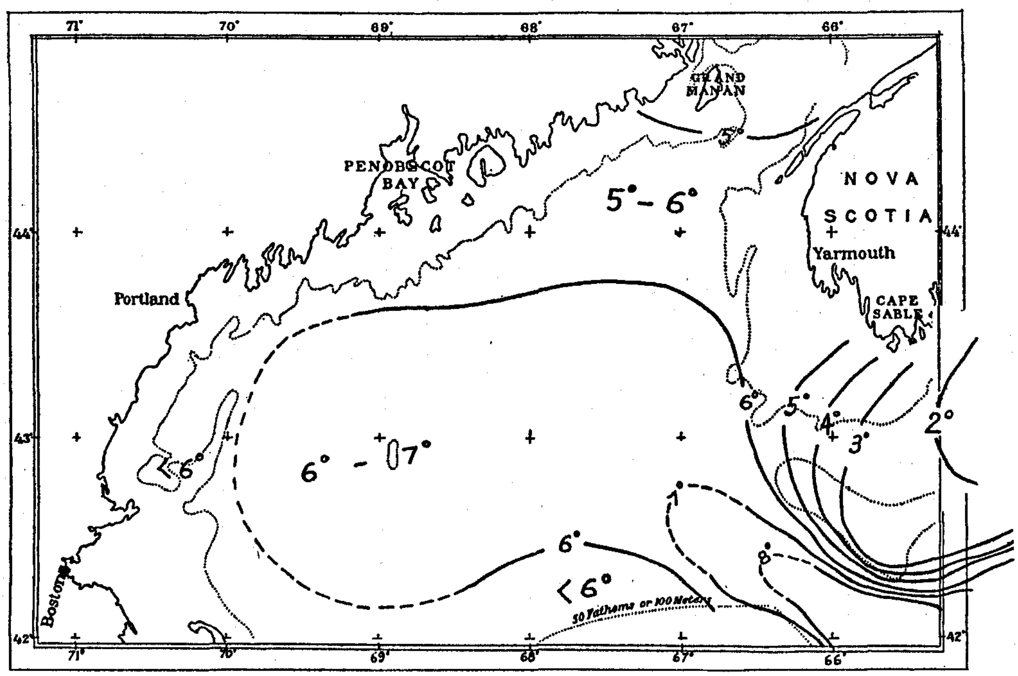

FIG. 42.—Temperature of the eastern side of the gulf at a depth of 40 meters, last half of June, 1915. The Bay of Fundy temperature is according to Mavor (1923); the temperatures along western Nova Scotia are from Dawson (1922)

The June chart for 40 meters (fig. 42) shows a gradation in temperature across the gulf from west to east of the same sort as appears at the surface (fig. 39). The influence of the Nova Scotian current on temperature at the 40-meter level is graphically illustrated by an expansion of water colder than 3° from the coast off Shelburne, Nova Scotia, out across the western part of Browns Bank, contrasting with higher temperatures (5° to 6°) on German Bank and along western Nova Scotia.

The most interesting feature of this 40-meter chart is the sudden transition between the cold water on Browns Bank to the much higher temperature (8.2°) in the Eastern Channel (a horizontal dislocation of 5° in a distance of only about 15 miles) and its demonstration that the latter is clearly a tonguelike intrusion from offshore. The records are not sufficient to outline exactly how far 7°-water then penetrated the southeastern part of the gulf; but the temperatures at such of the stations as lie in the course usually followed by the inflowing current (6.3° and 6.1° at 40 meters at stations 10288 and 10299) suggest that readings as high as 7° would not have been found farther west in the basin than is outlined on the chart at any time during June, 1915. Undoubtedly, however, wide fluctuations occur from year to year in this respect.

If the data for the two years 1915 and 1925 can justly be combined, as seems allowable because the preceding winters were not unusually severe, slightly higher temperatures are to be expected over the eastern and central parts of the basin generally than either in the northeastern corner of the gulf (including the Bay of Fundy), on the one hand (40-meter level about 4° to 5°), or off Massachusetts Bay, on the other, where the *Fish Hawk* recorded 40-meter temperatures of 3.5° to 4.5° at most of her mid June stations in 1925. A 50-meter reading of 5.18° in the southern side of the basin as late as June 25, 1915 (station 10298), suggests that the 6° to 7° water then takes the form of a pool, as it is shown in the chart, entirely surrounded by slightly lower temperatures except for its connection with still warmer water outside the edge of the continent, via the Eastern Channel. A regional distribution of temperature of this sort is interesting as evidence that the influence of the indraft through the Eastern Channel may raise the 40-meter temperature of the central parts of the gulf slightly higher in late June than the figure (4° to 5°) to which solar warming, unassisted, would bring it by that date.

At a depth of 100 meters (fig. 43) the isotherm for 5° shows a tendency on the part of this indraft to follow the eastern slope of the basin and to eddy to the westward around its northern side, but this drift seems not to have been active between the dates covered by this cruise (June 10 to 26) because not as clearly outlined as in March, 1920 (fig 13), but showing a gradation in temperature from 8° in the Eastern Channel to 5° at the mouth of the Bay of Fundy. Had water been flowing actively inward through the channel at the time, a uniformly high temperature (7° to 8°) naturally would have resulted over a considerable area in the eastern side of the gulf. A transition of the opposite sort along the Northern Channel, from 6° to 7° at its western end to 2° to 3° at its eastern end, is evidence equally clear that no general movement of the water was taking place through this trough, either westward into the gulf or vice versa.

Unfortunately, no data are available on the subsurface temperatures along the seaward slope of Georges Bank for June, but our Shelburne profile for June 23, 1915 (fig. 41), showed the warmest (8°) bottom water separated from the edge of the bank by a much cooler (about 4°) wedge at 100–120 meters, as seems always to be the case to the eastward of the Eastern Channel.

The temperature of the bottom water in the deeps of the gulf is always interesting because of the light it throws on the inward pulses (p. 922). During the last half of June, 1915, this was fractionally warmer than 6° in the eastern and south central parts of the basin at depths greater than 175 to 185 meters (stations 10288 and 10298), underlying a cooler stratum (4° to 5°) at 50 to 150 meters; and although no record was obtained of the bottom temperature in the western arm of the basin on this cruise, the presence of 6°-water there on May 4 (p. 566) at depths greater than 225 to 230 meters, and again on August 31 of the same year (station 10307), makes it almost certain that this was also the case in June.

The relationship which this warm bottom stratum bears to the cooler water above it and to the indraft from outside the edge of the continent, is made more graphic by the accompanying profile, running from the Eastern Channel westward and inward along the basin (fig. 44).[20] Obstructed on the north by the topography of the sea floor, this warm bottom water reaches the western part of the basin off Cape Ann via the southern branch of the trough, a route that entails its rising over the intervening ridge to within 190 to 200 meters of the surface.

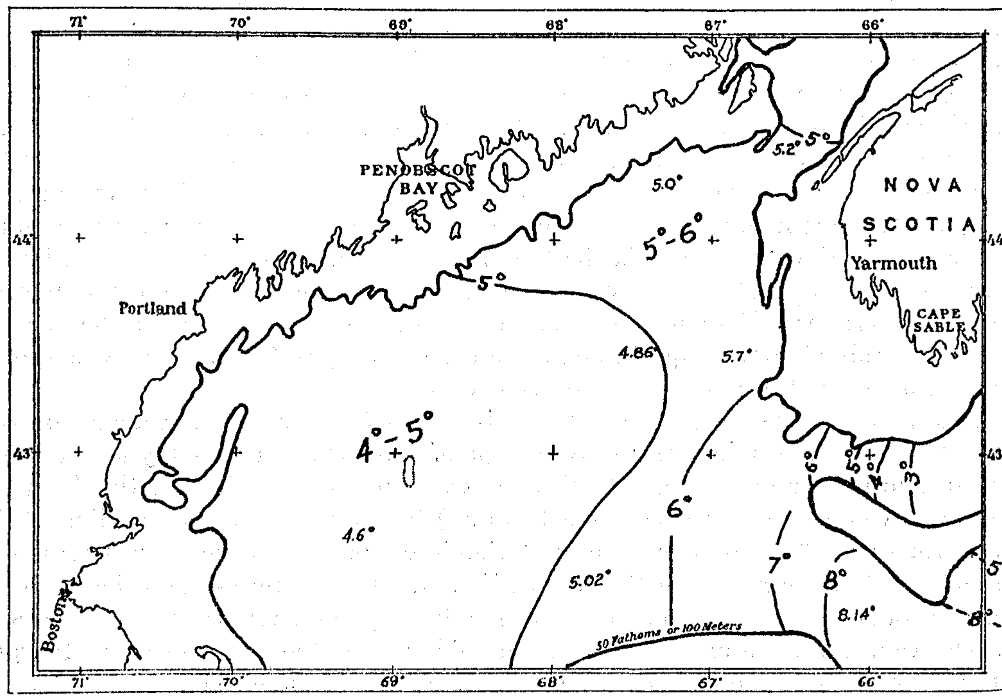

FIG. 43.—Temperature at a depth of 100 meters, last half of June, 1915. (The Bay of Fundy is according to Mavor, 1923.)

It is probable that overflows of this sort are intermittent—frequent enough, however, to maintain the bottom temperature of the western bowl fractionally above 6° for most of the year. The greater thickness of the warm bottom stratum in the southeastern side of the basin (into which the Eastern Channel opens) than elsewhere in the gulf corresponds to the proximity of the source of supply; and it is not unlikely that bottom temperatures of 7° or higher would have been found there at the end of June had readings been taken in depths greater than 275 to 300 meters.

In horizontal plan the bottom water of 6° takes the form of a Y, following the outlines of the trough of the gulf; its approximate outlines for May and June, 1915, are shown in the accompanying chart (fig. 45).

[20] The deepest readings in the western side of the basin are borrowed from the May station (10267).

JULY AND AUGUST

The vessels of the Bureau of Fisheries have taken a large number of observations within the gulf during the months of July and August since 1912. July and August temperatures have been recorded in various parts of the Bay of Fundy region under the auspices of the Biological Board of Canada over a series of years.[21] The tidal survey of Canada (Dawson, 1905 and 1922) likewise has gathered a considerable body of thermal information for the Fundian region and along the Nova Scotian side of the open Gulf of Maine. With such a wealth of material available, the chief difficulty in establishing the normal midsummer state of the gulf has been to appraise the importance of the annual and sporadic fluctuations that confuse the record.

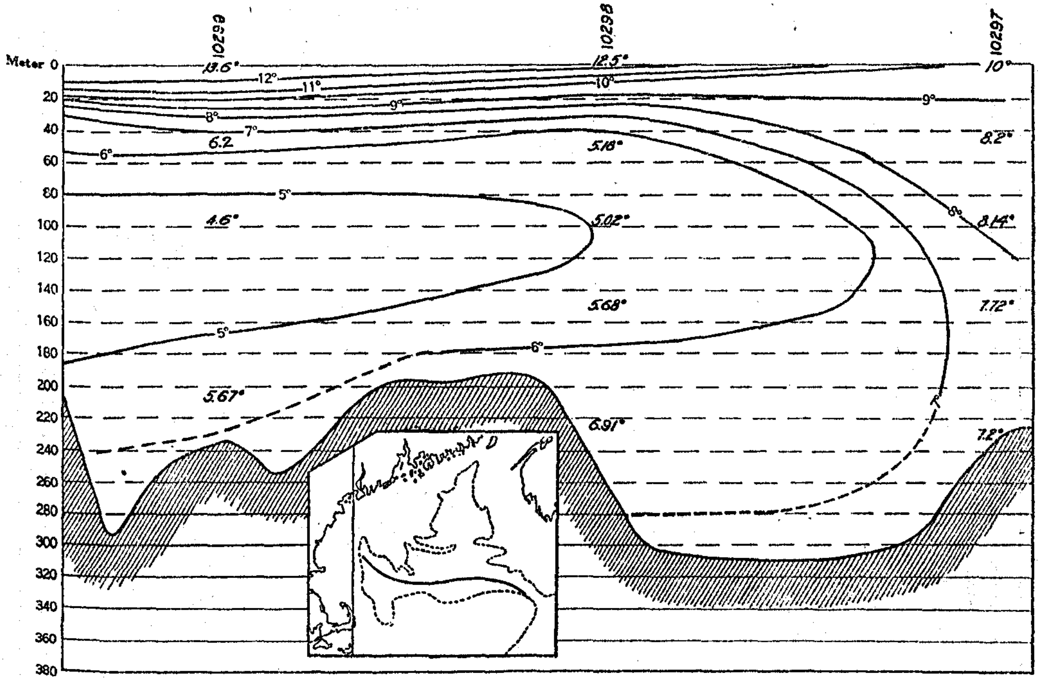

FIG. 44.—Temperature profile running easterly from the basin off Cape Ann along the trough of the gulf to the Eastern Channel for June 25 and 26, 1915

SURFACE

As the result of continued warming by the sun, the surface of all parts of the gulf is considerably warmer in July and August than it is in June, in most years rising nearly to its maximum by the last week of July over most of the gulf. The graphs for Gloucester and Boothbay Harbors (figs. 29 and 30) show that in inclosed situations of this sort the surface water is warmest then, mirroring the air temperature; but in the open waters outside warming continues slowly until well into August, depending on the weather, with the readings highest some time during the

[21] See Copeland (1912); Mavor, Craigie, and Detweiler (1916); Craigie (1916 and 1916a); Craigie and Chase (1918); Vachon (1918); and Mavor (1923).

last half of the month. On the whole, the surface temperature of the gulf may be described as more nearly stationary from July 25 to the end of August than over any equal interval during the spring, on the one hand, or during the autumn, on the other.

The surface chart for late summer (fig. 46) represents the average state during the last week of August. Deviations in one direction or the other from the precise values there given are to be expected, however, according as the year is warm or cold, the season forward or tardy (p. 626).

The surface temperature within the gulf rises highest over the western and southwestern parts of the deep basin, at the mouth of Massachusetts Bay, and in

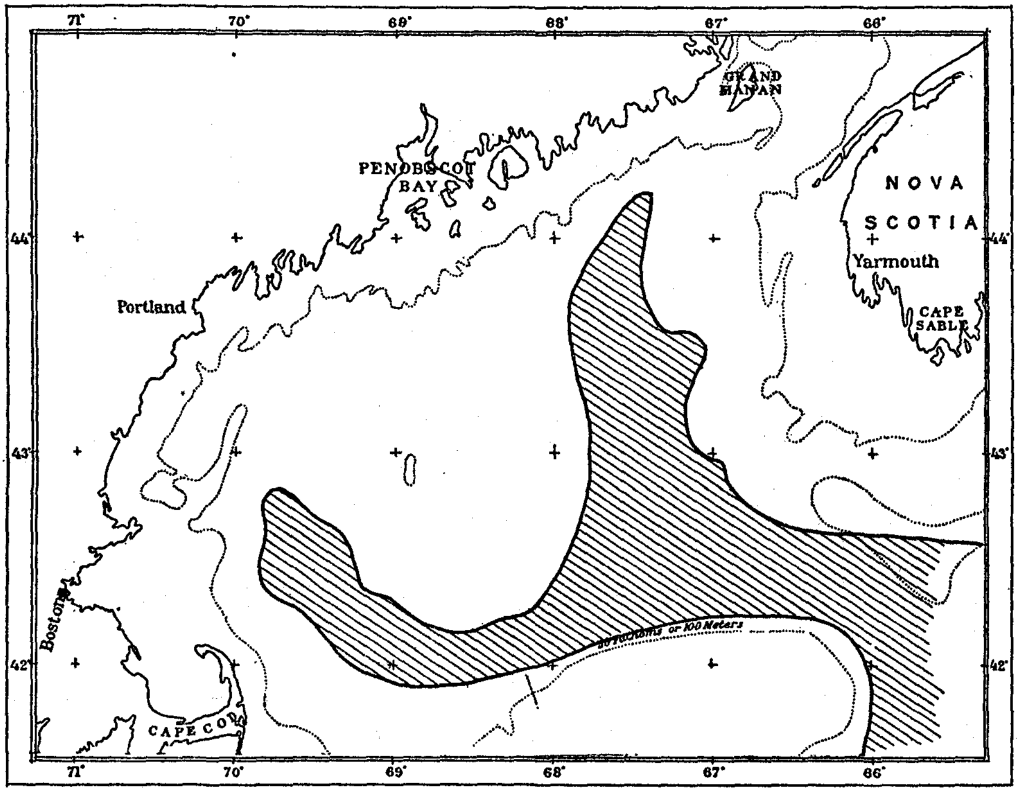

FIG. 45.—Extent of bottom water warmer than 6°, last half of June, 1915

Cape Cod Bay, as outlined by the isotherm for 18°. Within this area readings of 20° have been reported on three occasions, namely, twice by Doctor Kendall in the last week of August, 1897, and more recently on August 22, 1914 (station 10254). On the other hand, the lowest surface reading so far recorded for the last week of August in this warm subdivision, more than a few miles out from land, was 17.6° in the western basin on August 31, 1915 (station 10307). The data from the cruises of 1912, 1913, and 1914, compared with readings taken in August, 1922, and by Doctor Kendall in 1897, show that the temperature first reaches 18° at the mouth of Massachusetts Bay and out over the neighboring part of the basin in its offing, whence the limiting isotherm (18°) spreads south as well as north, to the confines laid down on the chart, as the summer draws to its close.

We have invariably had surface readings higher than 18° in the outer half of Massachusetts Bay after the first week of August, and in Cape Cod Bay; but off

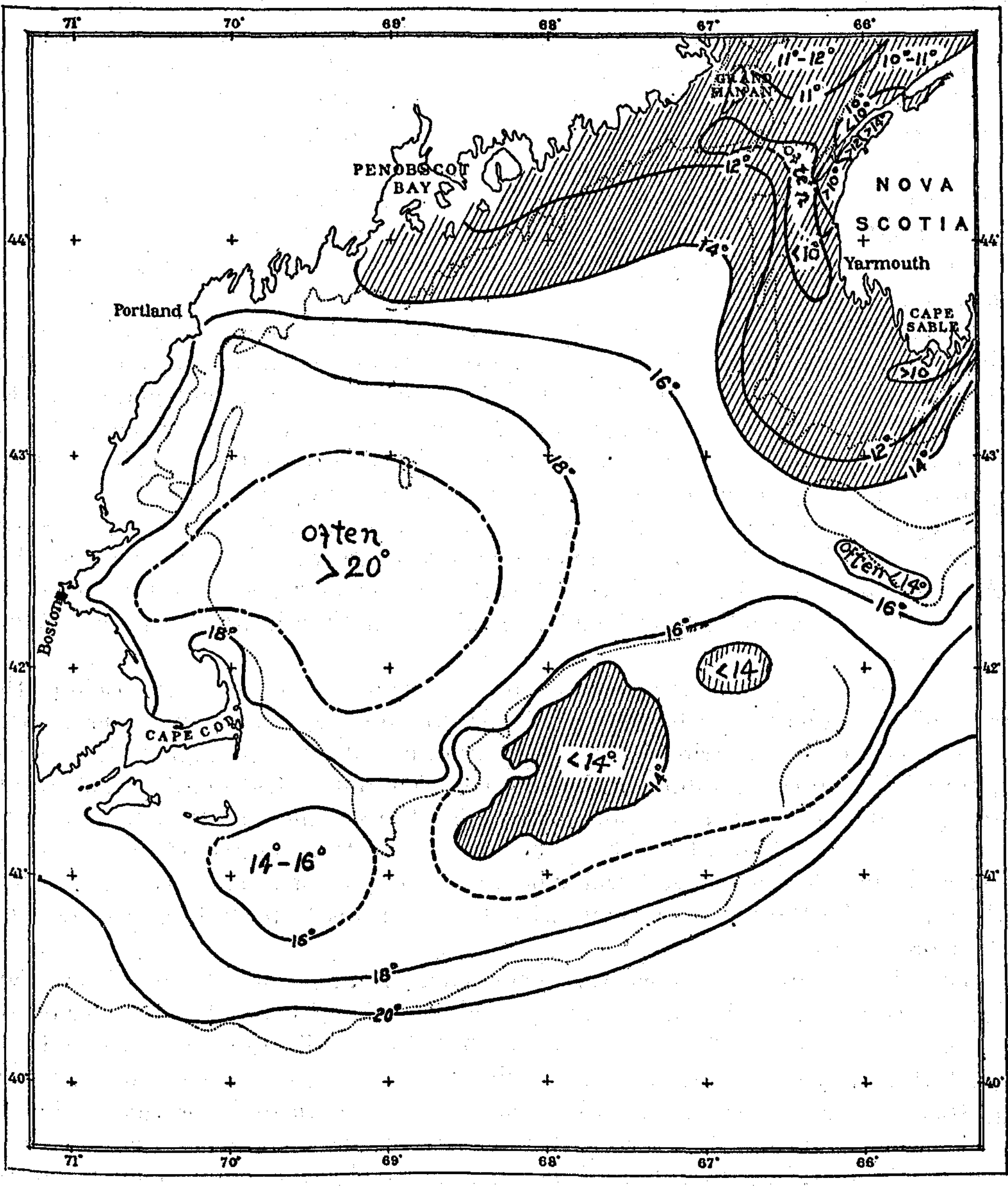

FIG. 46.—Normal surface temperature for mid-August, based on a combination of the recent station records with Rathbun's (1887) tabulation at lighthouses, the Canadian records, Dickson's (1901) data, and the daily surface readings, at Gloucester, Boothbay, and Lubec (figs. 29 to 31). (Close to Cape Sable, read < 10° for > 10°.)

the tip of Cape Cod, where tidal currents run strong, the surface is usually cooler locally, as is the general rule in such locations, with readings of 17° to 18° for the last half of August. For this same reason the coastal belt around the western and northern shores of Massachusetts Bay usually remains cooler than 18° on the surface throughout the summer, though warmer than 15°; but as every bather knows, continued onshore winds sometimes drive the warm offshore water right in to the beach there, though in a surface film so thin that one's legs may be in decidedly lower temperatures while swimming. On the other hand, when westerly winds drive the surface water out to sea, cooler water wells up from below, locally lowering the surface temperature. Upwellings of this sort, combined with local stirrings by the tides, are so common an event along the northern shore of the bay that usually this is fringed by a zone, a few miles wide, where streaks of surface water warmer than 16° alternate irregularly with patches cooler than 14° to 15°, and where we have occasionally had surface readings as low as 12° in July, with 10° reported to us in August. Cold streaks of this sort are most often to be expected about the bold promontory of Nahant and along the rocky shore between Gloucester and Cape Ann.

At Thatchers Island (the tip of Cape Ann) tidal disturbances may cause considerable and irregular fluctuations in the temperature of the surface from day to day, witness readings varying from 15.6° to 17.5° during the warmest periods of the summer of 1881 (Rathbun, 1887); but a temperature of 19.4° at the cape late in July, 1882, shows that the warm surface water from offshore may touch the coast line there during calm periods or after onshore winds, as it does elsewhere.

It appears from what little precise evidence is available, and from general reports by seaside dwellers, that similar fluctuations prevail all along the coast line in August, from Cape Ann northward about to Cape Porpoise; but the surface of the coastal belt averages 1° to 2° colder in this sector than in Massachusetts Bay—usually below 16°.

It is unfortunate that daily records are not available for any station along this stretch of coast line or for the Isles of Shoals, which occupy a commanding position off the mouth of the Merrimac River. Most of our August passages, also, to and fro, have followed courses outside the 100-meter contour. Rathbun's (1887) record of maxima of 15.6° to 16.7° at Boon Island for the summers of 1881 to 1885, with our own stations between Cape Elizabeth and Cape Ann, suggest 15° to 16° as the usual maximum for the coastal sector between the Isles of Shoals and Cape Elizabeth, out to the 100-meter contour, with temperatures 1° to 3° higher a few miles farther out at sea.

The rise in surface temperature experienced as one runs offshore from Cape Elizabeth is illustrated by the following readings taken by W. C. Schroeder on the *Halcyon* on a trip to Platts Bank, July 20, 1915: 8 miles out from Cape Elizabeth, 16.1°; 17½ miles out, 19.44°; 20 miles out, 19.44°; on Platts Bank, 30 miles out, 18.9°. This agrees closely with the gradation indicated for this region on the charts (figs. 46 and 47); also with the state of the surface on August 7, 1912, when the temperature rose, progressively, from 15.6°, at a point 8 miles off the cape, to 17.8° on Platts Bank (Bigelow, 1914, p. 46).

It has long been common knowledge that the coastal waters along eastern Maine and in the Bay of Fundy are cold in summer, with a maximum difference of almost 10° C. (18° F.) between the surface there and in the offing of Cape Ann. This cold area, outlined by the isotherm for 12° on the chart (fig. 46), also includes the whole eastern side of the gulf, off western Nova Scotia, out to the 100-meter contour, in an undulating outline more easily represented graphically than verbally.

The transition from warm to cool is often very noticeable as one runs from the offing of Cape Elizabeth, across the mouth of Casco Bay, to the neighborhood of

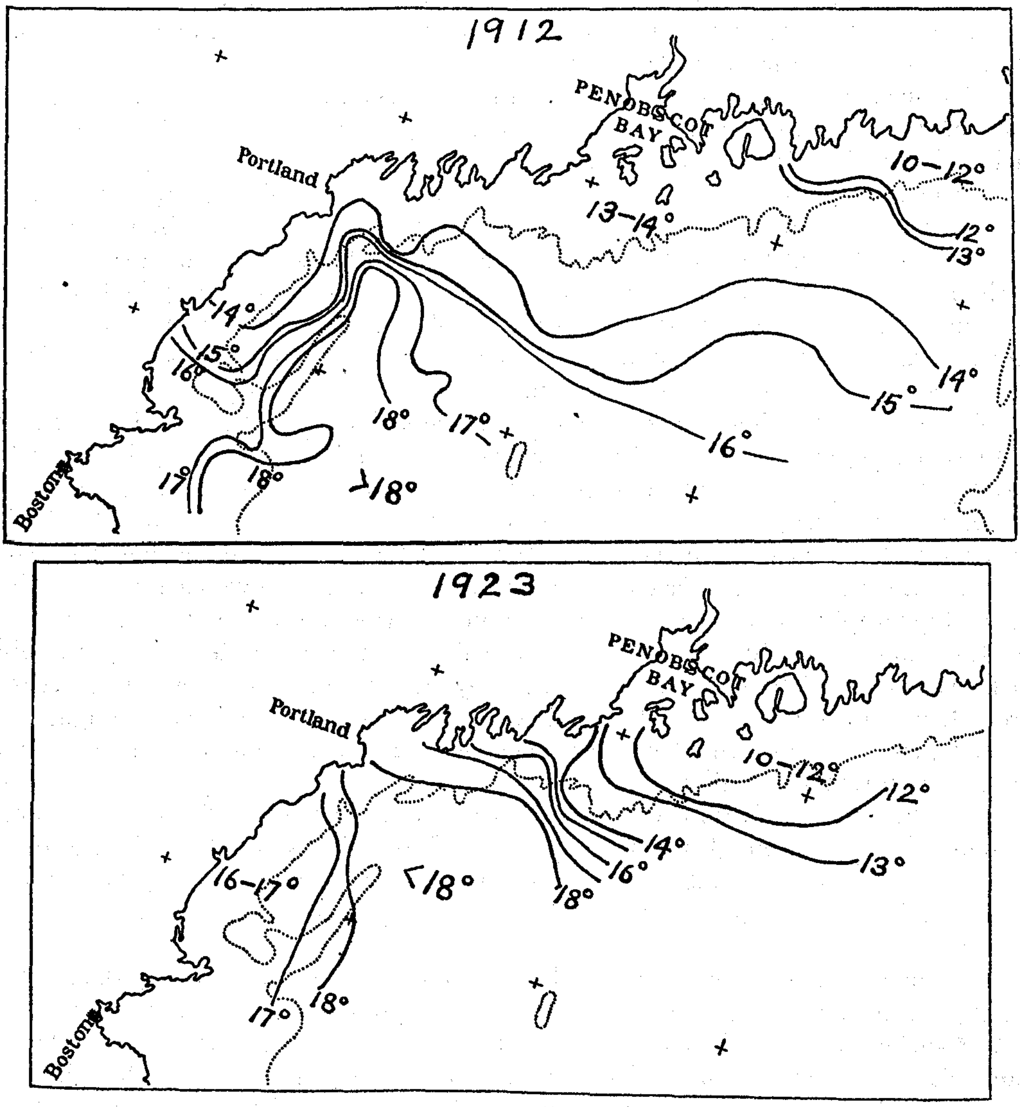

FIG. 47.—Surface temperature, July to August, 1912 (above), and July to August, 1923 (below)

Boothbay Harbor. On August 13, 1925, for example, the *Halcyon* had surface readings of 16° at the mouth of the bay but only 12.8° close to Seguin Island. Next the shore surface temperatures ranging from 13° to 15.3° have been recorded between Casco Bay and Penobscot Bay in August; usually cooler than 14°, but with much local variation as the tide swirls around the islands and ledges. The maximum temperatures at Seguin Island Lighthouse for the years 1881 to 1885 (Rathbun, 1887), were, respectively, 13.3° to 13.9°, 13.3° to 13.9°, 13.9° to 14.4°, 13.9° to 14.4°, and 14.4°. This agrees with readings of 13.9° at two localities within a few miles of the island on August 22, 1912, and with 12.8° to 14° in that general neighborhood on July 18, 1925; but one need run only a few miles offshore from this part of the coast to find the surface warmer than 16°, and Doctor Kendall records a reading of 16.7° within about 8 miles of the land off Seguin on August 16, 1897.

The surface temperature rises to 16° to 18° in Boothbay Harbor during the last week of July and the month of August (fig. 30); equally high, no doubt, in other sheltered bays in this neighborhood.

Surface readings taken on a line across the mouth of Penobscot Bay ranged from 12.8° to 13.9° on August 21, 1912, while Rathbun (1887) gives maximum temperatures of 11.7° to 12.2° at the lighthouse on Matinicus Rock at the western gateway to the bay, where the water may be somewhat chilled by the swirling tidal currents. The surface in sheltered situations within Penobscot Bay may warm to a temperature several degrees higher than this before autumnal cooling sets in, but information is scant for this particular region.

Our surface readings among the outer islands along the coast of Maine, east of Penobscot Bay, and out to the 100-meter contour usually have ranged between 10° and 12° for the last half of July and for the month of August (fig. 47). After a few calm, warm days the temperature of this zone may rise locally to 13° (12.78° off Mount Desert Island, August 13, 1913, station 10099, has been our highest record there). The surface water is considerably warmer up the bays, locally, depending on the topography of the bottom as determining how actively the water is stirred by the tide, and especially on the extent of the flats laid bare to the sun on the ebb. Surface readings of 10.6° to 11.7°, recorded by the *Halcyon* within a mile or two of Great Duck and Little Duck Islands, Bakers Island, and Long Island on August 8 to 11, 1925, cover the usual midsummer range close in to the islands and among them for the Mount Desert region.

Rathbun (1887) gives maximum summer temperatures of 11.6° to 13.3° at Petit Manan light, and although the surface water off Machias was only 8.9° on July 15, 1915 (station 10301), probably it is always as warm as 10°, or warmer, there during the last half of August, and usually 11° to 12°, except where some local upwelling is taking place.

The hourly temperatures taken off the eastern coast of Maine during the last half of August, 1912, are especially interesting because they suggest a movement of the coldest surface water (colder than 13.5°) offshore (i. e., to the southwest), out past Mount Desert Rock (fig. 47). Unfortunately I can not state whether this phenomenon is regularly recurrent in summer; but the fact that the surface was slightly cooler (9.3°) near Mount Desert Rock on September 15, 1915, than close in to Mount Desert Island (9.8° to 10.8°), near Petit Manan Island a few miles eastward along the coast (10.5°), or near Swans Island to the westward (10.8°), suggests that some such distribution of surface temperature is at least not unusual for that general region.

On August 17, 1912, and again on the 19th, we had readings of 10 to 11.7° as the *Grampus* sailed lengthwise through the Grand Manan Channel; and it is probable that this is about the highest temperature attained in the tide-swept Lubec Channel, because the highest 10-day average was about 10° there during the last of August and first of September of 1920 (fig. 31). The highest mean temperature recorded at Eastport for a 10-day period for the years 1878 to 1887 was 10.7° (Moore, 1898) in the second week of September.

The surface temperature of the greater part of the open Bay of Fundy likewise ranges from 10° to 12° in August, rising above 12° only exceptionally and locally (Huntsman, 1918; Vachon, 1918). Thus, Mavor (1923) records a range from 9.44° to 12° at 19 stations on three traverses of the bay inward from Grand Manan on August 22 to 27, 1919, warmest along the New Brunswick shore, coldest (9° to 10°) near Digby Neck on the Nova Scotian side. A similar gradation is described by Dawson (1922) for the first half of August, 1907. The records given by Craigie (1916), Craigie and Chase (1918), and Vachon (1918) for the open bay, with a maximum of 12.68°, a minimum of 8.93°, in July and August, are consistent with this on the whole.

Dawson (1922, p. 92) records surface temperatures somewhat higher (14.17° to 13.33°) than this on a run from Digby to the middle of the bay on the meridian of St. John, New Brunswick (his station A), for July 22, 1907, but this may have been an unusually warm summer in the bay. At any rate, temperatures so high were briefly transitory, for the surface at his outer station had cooled to 13.6° by the next day and to 12.8° three days later (Dawson, 1922, pp. 88–92), when the surface temperature along the land from Digby Gut to Brier Island was only 8° to 9°. With a variation from 10° to 11.7° over the Fundy Deep for the three-day period, August 23 to 25, 1904, independent of the stage of the tide (Dawson, 1922, p. 95), slight changes evidently are to be expected in the bay from day to day, perhaps governed by the roughness of the sea.

Many records of temperature, surface and subsurface, have been published for the Passamaquoddy Bay region by Copeland (1912), by Craigie and Chase (1918), and by Vachon (1918), showing a considerable regional variation in the temperature to which the surface attains by the end of the summer. Copeland found the surface warmest (13.9° to 15.6°) in the northern part of the bay, coldest (10.4° to 11°) near Deer Island and in Letite Passage, with the central and western parts of the bay ranging from 11.1° to 15°. Vachon (1918, station 4), likewise records the surface of the center of the bay as warming from 11.4° on July 20 to 15.9° on July 27 in 1916, cooling to 11° on August 3 and 17, but warming again to 12.48° on the 25th and to 14.91° on the last day of the month. In the mouth of the St. Croix River, however, the water is kept so thoroughly stirred by the strong tides that Vachon's highest reading was 13.4°, the lowest 10.95°, for the period July 17 to August 31, coolest after northwest winds. Low surface temperatures also rule in Friar Roads between Campobello Island and Eastport, where Vachon reports 8.7° to 10.3° between August 2 and September 17, with 9.5° to 12.62° in the western passage between Deer Island and the coast of Maine, and with about this same range of temperature at a station near St. Andrews.

Vachon's and Copeland's records, combined, show that the temperature of the surface of the northwestern part of Passamaquoddy Bay may be expected to reach 15° for a brief period in August in warm summers, though perhaps not every year. At the other extreme, the surface water in the channels between the islands of western New Brunswick, where tidal stirring is more thorough, is seldom warmer than 11° to 11.5°. Considerable fluctuations are also recorded within brief periods in the central part of the bay, where the surface temperature is intermediate between these two extremes, and in the mouth of the St. Croix River, connected with the direction of the wind and with the stage of the tide.

It is interesting to find that no part of the surface of the Bay of Fundy,[22] with its much stronger tides, is as warm as the greater part of Massachusetts Bay, though the maximum readings for these two areas differ by only about 3° (15° for Passamaquoddy and about 18° to 19° for Massachusetts Bay).

Craigie and Chase (1918) found the surface about as cold (9° to 11°) in the outer part of the Annapolis basin on July 23 to 24, 1915, as it is along the Nova Scotian side of the Bay of Fundy outside, but progressively warmer, passing inward, to 15.33° near the head. According to Huntsman (1924), Minas Basin, at the head of the Bay of Fundy, also warms faster than the latter in summer, but the definite values have not yet been published for it.

Dawson's (1922) very considerable list of surface temperatures for 1904 and 1907, with our yearly stations off Lurcher Shoal, on German Bank, and near Cape Sable, unite to show that a cool surface is characteristic of the whole coastal zone along western Nova Scotia out about to the 100-meter contour, usually with the readings falling between 9° and 12°, as outlined by the isotherm for 12° on the chart (fig. 46). More specifically, our own surface records for the Lurcher Shoal and German Bank stations have been as follows:

Locality and date	Station	Surface temperature
Near 100-meter contour, off Lurcher Shoal:		°C.
Aug. 15, 1912	10031	13.33
Aug. 12, 1913	10096	12.22
Aug. 12, 1914	10245	14.44
Sept. 7, 1915	10315	12.20
German Bank, outer part:		
Aug. 14, 1912	10029	10.44
Do	10030	11.11
Aug. 12, 1913	10095	8.89
Aug. 12, 1914	10244	10.00
Sept. 2, 1915	10311	9.40

The constant difference between these two localities shows that surface temperatures lower than 12° do not reach offshore beyond the 100-meter contour in the offing of Lurcher Shoal, but on August 12, 1913 (station 10094), we found the surface as cold (8.89°) 12 miles out from the edge of German Bank as it was over the latter (station 10095).

As Dawson (1922, p. 99) has remarked, "as a rule, the temperature nearer shore becomes higher when the weather remains quiet," his data showing that the

[22] For further details regarding the Bay of Fundy the reader is referred to the extensive tables given by Copeland (1912), Craigie and Chase (1918), and Vachon (1918).

water close in to the western coast of Nova Scotia warms to 10° to 12° by August from St. Marys Bay to Yarmouth. Yarmouth Harbor he found only slightly warmer (12° to 12.5°) than the open waters at its mouth, and it had about this same temperature on September 8, 1916,[23] but the surface of St. Marys Bay rises to a considerably higher temperature. The maximum for this bay can not be stated, data for the inner part of the bay for August being lacking. Craigie and Chase (1918), however, found its surface progressively warmer, passing inward, from 9° to 10° at the mouth to about 11° abreast of Petite Passage, 13° to 13.5° off Weymouth, and to 14.8° at the head during the second week of July in 1915; and as Vachon (1918) again had readings of 11.08° abreast of Petite Passage and 12.92° off Weymouth on September 4 to 5, 1916, it is not likely that August sees the surface temperature rise much above 15° anywhere in St. Marys Bay.

A coastal belt skirting Cape Sable, 12 to 15 miles wide, like the vicinity of Lurcher Shoal, is characterized by surface temperatures lower than 10° throughout July. This, no doubt, results from thorough stirring by the tides, which proverbially run strong around the cape, causing a mixture in varying amount with the icy water that persists until midsummer in the deeper strata next the coast, a few miles to the eastward (p. 681).

Near the cape Dawson (1922, p. 85, station Q) had surface readings of 5.3° to 7.5° (usually from 0.5° to 1° higher at high water than at low water) during the first half of July, 1907. By the last week of that month he found that the mean surface temperature 12 miles out from the cape had risen to about 9° at high tide and to about 8.4° at low, with a slightly greater difference between high and low tide temperatures (average about 9° and 7.2°) closer in to the land, and with a maximum of 11.95° at the high-water slack and a minimum of only 5° at low-water slack on the 20th. Our own more recent record of 10.28° near by on July 25, 1914 (station 10230), falls well within these extremes.

These temperatures suggest that the flood current, flowing westward past the cape, draws warmer surface water toward the land from offshore, but that the ebb, flowing to the eastward, carries out water that has been thoroughly mixed by the currents swirling around the cape.

Surface readings of 10° to 12° on several lines along the coast sector between Yarmouth, Nova Scotia, and the cape, for the middle of July (Dawson, 1922), show that this narrow cold pool off Cape Sable becomes entirely isolated from the low temperatures about Lurcher Shoal before the last of that month by the development of a warmer surface over the intervening area, but is continuous with still lower temperatures to the eastward along the outer coast of Nova Scotia until August, witness a surface reading of 6.62° at low water a few miles off Shelburne on July 27 in 1914 (station 10231), no doubt reflecting some updraft of the icy water from below with the outflowing tide. In 1915, however, the Canadian Fisheries Expedition found no surface water colder than 9.7° off this part of the coast on July 21 (Bjerkan, 1919). On September 6 of that year (station 10313) the surface was 15° 10 miles off Cape Roseway, 13.3° 10 miles south of Cape Sable on September 2 (station 10312), and 13.6° near by on August 11, 1914 (station 10243). Apparently, then, if the cold surface persists as late as August off the Cape, it becomes reduced to an isolated pool

[23] Varying from 11.3° to 12.7° during that day (Vachon, 1918).

not more than half a dozen miles wide by the end of the summer, persisting only as a reflection of purely local activity of tidal stirring.

Our Gulf of Maine cruises have not crossed the southeastern part of the area in August; hence the isotherms for this region (fig. 46) are only tentative for that month, combined from the July cruise of the *Grampus* in 1914, the Canadian Fisheries Expedition stations off southern Nova Scotia for July, 1915, temperatures taken by the *Albatross* in August, 1883, and July, 1885 (Townsend, 1901), and from scattering records from other sources. These combine to show a rather abrupt transition in surface temperature in the region of the Northern Channel between the cool area along western Nova Scotia (12°) and somewhat higher readings (14° to 16°) on Browns Bank, but make it unlikely that the surface normally warms above 16° over the latter at any season. It is probable, too, that much local variation in temperature exists on Browns Bank, with cool and warm streaks caused by tidal mixings, especially along its southwestern edge fronting the Eastern Channel, where the *Albatross* had surface readings of 12.78 to 13.3° at four stations on August 31, 1883.

The surface temperature in the center of the Eastern Channel was 15.1° on July 24, 1914 (station 10227), but readings of 12.8°, 16.1°, 14.2°, and 13.3° at four successive stations on a line crossing the deep water from Georges Bank to Browns Bank on August 31, 1883, suggest that while the central core of the channel is usually fractionally warmer than 16° by the end of the summer, vertical stirrings or upwellings are sufficiently active along the edges of the two banks to maintain narrow lanes there colder than 16° on the surface.

It is probable that the surface is from 1 to 3 degrees cooler over the eastern, northern, and central parts of Georges Bank, as a whole, than in the basin of the gulf to the north throughout the summer, and certainly it is considerably cooler than the oceanic waters outside the edge of the continent to the south, just as it is in June (fig. 39). Thus, Dr. W. C. Kendall had surface readings of 12.8° to 15.3° (averaging about 14.5°) at 55 stations along the northwestern edge of the bank on August 21 to 25, 1897, and the isotherm for 16° for this region is located on the chart (fig. 46) from these observations.

This part of the bank offers an excellent illustration of the chilling of the surface that follows when cooler water from below is brought up over and around shoals by the tides, with the surface averaging 1° to 3° cooler over the shoal ground than elsewhere on the bank and (generally) coldest (13° to 14°) over the shoalest part, where the water is less than 50 meters deep. Even small isolated shoal spots may cause cool pools at the surface in this region, and the effect of projecting submarine promontories or ridges may be made evident for some miles by lowered surface temperature. Where the water is not only shoal, but the topography of the bottom is broken and tidal currents run strong, considerable variations in surface temperature also are to be expected from ebb to flood, as Dawson found to be the case near Cape Sable (p. 593). Doctor Kendall records several such alterations on Georges Bank, notably a drop of about 1.5° at a station on its northern edge during a period of a few hours on August 21. A few yards' sailing may also be enough to bring the vessel from a cool streak into a warm one, or vice versa, the explanation for which is apparent enough on calm days when the lines of contact between different runs of tide are often made visible by miniature rips, oily slicks, or by the accumulation of floating débris of one sort or another. In all this, Georges Bank, in the south of the gulf, agrees with the coastal belt generally in the northeast, as it does in being colder at the surface than is the intervening basin where "the water moves to and fro in an unbroken sheet, clear of obstruction," as Dawson (1905, p. 15) expresses it.

Doctor Kendall's temperatures, added to readings taken by the *Grampus* in July, 1908 (Bigelow, 1909), and from the *Halcyon* in the summer of 1923, show that the surface is correspondingly cool (12° to 16°) in August over the shallow broken bottom south of Nantucket, with similar fluctuations within short distances and at different stages of the tide, due to the same disturbing influence of tidal mixings. Thus, the *Halcyon* had surface readings varying from 11.6° to 15° in August, 1923, as she fished at various locations within a mile or two of Round Shoal bouy; 13.3° to 16.4° over Rose and Crown Shoal; 15.5° over the slightly deeper channel between Round Shoal and Rose and Crown Shoal; and 13.8° to 15.5° on the Great Rip fishing ground 12 miles southeast of the island of Nantucket. Unfortunately, it is not yet known whether this cold area is separated from the equally low surface temperatures of Georges Bank by a band of warm surface water along the so-called "south channel," as seems probable, or whether the cool surface forms an unbroken band, west to east, from the one shoal ground to the other.

In 1913 the surface to the seaward of the 50-meter contour off Nantucket had warmed to upward of 19° by the last week in August (Bigelow, 1915, p. 350, fig. 2, stations 10107 to 10112). This was true also of the whole breadth of the shelf abreast of Marthas Vineyard on the 26th of the month in 1914, except close in to the land (station 10263), where a surface reading of only 17.9° probably reflected some tidal disturbance or other. With this same exception, Doctor Kendall likewise had 18° to 19° at every station off Marthas Vineyard early in September, 1897, paralleling Libbey's (1891) record of surface warmer than 19° over this part of the continental shelf during August, 1889.

These data locate the isotherm for 18° as following the southern and western edges of Nantucket Shoals around into the submarine bight west of the latter, but with cool pools next the southern shores of Marthas Vineyard, as just noted.

It is probable that the surface temperature rises higher than 20° over the outer part of the continental shelf off southern New England every August, and Libbey's (1891) extensive data show that in some years temperatures slightly higher than 20° are to be expected within a few miles of Marthas Vineyard. But his records also show that a considerable variation in surface temperature is to be expected within short periods of time over the inner half of the shelf, where a sudden cooling of the surface would be the natural accompaniment of any unusual stirring of the water or of the upwellings that so often follow offshore winds.

There is also considerable variation in the surface temperature off Marthas Vineyard from year to year. In 1914, for example, the isotherm for 20° included only the outer half of the continental shelf on August 21 at longitude 71° (fig. 46).

In spite of these fluctuations, it is safe to say that the surface is invariably warmer than 20° along the edge of the continent in the offing of Marthas Vineyard and Nantucket Island by the end of August. To find the surface warming to upward of 22° to 23° it is only necessary to sail seaward a few miles farther.

Passing eastward from the longitude of Nantucket, we find a more sudden transition from the comparatively cool water (18°) over the southwestern part of Georges Bank to the high temperature of the oceanic water outside the 200 meter contour, accompanied, however, by such irregularities as might be expected along the zone of contact of waters differing in salinity as well as in temperature. At times the north-south gradation in surface temperature along this sector of the edge of the continent is also interrupted by a cooler band. On July 20 to 21, 1914 (stations 10216 to 10218),[24] this was indicated by surface readings of 18.6°, 17.3°, and 20.48° at three successive stations from north to south on a line crossing the southern slope of the bank.

Such data as are available point to an abrupt increase in the breadth of the cool wedge eastward from Georges Bank between the edge of the continent and the warm oceanic temperatures of >20°, to the seaward of the latter. Thus the surface was only about 17° at our outermost station off Shelburne on July 28, 1914 (station 10233), while the Canadian Fisheries Expedition crossed a band of 17° to 19.7° water some 70 miles wide outside the 200-meter contour in the offing of Cape Sable on July 22, 1915 (Bjerkan, 1919; *Acadia* stations 41 to 44). Unfortunately no temperatures have been taken off the slopes of Georges or Browns Banks during the last half of August of late years, but even if the isotherm for 18° should encroach a few miles farther inward by the end of the month than is represented on the chart (fig. 46), there is no reason to suppose that the surface temperature rises higher than 20° inside the 100-meter contour on the banks anywhere east of Nantucket Shoals at any season, except possibly for brief periods following persistent southerly winds.

TEMPERATURE GRADIENT IN THE UPPER 100 METERS

A differentiation in the vertical distribution of temperature between the western and eastern sides of the gulf begins to develop in June, widening with the advance of summer, until the extremes, as represented by the western basin on the one hand and by the Bay of Fundy and coastal banks off western Nova Scotia on the other, yield graphs differing widely in the upper 100 meters by August.

The most striking feature of the western type, as exemplified by the basin off Cape Ann (fig. 48) and by the bowl at the mouth of Massachusetts Bay off Gloucester (fig. 4), is that the water cools very rapidly from the surface down to a depth of 40 to 50 meters, succeeded by only a slight fall in temperature down to the 100-meter level. Whether increasing depth is accompanied by a further slight cooling or by a slight warming depends on the locality, the topography of the bottom, and to some extent on yearly fluctuations, as discussed later (p. 602). In August we have found the 40-meter level averaging from 10° to 14.5° cooler than the surface in the western side of the basin and 9° to 13° cooler at the mouth of Massachusetts Bay (figs. 4 and 5), illustrating the remarkably sudden change that any animal would experience there, from warm water to cold, by sinking down for a few meters only. Observations taken farther up the bay on August 22 to 24, 1922 (stations 10630 to 10645), showed a similar vertical chilling down to 50 meters or so, except that the

[24] This cool band is more clearly marked, by temperature, at deeper levels, as described on page 608.

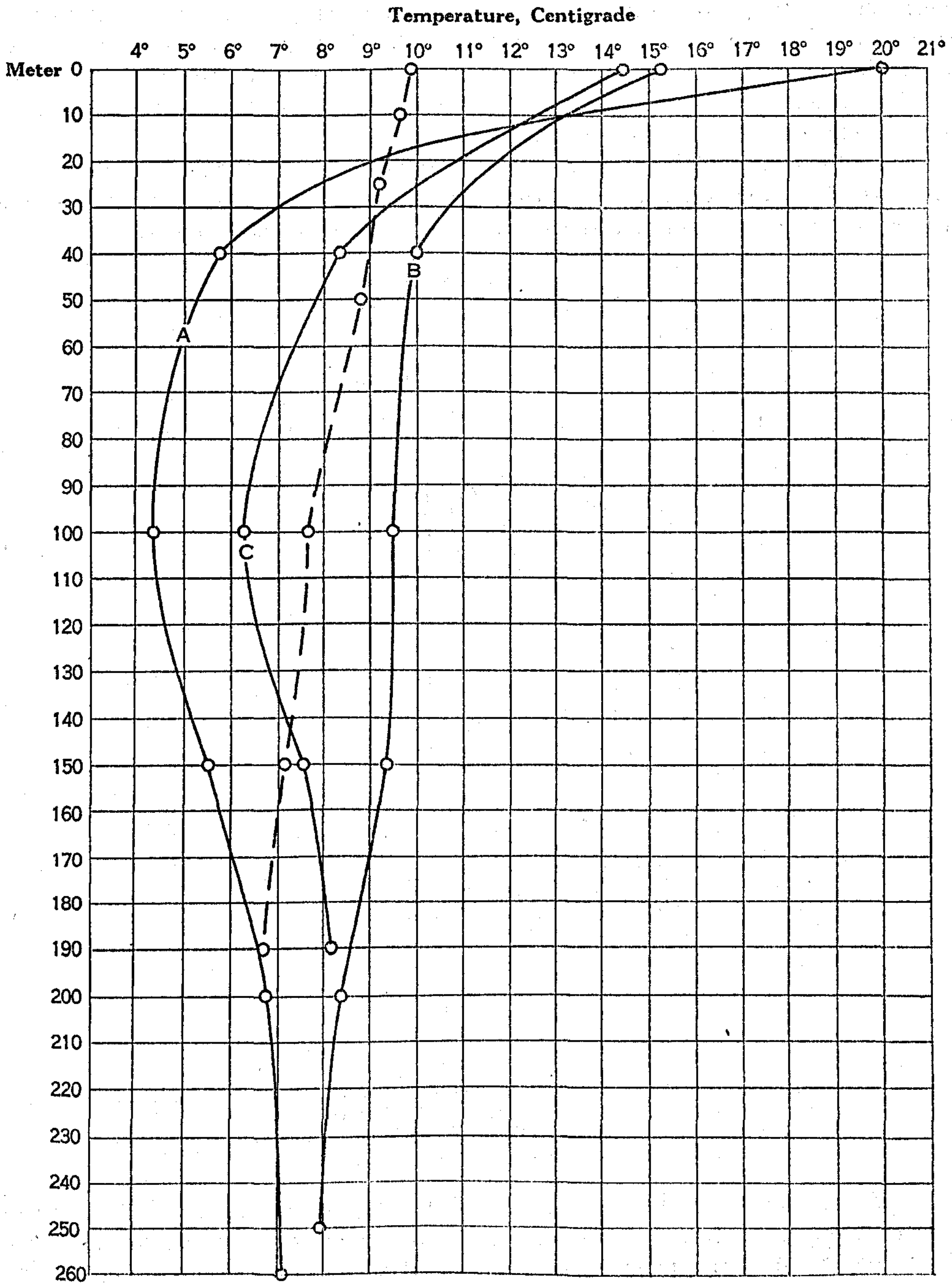

FIG. 48.—Vertical distribution of temperature at representative localities in the basin of the gulf. A, western arm of basin, off Cape Ann, August 22, 1914 (station 10254); B, southeastern part of the gulf, July 23, 1914 (station 10225); C, northeastern arm of the basin, August 12, 1914 (station 10240). The broken curve (D) is for Mavor's (1923) station 24, off the western end of Grand Manan Island, August 27, 1919

uppermost stratum, 5 to 10 meters thick, was then nearly homogeneous in temperature at several of the stations closest to the land. Although the precise rate of vertical cooling varies from station to station even over the small area of Massachusetts Bay, the surface temperature of its whole area usually warms upward of 10° above that of the 20 to 50 meter level by the end of the summer.

Serials have also yielded curves of this same general type in the west-central parts of the basin, generally, and in the northwestern part of the gulf between the latitudes of Cape Ann and of Cape Elizabeth during July and August.

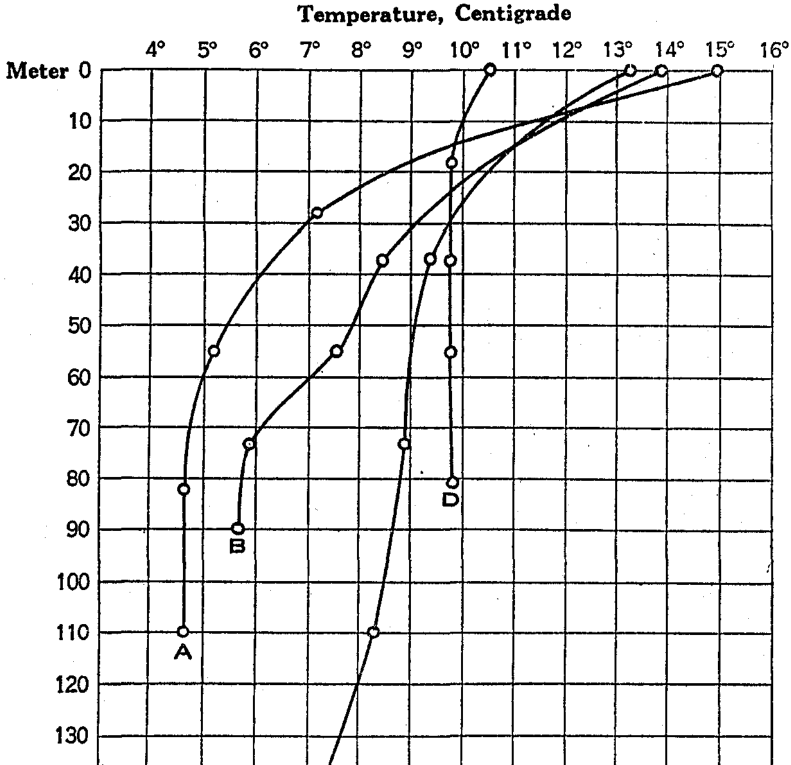

FIG. 49.—Vertical distribution of temperature at successive stations, from Cape Ann to Grand Manan, in July and August, 1912. A, near the Isles of Shoals, July 17 (station 10011); B, off Cape Elizabeth, July 29 (station 10019); C, off Penobscot Bay, August 22 (station 10039); D, off the western entrance to the Grand Manan Channel, August 19 (station 10035)

Our first summer's cruise (Bigelow, 1914, p. 51), however, proved that the difference of temperature between the surface and the underlying water (which is nearly uniform, depth for depth, from Cape Ann to Platts Bank) decreases along the coast to the eastward (fig. 49). Observations taken in the summers of 1914, 1915, and subsequently have not afforded a single exception to the rule (stated in Bigelow, 1917, p. 168) that the surface temperature is progressively lower and lower in summer, the bottom temperature (depth for depth) progressively higher and higher, around the margin of the gulf from Cape Cod to the Bay of Fundy, with the average vertical range of temperature decreasing from about 12° off Cape Ann to virtually nil in the Grand Manan Channel.

Thus, the difference of temperature between the surface and the 50-meter level (never less than about 10° at the mouth of Massachusetts Bay in summer) was only about 5° to 8° off Casco Bay (stations 10019 and 10103), 4° to 5° near Monhegan Island on August 4, 1915 (station 10303), and about 4° at the west entrance to Penobscot Bay on August 22, 1912 (station 10039). Near Mount Desert Island the vertical range for the corresponding column of water was only 2° on August 18, 1915 (station 10305), about 4° on August 13, 1912 (station 10099),[25] about 4.5° on the 5th of the month in the very cold year 1923, or an average of 3° to 4°. The water is kept even more nearly homogeneous in temperature among the islands of the Mount Desert region by strong tides, so that the surface was only 1.5° to 0.1° warmer than the bottom a couple of miles off Little Duck Island on August 8 to 11, 1925, in depths of 25 to 30 meters.

This also applies off the open coast farther east. Off Machias, for example, the surface reading was only about 1° higher than the bottom reading on August 16, 1912 (station 10033), 1.2° higher on August 13, 1913 (station 10098), 1.5° higher on August 12, 1914 (station 10247), 1.7° higher on July 15, 1915 (station 10301), and 0.33° higher on September 11 (station 10316) in 60 to 70 meters (fig. 50).

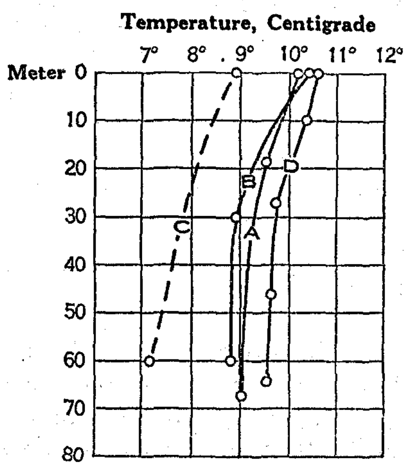

FIG. 50.—Typical summer temperatures off Machias, Me. A, August 13, 1913 (station 10098); B, August 12, 1914 (station 10247); C, July 15, 1915 (station 10301); D, August 16, 1912 (station 10033)

We found the surface at the two ends of the Grand Manan Channel, through which the tidal currents run with great velocity, only fractionally warmer (10° to 10.6°) than the bottom (9.6° to 9.7°) in 80 to 100 meters on August 17 and 19, 1912 (stations 10034 and 10035). Vertical stirring is thus complete at this locality.

The temperature gradient that develops within the Bay of Fundy by the end of the summer differs regionally, depending on local variations in the tidal circulation. At the mouth, between Grand Manan and Brier Island, where tidal disturbances are proverbially strong, Mavor (1923, p. 6, Sec. IV) records a maximum difference of only 0.7° to 1.3° between the surface and 50 meters for August 27, 1919; but his Section I shows a slightly greater average range (2.2°) for the corresponding stratum at three stations halfway up the bay. This thermal difference, which develops between the Bay of Fundy and the western side of the gulf during the summer, is summarized in the following tabulation:

[25] Forty meters was the deepest reading taken at this station.

Locality	Approximate temperature		
	Surface	50 meters	100 meters
	°C.	°C.	°C.
Bay of Fundy	10-12	7.5-9	7-8
Off Massachusetts Bay	16-20	5.5-8	4.5-6

The fact that the deep water is warmer in the Bay of Fundy, and for that matter in the northeastern part of the gulf generally, than in the southwestern, while the surface is so much colder, deserves special emphasis because of its bearing on the circulation of the two regions (p. 924).

In St. Marys Bay the relative difference between surface and bottom temperature increases from the mouth, inward, in July, as follows, if the total depth of water be taken into consideration.

Surface and bottom temperatures at successive localities from the mouth of St. Marys Bay toward its head, July, 1915. (From Craigie and Chase, 1918.)

Station	Depth, meters	Surface temperature	Bottom temperature
		°C.	°C.
21	43	9.28	8.06
15	34	10.12	8.44
11	32	11.96	9.29
8	33	12.98	9.03
6	21	13.52	10.36
4	28	13.95	11.37
2	13	13.78	11.82
1	7	14.8	13.40

The water is likewise kept comparatively homogeneous in temperature out to the 100-meter contour over the coastal banks off western Nova Scotia by active tidal stirring throughout the summer. Dawson (1905, p. 15) has already called attention to the thermal effect of vertical circulation in this region, where the topography of the bottom causes "a long trail or wake of colder water to extend from islands or shoals along the line of the current; as, for example, north and south from Lurcher Shoal." He also points out that "when the islands and shoals are numerous, the general effect of these strong currents is to chill the water in the vicinity of the coast by mixing the surface water with the colder water from below." As the result of local disturbances of this sort, the vertical range of temperature is much narrower along the 100-meter contour off Lurcher Shoal in August than at corresponding locations over the western slope of the gulf. The temperature on German Bank has proved almost perfectly homogeneous from surface to bottom in August and September, as follows:

German Bank approximate temperatures

Depth, meters	Aug. 14, 1912, station 10029	Aug. 12, 1913, station 10095	Aug. 12, 1914, station 10244	Sept. 2, 1915, station 10311
	°C.	°C.	°C.	°C.
0	10.33	8.89	10.00	9.44
20	9.83	8.67	9.85	10.30
40	9.67	8.61	9.64	10.20
60	9.61	8.56	9.65	10.10

Dawson's (1922) records for 1904 and 1907 show only a slightly greater vertical range of temperature close in to the west Nova Scotian coast, with little change during the month of August.

Temperatures for 1907. (After Dawson, 1922)

Depth	Seventeen miles southwesterly from Yarmouth		Six miles easterly from Lurcher Shoal
	July 29 to 31	Aug. 28 to 31	Sept. 2
	°C.	°C.	°C.
Surface	9.7–10.8	9.4–10.6	10.8
27 meters	7.5– 8	8 – 8.6	9.2
55 meters	7.2– 7.5	7.8– 8	

Tidal currents keep the water as thoroughly stirred near Cape Sable as they do on German Bank, so that Dawson (1922, station Q) found the temperature virtually uniform (about 4°) from surface to bottom 12 miles south of the cape on July 2, 1907. Observations taken by Dawson in this neighborhood later in the summer, however, in three different years, and from the *Grampus* in 1914 and 1915, show that the surface then warms rapidly enough to produce a considerable range of temperature by the end of August, except when temporarily disturbed by the tide, as just described (p. 593).

Temperatures 12 miles south of Cape Sable, °C. (From Dawson, 1922, station Q)

Depth	July 2, 1907	July 10, 1907	July 13, 1907	July 19, 1904[1]	July 20, 1904[1]	July 20, 1904[2]
Surface	4.2	6.7	7.0	9.4	12.0	5.0
27 meters	3.9	6.4	6.4	3.0	3.3	4.3
55 meters	3.9			2.8	2.8	3.9

[1] High tide. [2] Low tide.

Grampus temperatures near Cape Sable, °C.

Depth	July 25, 1914, station 10230	Aug. 11, 1914, station 10243
Surface	10.28	13.61
30 meters	3.03	7.47
50 meters	3.14	
55 meters		3.51

A wide vertical range of temperature also has been recorded across the whole breadth of the continental shelf, in the offing of Shelburne, for the last week of July, both in 1914 and in 1915, with the surface averaging about 7.3° warmer than the 50-meter level for all these stations[26] (maximum difference about 11°, minimum 4.6°). This thermal contrast continues to develop during the summer near the land off Shelburne, where the surface (15°) was nearly 13° warmer than the bottom (2.2°) at a depth of 70 to 80 meters on September 6, 1915 (station 10313).

[26] *Grampus* stations 10230 to 10232; *Acadia* stations 37 to 40 (Bjerkan 1919).

TEMPERATURE GRADIENT IN DEPTHS GREATER THAN 100 METERS

The deeps of the gulf at depths greater than 100 meters have shown interesting variations, regional and annual, in the vertical distribution of temperature in summer. In the bowl off Gloucester, isolated from the bottom water of the open gulf by its barrier rim (p. 520), the temperature has either proved virtually homogeneous vertically, from the 100-meter level downward, or has been fractionally coldest on the bottom at that season. The water has also been slightly colder at the bottom than at 100 meters at all our summer stations in the deep trough north of Cape Ann, which is inclosed by the shoal ridge known as Jeffreys Ledge (fig. 6).[27]

In the open basin of the gulf, however, the bottom water may either be about the same temperature as the mid-stratum or may be decidedly warmer and much salter, depending, probably, on the amount of slope water flowing into the gulf at the time (Bigelow, 1922, p. 165), and the records suggest a tendency for the one or the other of these alternate states to persist over a period of years.

In July and August, 1912, the western, northwestern, and northeastern parts of the basin were virtually homogeneous in temperature (4.6° to 5.2°) from the 100 to 150 meter level down to the bottom in depths of 190 to 230 meters (stations 10007, 10023, 10024, 10036, and 10043); equally uniform vertically at depths greater than 75 to 100 meters in the eastern side (station 10028, 7.4°), or slightly colder on bottom there (station 10027, 6°).

During the summer of 1913, however, we found this type of vertical distribution replaced by the alternate state just described, with the water of the basin coldest at about 100 to 110 meters, warmer at greater depths, both in July and in August, as follows:

Depth, meters	Station 10058	Station 10088	Station 10090	Station 10092	Station 10093
	°C.	°C.	°C.	°C.	°C.
82				5.56	
91		5.17	6.39	5.83	5.56
110	4.78				
165	5.17				
183		6.28	6.61	6.11	
220					5.89
238				6.05	
274		6.33			

Only at the head of the eastern trough (stations 10096 and 10097) and on the northern slope of the basin off Monhegan Island (station 10102) was the bottom slightly colder than the 100-meter level in that summer (fig. 8).

The water was again coldest at about the 100-meter level at every deep station in the inner parts of the gulf in July and August of 1914, and with the vertical warming of the deep water not only much more pronounced than in 1913 but extending right down to the bottom in most cases. Only at one station (10249) for that summer was the temperature slightly lower on bottom than at 150 meters, as follows:

[27] The 100-meter temperature at this locality has ranged from 4.4° to 5.4° in August of 1913 and 1914 (stations 10104, 10105, and 10252), with 3.6° to 4.7° at 130 meters, 4.3° at 155 meters. On Aug. 7, 1923, the 30 to 80 meter stratum (about 4°) was 2° to 3° colder.

Deep temperatures (°C.) in the western, central, and northeastern parts of the basin, July and August, 1914

Depth, meters	Station 10214	Station 10246	Station 10248	Station 10249	Station 10251	Station 10254	Station 10255	Station 10256
100	4.22	6.28	7.18	5.31	4.41	4.36	3.95	4.24
145					4.93			
150	5.12	7.58	6.04	6.04		5.51	5.13	5.38
180							6.24	5.68
190	5.53	8.17	8.34					
200						6.8		
220				5.83				
260						7.09		

However, this type of gradient did not extend to the southeastern part of the basin (station 10225), where the temperature decreased, though at a decreasing rate, from the surface right down to the bottom. This was also the case in the Eastern Channel (station 10227).

In 1915 the deep stations again exhibited vertical warming with increasing depth in both sides of the basin in August and the first part of September, from the 100 to 150 meter level down to the bottom; but the depth at which the water was coldest (100 to 150 meters) was not so uniform as it had been the year before, nor was the vertical range of temperature below this stratum as wide. One station in the center of the basin (10308) showed a progressive cooling toward bottom instead of the more general rise in temperature, perhaps reflecting some disturbance of the normal circulation by the tides flowing around the slopes of Cashes Ledge.

Deep temperatures, °C., August to September, 1915

Depth, meters	Station 10304	Station 10307	Station 10308	Station 10309	Station 10310
90			6.36		
100	6.22	5.01		5.72	5.56
150	4.78	5.1		5.77	
165			5.63		
190					7.1
200	6.89	5.7			
210				5.98	
235		6.36			

Only one deep serial was taken in the basin of the gulf north of Georges Bank during the summer of 1916 (10345, July 22; southwest part of basin off Cape Cod), again proving the water coldest at the 100-meter level (3.85°) and fractionally warmer (4.06°) on the bottom in 150 meters. Thus the fact that this was an unusually cold year, from the gulf southward to Chesapeake Bay (p. 628; Bigelow, 1922), both in land climate and in the upper 100 meters of water, was not reflected in the vertical distribution of temperature in the deeps of the gulf. Again, this also applies to August, 1923, another cold summer (p. 632), when the temperature off Mount Desert Rock[28] was lowest (4.5°) at about 90 meters, warming to 4.9° at about 130 meters and to 5.4° at 165 meters.

A considerable body of evidence has thus accumulated to prove this the usual state in the inner parts of the open basin of the gulf during the late summer, just as

[28] Lat. 43° 52′ N., long. 67° 54′ W., Aug. 6.

it is earlier in the season, with the temperature lowest between the 100 and 150 meter level, though with its precise gradient varying from summer to summer.

Temperatures fractionally higher close to bottom than in the mid depths have also been recorded at several stations in the deeper parts of the Bay of Fundy in the summers of 1915, 1916, and 1919. Craigie and Chase (1918), for example, found the water midway between Letite Passage and Grand Manan coldest (5.59°) at 55 to 110 meters and fractionally warmer (5.7°) at 137 meters and 208 meters (5.66°). Vachon (1918) again found the bottom water slightly warmer than the mid-stratum at *Prince* station 3, off the eastern end of Grand Manan, on July 24, 1916, and Mavor (1923) records a similar gradient at this same locality on September 4, 1917—from 5.94° at 125 meters to 6.15° at 150 meters and 6.06° at 175 meters. However, the water was coldest there on bottom on August 25, 1916, and again on August 26, 1919 (Vachon, 1918; Mavor, 1923), just as Craigie (1916a) recorded it for August, 1914.

TEMPERATURE GRADIENT ON THE OFFSHORE BANKS

No serial observations have been taken in the Northern Channel between the coastal bank off Cape Sable and Browns Bank in August; but a range of nearly 5.5° there on July 25, 1914 (station 10229) between the temperature at the surface (11.44°) and near bottom in 100 meters (5.96°) makes it likely that the contrast is still wider at the onset of autumn.

Our only late summer serial on Browns Bank (station 10228, July 24, 1914) showed a vertical range of about 6.2° between the surface (14.72°) and the 40-meter level (8.35°), with the temperature then rising fractionally, with increasing depth, to 8.5° near bottom in 85 meters. The surface was also about 6° warmer than the bottom at two *Albatross* stations[29] on the western and southern slopes of this bank on August 31 to September 1, 1883, in depths of 146 and 119 meters, as tabulated below:

Temperatures on the slopes of Browns Bank, °C.

Date and station	Surface	40 meters	Bottom
Aug. 31 to Sept. 1, 1883:[1]			
20065	12.8	----------	7° at 146 meters.
20066	12.2	----------	6.4° at 119 meters
July 24, 1914:			
10228	14.72	8.35	8.5° at 85 meters.

[1] From Townsend (1901).

Values slightly lower here in 1883 than in 1914 probably reflect the difference to be expected between warm and cool summers, and not a seasonal succession, because there is every reason to expect higher temperatures here late in August than in July.

The Eastern Channel was also about 6° warmer at the surface than at 40 meters on July 24, 1914 (station 10227).

The shoaler parts of Georges Bank correspond more nearly to the waters along western Nova Scotia in the temperature gradient, with strong tidal currents, with which every fisherman is familiar, responsible for a nearly homogeneous state of the water over the parts of the bank where they are most active.

[29] Dredging stations 20065 and 20066 (Townsend, 1901, pp. 393 and 394).

Such, for example, was the case near the northern edge of the bank on July 23, 1914 (station 10224), when surface and bottom temperatures (11.11° and 10.78°) differed by less than 0.5° in 55 meters depth. This same state prevailed at a station on the western end of the bank (10059) on July 9, 1913 (surface 13.3°; bottom 12.6°), and again on July 23, 1916.[30] In August, 1896, Doctor Kendall found a maximum difference of only about 1° between surface and 18-meter readings at many localities along its northern and northwestern sides.

On the parts of the bank where the water is more than 50 to 60 meters deep, and where tidal currents do not run so strong, the surface warms more rapidly during the progress of summer, the bottom less so; witness readings of 14.8° to 17.8° at the surface and 6° to 9° on bottom in 60 to 70 meters on the northern and eastern parts in August, 1926 (stations 20203 to 20208). The temperature gradient likewise differs widely from place to place in the Nantucket Shoals region in the late summer, depending on the topography of the bottom, with the water most nearly homogeneous over the shoal banks and ridges. Thus, the temperature of the entire column of water was 10° to 10.5° in 30 meters at a station 12 miles ESE. from Round Shoal buoy on July 15, 1924 (station 10655); and in August, 1925, when a greater number of serials was taken, the surface was invariably less than 1° warmer than the bottom on Rose and Crown Shoal, Round Shoal, and Great Rip in depths ranging from 20 to 30 meters, the actual temperatures ranging from 11.5° to 15° from station to station (p. 595).

The surface temperature rises high above that of the bottom water by the end of the summer over the smoother bottom to the south of the shoals, a regional contrast illustrated by two *Grampus* stations for July 25 and 26, 1916. One of these, located on the southern edge of the shoals (station 10355), was only about 1° warmer (11.95°) at the surface than at the bottom (10.97° in 30 meters). The other, in deeper water 23 miles to the southeast (station 10354), was 5° warmer at the surface (13.6°) than at the 30-meter level, and 7.6° warmer than on bottom at a depth of 70 meters. Readings of 16.1° at the surface, 14.1° at 18 meters, and 10.2° at 46 meters, near by, show about this same vertical range on July 9, 1913 (station 10060). A steep temperature gradient also develops to the west of the shoals by the end of August, illustrated by *Grampus* stations 10258, 10259, and 10263 (p. 987), and by the many serials taken off southern New England by Libbey (1891) in 1889.

TEMPERATURE GRADIENT ALONG THE CONTINENTAL EDGE

Sudden fluctuations in temperature are to be expected along the edge of the continent where the conflict between warm oceanic and cool coastal waters is constant. The station data do, in fact, show wide variations in the upper 100 meters along this zone (fig. 51). The one extreme, which may fairly be described as subtropical, is exemplified by stations 10218, southwest of Georges Bank, July 21, 1919, and station 10261, in the offing of Marthas Vineyard, August 26, 1914. These chill, with increasing depth, from a very warm (20° to 24°) surface stratum to 7° to 9° at 400 meters and to about 5.25° to 6° at 500 meters. These contrast with stations showing a well-marked cold stratum at 40 to 80 meters, as south of Cape

[30] Station 10347, surface 11.39°, bottom 9.61° in 60 meters; station 10348, surface 11.07°, bottom 11.26° in 51 meters.

Sable on June 24, 1915 (station 10295), south of Georges Bank on July 24, 1916 (station 10253), and at several of Libbey's (1891) August stations in the offing of Marthas Vineyard. Various intermediate gradients are to be expected, also. Serials taken southeast of Georges Bank on July 24, 1914 (station 10220), and off Shelburne

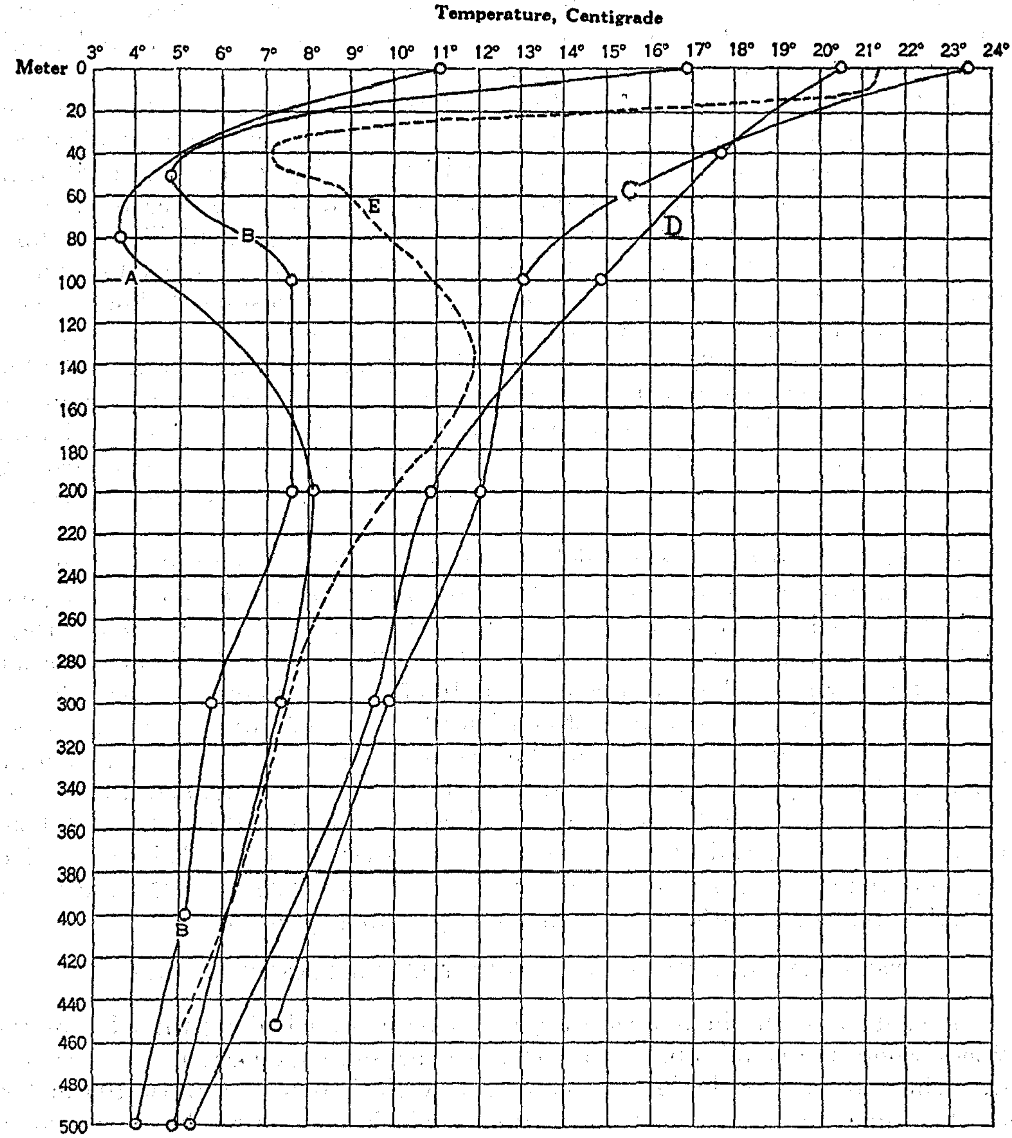

FIG. 51.—Vertical distribution of temperature on the continental slope in summer. A, abreast of Shelburne, Nova Scotia, June 24, 1915 (station 10295); B, on the southwestern slope of Georges Bank, July 24, 1916 (station 10352); C, on the southwest slope of Georges Bank, July 21, 1914 (station 10218); D, south of Marthas Vineyard, August 26, 1914 (station 10261). The dotted curve (E) is for Libbey's (1891) station 9, line G, south of Marthas Vineyard, August 17, 1889

a few days later (station 10233), are cases in point. So, too, are many of Libbey's stations and the *Acadia* stations in the offing of Cape Sable for July, 1915 (Bjerkan, 1919).

TEMPERATURE AT 40 METERS

The regional differences that developed in the vertical distribution of temperature between various parts of the Gulf of Maine, as the summer advances, tend to make the temperature (as plotted in the horizontal projection) more nearly uniform in the mid depths than it is at the surface. Thus, all the 40-meter readings for the month of August of the years 1912 to 1915 (figs. 52 to 54), and 1922 (omitting for the moment the cold summers of 1916 and 1923), have fallen within a range of 6°, from a maximum of 11.5° off Lurcher Shoal (station 10031, 1912) to a minimum of 5.5° off Cape Sable (station 10243, 1914). Only 6 August readings at 40 meters, out of a total of 64, have been as warm as 10° to 11°; only 3 cooler than 6°, and

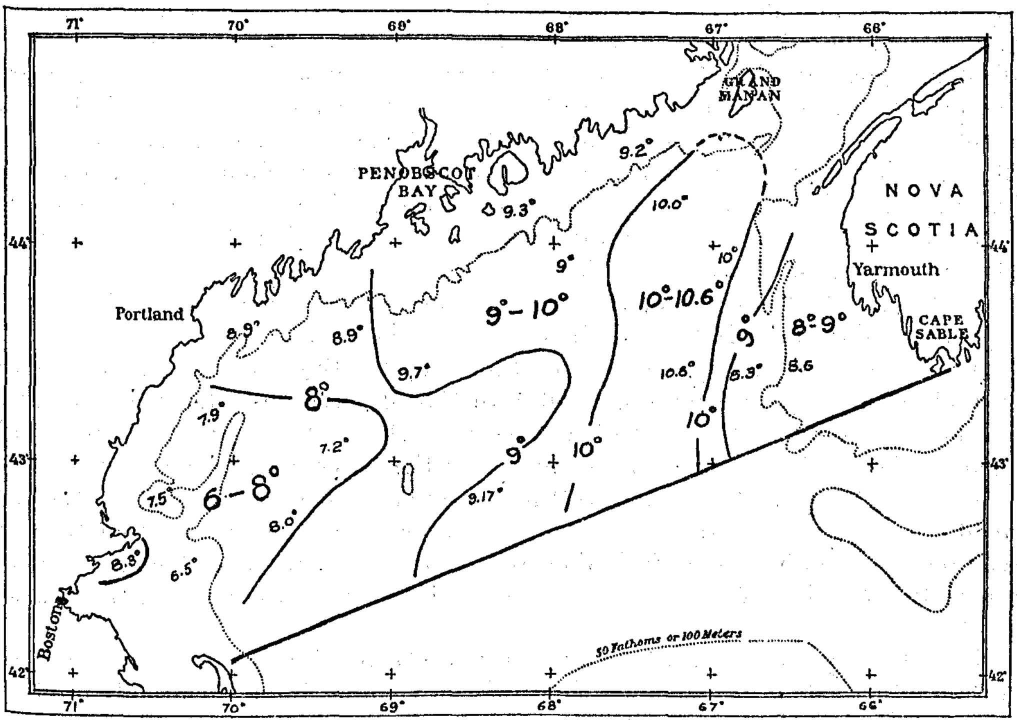

FIG. 52.—Temperature at a depth of 40 meters, August 5 to 20, 1913

the great majority have fallen between 7° and 9.5°, irrespective of precise geographic location. Consequently, this may be taken as the normal temperature to which the 40-meter stratum of the gulf as a whole warms by the end of the summer.

With so narrow a range, and with the water continuing to warm until well into the autumn, a difference in date of a few days one way or the other will be accompanied by a greater difference in temperature, at this level, than any regional difference that might be disclosed by a simultaneous survey of the whole western and northern part of the gulf.

Differences between cold and warm years, illustrated by a temperature of about 8° on August 9, 1913 (station 10088), but only 5.75° at the same locality in 1914 on the 22d of that month (station 10254), likewise outweigh the regional differences for this station. Consequently, I have not found it possible to chart the normal isotherms for values between 6° and 10° for the 40-meter level for August, except for the very obvious fact that the whole Gulf of Maine is then 4° to 5° warmer at this level than is the water along the outer coast of Nova Scotia, where the 40-meter temperature was about 1.9° to 3° in July, 1914, warming to about 3.4° off Shelburne by the first week of September in 1915 (stations 10313 and 10314).

If the gulf north of Georges Bank be arbitrarily divided into two subdivisions by the meridian of Penobscot Bay (69° W. long.), the average of all the 40-meter readings to the west of it is 7.4° for August, 8.8° in the eastern subdivision (omitting the Bay of Fundy).

When the August temperatures for the several years are studied individually, instead of in combination, this separation into a cooler western and a warmer eastern subdivision of the gulf proper, but with much colder water east of Cape Sable, becomes still more apparent (figs. 52 to 54). Although the precise readings vary a degree or two at any given station from year to year, the 40-meter charts agree in locating the coldest area (6° to 8° in 1914; 9° in 1913 and 1915) in the western side of the gulf, extending eastward into the south-central part of the basin in wedgelike outline. Thus a line running from north to south across the gulf in the offing of Penobscot Bay would alternately cross warm water next the coast, fractionally cooler farther out, and warmer again in the southern side.

In August, 1913 and 1915, the 40-meter level was warmest along the eastern side of the basin; closer in to western Nova Scotia in 1914.

A detailed temperature survey of Massachusetts Bay, carried out during the last week of August, 1922 (stations 10631 to 10645), gave 40-meter values of 7° to 8.5°—lowest close in to the land off Gloucester (where upwelling is so often made evident by low surface temperature) and along the inner edge of Stellwagen Bank (5° at station 10632), where tidal overturnings are to be expected because of the contour of the bottom. In other years August readings in the bay at the 40-meter level have ranged from about 6.5° (off Gloucester, August 9, 1913, and August 22, 1914, stations 10087 and 10253) to 8° at that same locality on August 31, 1915 (station 10306).

The 40-meter chart for 1914 (fig. 53) shows a band 1° to 3° cooler than the water on either side of it extending lengthwise of Georges Bank. Our July profile of the western end of the bank, in 1916, also cut across a similar but still cooler band (p. 629; about 4° to 5°) just outside the 100-meter contour (station 10352). Although nothing in our previous experience foreshadowed summer temperatures there as low as those of that year, the presence near by of a similar cold stratum (10.8°) at about 75 meters in July, 1913 (station 10061), and temperature gradients of the same sort recorded in the offing of Marthas Vineyard by Libbey (1891), show that a cool band of this sort may be expected along the offshore edge of Georges Bank in most summers. In some years this extends as far west as the longitude of Marthas Vineyard as late as August, but in other years it is obliterated there at an earlier date by encroachments of the warm oceanic water from outside the edge of the continent, as happened in 1914 when the 40-meter level had warmed to 12.5° to 13.7° right across the shelf abreast of Marthas Vineyard by the last week of August.

Temperatures higher than 15° are always to be expected only a few miles outside the edge of the continent during July and August at 40 meters, as illustrated by our station data for 1914 (fig. 53), but there is no evidence that the 40-meter stratum

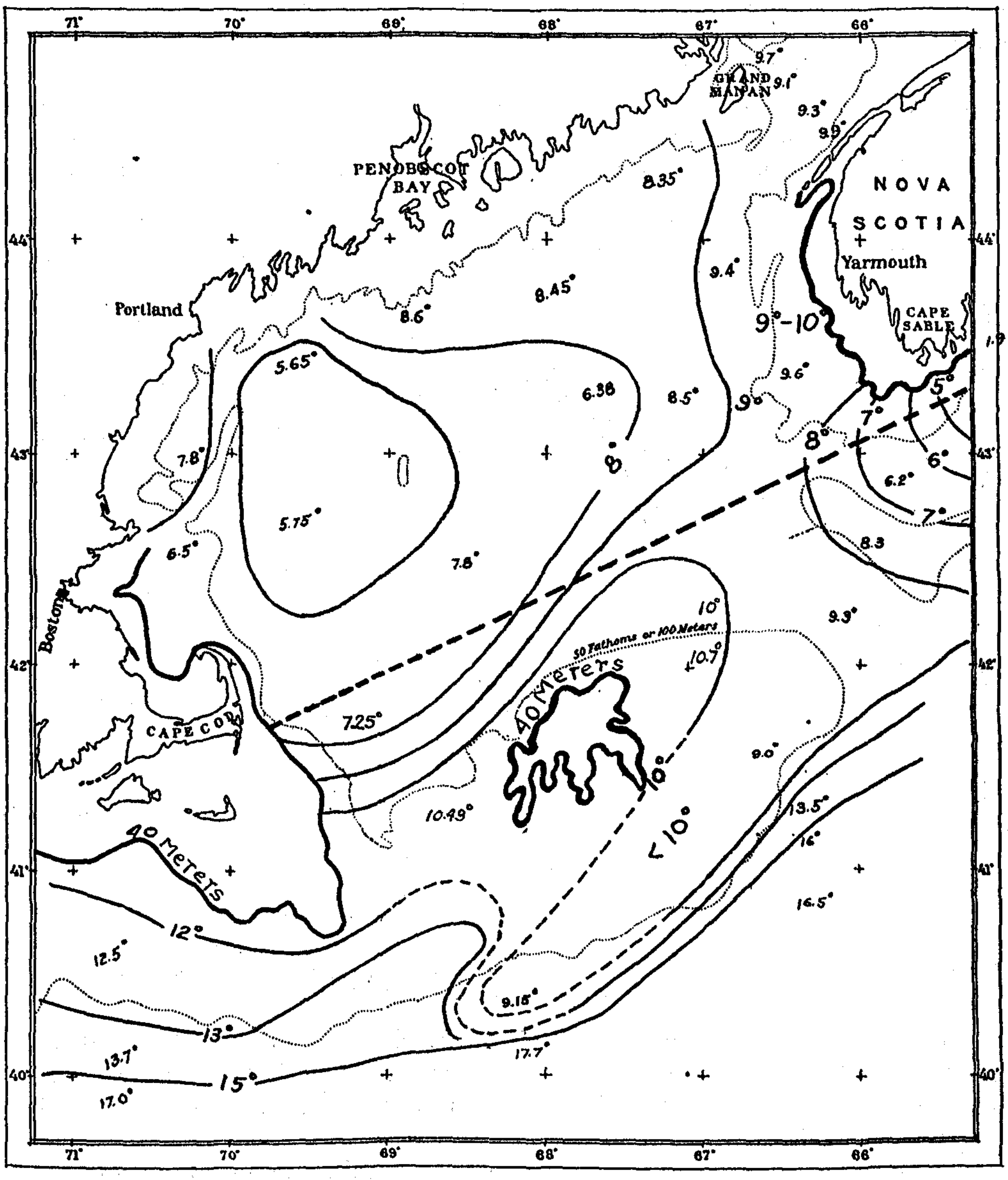

FIG. 53.—Temperature at a depth of 40 meters for July–August, 1914. North of the heavy broken line (Cape Cod to Cape Sable) the chart represents the state of the gulf from August 11 to 24; south of it, for July, combined with August. The Bay of Fundy temperatures are from Craigie (1916b)

ever warms to so high a temperature as this anywhere within the 200-meter contour abreast the Gulf of Maine.

TEMPERATURE AT 100 METERS

The 100-meter level has an especial interest as representative of the stratum usually coldest in the gulf in summer. Here the extremes of temperature so far recorded to the north of the Cape Cod-Cape Sable line late in summer have been 3.95° south of Cashes Ledge on August 23, 1914 (station 10255), and 10° near Lurcher Shoal in the first week of September, 1915 (station 10315).

The western side of the gulf has proven cooler than the eastern at the 100-meter level. Thus, 100-meter readings as low as 4.4° to 5° have been recorded only to the west of the longitude of Mount Desert Island (long. 68° 30′ W.), with the single

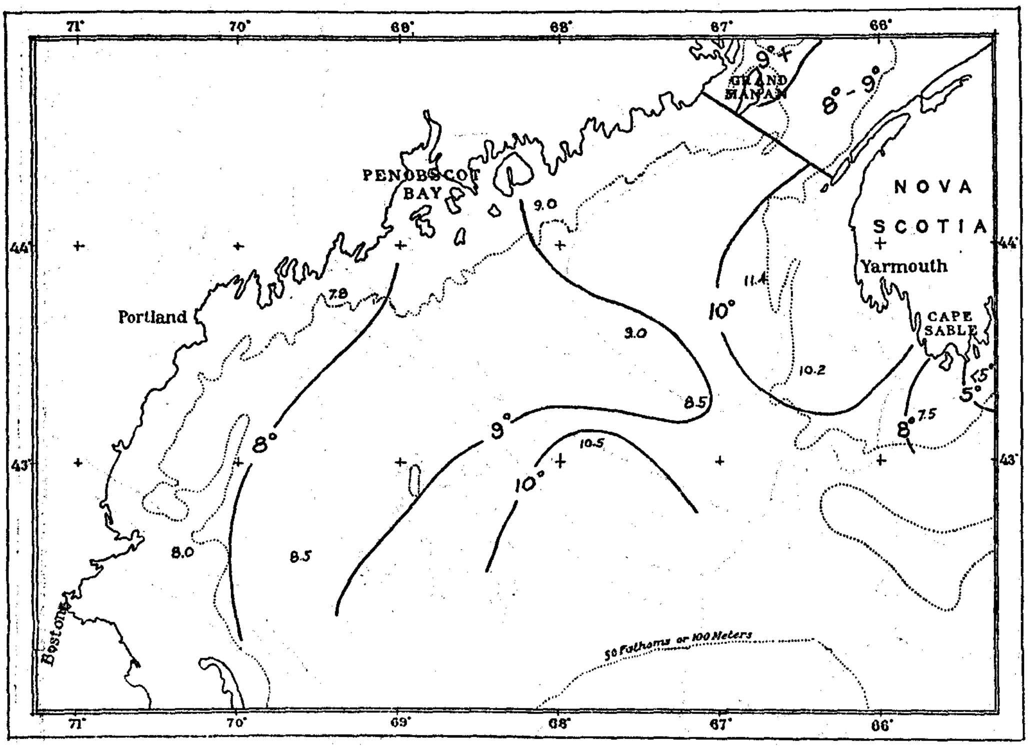

FIG. 54.—Temperature of the northern part of the gulf at a depth of 40 meters, August 31 to September 11, 1915. The Bay of Fundy temperature is for 1919, according to Mavor (1923)

exception of the one station off Mount Desert Rock on August 9. The fact that all but one of the 100-meter temperatures for August west of that longitude have been below 5.5° [31] is evidence that this side of the gulf is uniformly the cooler at this level, not merely so locally.

The absolute values vary from year to year within narrow limits, so that the isotherm most graphically dividing the cold western area from the warm eastern area in any given summer may be 5°, 6°, or even 8°. In each August of record this critical curve, parting the gulf, has followed a characteristic S-like course (figs. 55 and 56), with the warmest water following the eastern side of the basin around to

[31] The exception is station 10043 off Cape Cod, with a 100-meter temperature of about 6° on August 29, 1912.

the north and west, so that a line run south from Mount Desert Island would alternately cross a warm tongue and then cooler water at 100 meters, just as at 40 meters (p. 608).

This regional distribution of temperature is precisely the opposite of the surface state (fig. 46), where the gulf is warmest in the west and coolest in the northeast, a

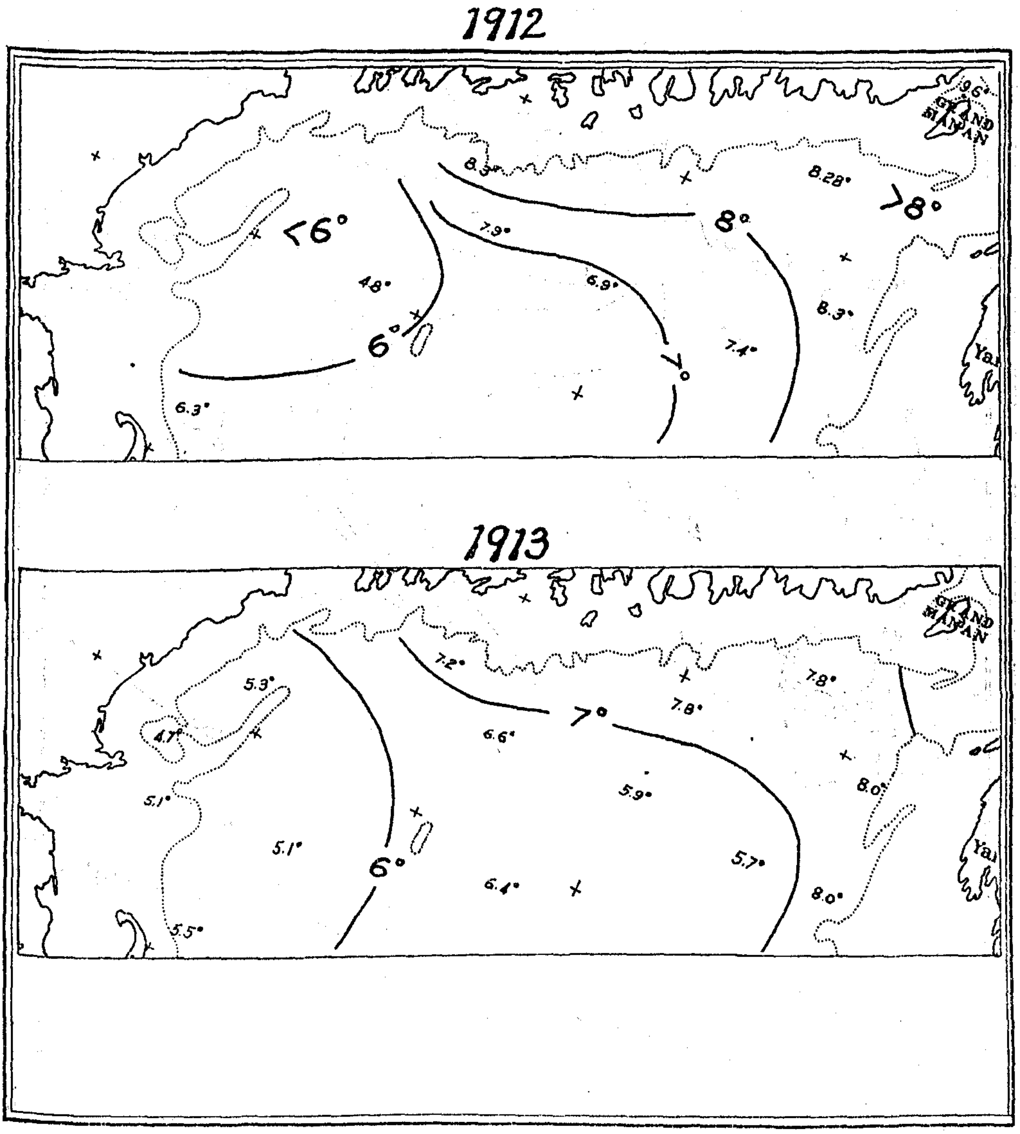

FIG. 55.—Temperature at a depth of 100 meters, August, 1912 (above), and August, 1913 (below)

difference discussed in a later chapter (p. 924). In August, 1912 and 1913, this warmest zone at 100 meters extended westward along the coast of Maine as far as longitude 69° 30′. In 1914 it hardly passed the mouth of Penobscot Bay. In all three years—1913 to 1915—the 100-meter temperature was 3° to 4° higher along the eastern slope of the basin (8° to 8.6°) than in the opposite side of the gulf.

Craigie (1916a) had temperatures of 8.15° to 9.25° at 100 meters in the Bay of Fundy on August 27 to 29, 1914, corresponding closely to about 9.6° in the Grand Manan Channel at this depth on August 17, 1912 (station 10034). In 1919, Mavor (1923) found the 100-meter level about 2° colder than this (6.9° to 8.5°) at a

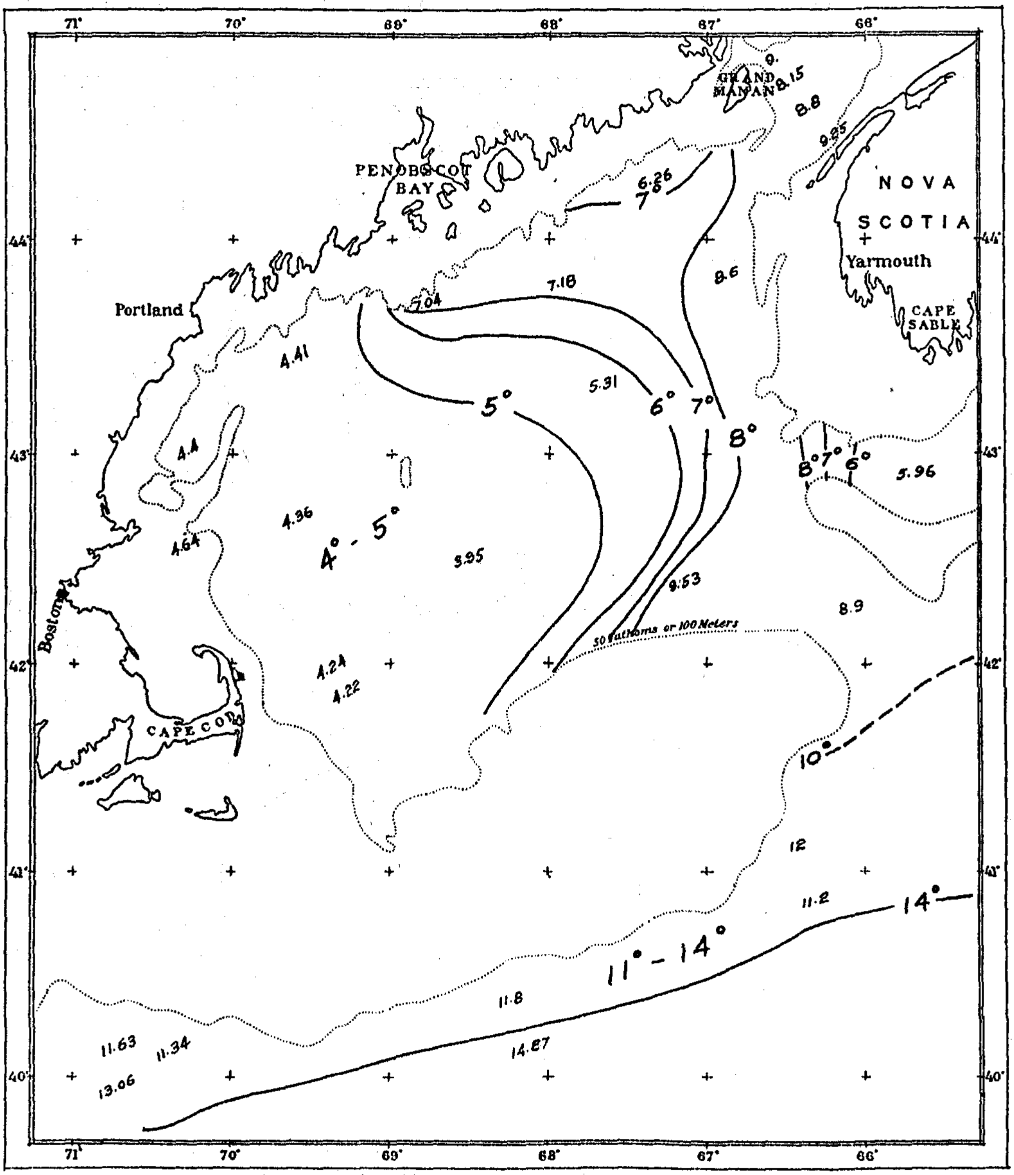

FIG. 56.—Temperature at a depth of 100 meters, July to August, 1914. North of Georges Bank the chart represents the state of the gulf during the last half of August; south of the bank the data are for July and August combined

number of stations in the lower half of the bay at the end of August; but it is probable that the regional distribution of temperature was about the same in the two summers, with the water slightly coldest in the center of the bay abreast of the western end of Grand Manan Island.

Notwithstanding the paucity of August data for the open gulf proper south of the Cape Cod–Cape Sable line (p. 594), it is possible to estimate the 100-meter temperature of the southeastern part of the basin, of the Northern and Eastern channels, and along the oceanic slope of Georges Bank from the July stations for 1914, because the general cycle of temperature makes it practically certain that these localities would have been found slightly warmer in August. On this assumption, the 100-meter level is about 3° colder in the Northern Channel[32] than in the neighboring part of the basin of the gulf to the west, with still lower temperatures (2° to 5°) over the inner half of the continental shelf along the outer coast of Nova Scotia (Bigelow, 1917, p. 182, fig. 16). The rather abrupt east-west transition in temperature at the western end of this channel (fig. 56) also is evidence that no general movement was taking place in either direction along its trough at the time.

In the Eastern Channel, however, the 100-meter water (8° to 9°) is about as warm as it is in the eastern side of the gulf, with a gradual transition to still higher readings (11°) along the continental edge and to 14° and higher a few miles farther offshore. However, the precise distance it is necessary to run out from the edge of the continent to find water as warm as this at the 100-meter level, on any given date, depends on the circulatory interaction between the cool banks water and the much warmer and salter oceanic water of the Atlantic Basin. Probably, however, the isotherm for 14° is always closer to the edge of the banks to the west of longitude 68° than to the east of that meridian.

The low temperature (8.98°) on the southeastern face of Georges Bank at 90 meters (station 10222) deserves attention because it suggests a drift of cool water out of the gulf around the peak of the bank, salinity being too low there (34.18 per mille) to allow of upwelling up the continental slope from the mid depths offshore as a possible cause. This is corroborated by the density there, as explained below (p. 958).

The 100-meter level remains much more nearly constant in temperature throughout the summer than do the overlying waters, with readings only about 1° higher in the western side of the gulf at the first of September, 1915, than they had been during the last week of the preceding June.

In the eastern side of the gulf, where solar heat is more rapidly dispersed downward by more active vertical circulation, the 100-meter level may be expected to warm by 2° to 3° from June to the end of August; most rapidly along the eastern slope of the basin and in the Bay of Fundy, where Mavor (1923) records an increase in the 100-meter temperature from 3.92° on June 15 to 6.13° on September 7, 1919.[33]

TEMPERATURE AT 150 METERS AND DEEPER

Annual variations in temperature have proved wider than the regional differences at depths greater than 100 to 150 meters; nor has the regional distribution at different levels been parallel from summer to summer. The following table shows the western, central, and northeastern deeps of the basin fractionally warmer than its eastern side in August, 1913.

[32] The 100-meter temperature was 5.96° on July 25, 1915, at station 10229.

[33] At *Prince* station 3, about 10 miles southeastward from the western end of Grand Manan.

Station	Depth, meters	Locality	Temperature, ° C.
10088	183	Offing of Cape Ann	6.28
10090	183	Center of gulf	6.61
10092	183	Eastern arm of basin	6.11
10100	183	do	6.22
10093	219	Near German Bank	5.89

In August, 1914, however, the bottom water was appreciably warmer (7° to 7.9°) in the eastern and northeastern parts of the basin than in the western and central parts (6° to 6.24°), apparently banking up against the Nova Scotian slope, as indicated on the chart (fig. 57). Successive stations, from the offing of Cape Ann to the Nova Scotian slope, again showed a slight rise in the temperature of the of the bottom water (at 175 meters) from west to east across the basin on August 31 to September 2, 1915, as follows: Station 10307, 5.4°; station 10309, 5.8°; and station 10310, 6.8°. The amount by which the temperature of the one side of the gulf differs from that of the other, in this stratum, varies so widely from year to year that it would not be surprising to find it virtually uniform over the whole area of the basin in some future summer.

Other features of the temperature at 175 meters worth mention are its constancy in the southwestern part of the basin from July 19 (station 10214, about 5.4°) to August 23 (station 10256, 5.6°) in 1914, and the fact that the southeastern part was warmer than the Eastern Channel in that summer,[34] although the latter offers the only route by which water of high temperature can flow into the gulf from offshore. Barring the possibility of higher temperature in one or the other sides of the channel than in its center, where the observations were taken, the most reasonable explanation for this apparent anomaly is that a considerable indraft had taken place late in June, but that this had then slackened, allowing the temperature of the channel to be reduced slightly by mixture with the cooler water to the east and west of it.

Our data for 1914, combined with temperatures taken south of Marthas Vineyard by Libbey (1891) in 1889, show the water along the continental edge abreast of the gulf as 10° to 11° at the 175-meter level in late summer, warming to 12° a few miles farther offshore (fig. 57). In 1914 the mouth of the Eastern Channel marked a division at this and greater depths between these comparatively high temperatures to the west and lower temperatures to the east, with the isotherms swinging offshore, abreast of Browns Bank, and a 175-meter value of only about 7.7° in the offing of Shelburne on July 28 (station 10233). But with the temperature between 11.3° and 11.85° there at this same level and at about the same date a year later (Bjerkan, 1919, p. 393; *Acadia* station 41), the ocean water was evidently closer in to the slope—annual variation sufficient to exercise considerable biologic effect on the bottom fauna along the southeastern slopes of Browns Bank and Georges Bank.

Only a small portion of the basin of the gulf is deeper than 175 meters. The bottom of the western bowl, at 260 meters (entirely inclosed at this level), was 7° in August, 1914, that of the eastern branch ranging from about 6° in its western

[34] Station 10225 about 8.8° and station 10227 about 7.1° at 175 meters on July 23 and 24, 1914.

side (station 10249) to about 8° in its northeastern side off Machias, Me. (station 10246), with 7.9° recorded for the southeastern part of the basin (station 10225) and about 7° on the floor of the Eastern Channel (station 10227) that July.

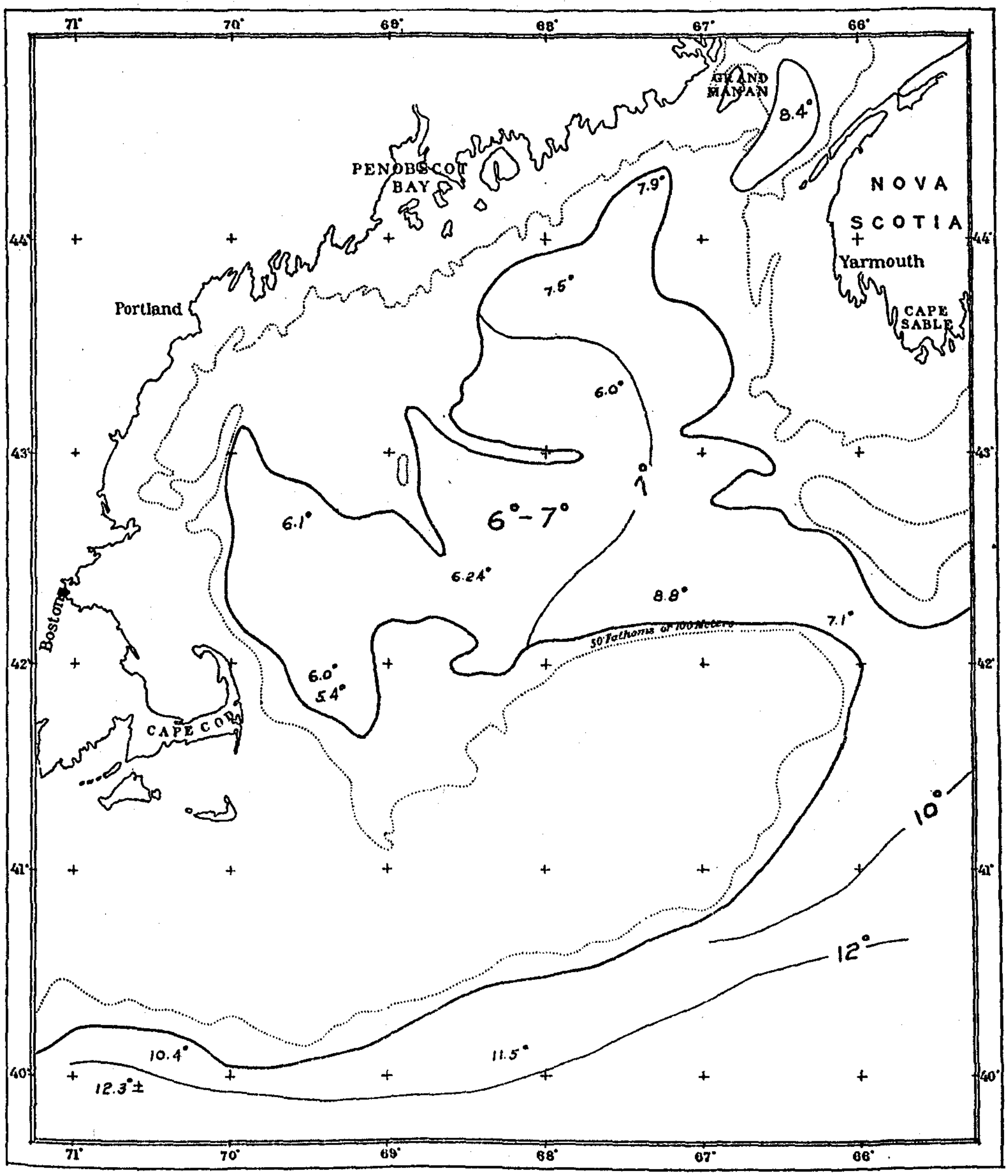

FIG. 57.—Temperature at a depth of 175 meters within the gulf for August, 1914. The temperatures along the continental slope are for July and August of that year, combined

PROFILES

The most striking thermal feature of the western side of the gulf in summer—certainly the one most often commented on—is its low temperature below the 40 to 50 meter level, contrasted with the warm surface water and with the still warmer oceanic water outside the edge of the continent to the south, illustrated more graphically in profile (fig. 58) than in horizontal projection. To find water on the continental slope along this profile as cold as the 100-meter reading in the gulf it is necessary to descend below 500 meters, while 10° water was within 40 meters' depth of the surface in the gulf but deeper than 180 meters on the slope. Farther east, where

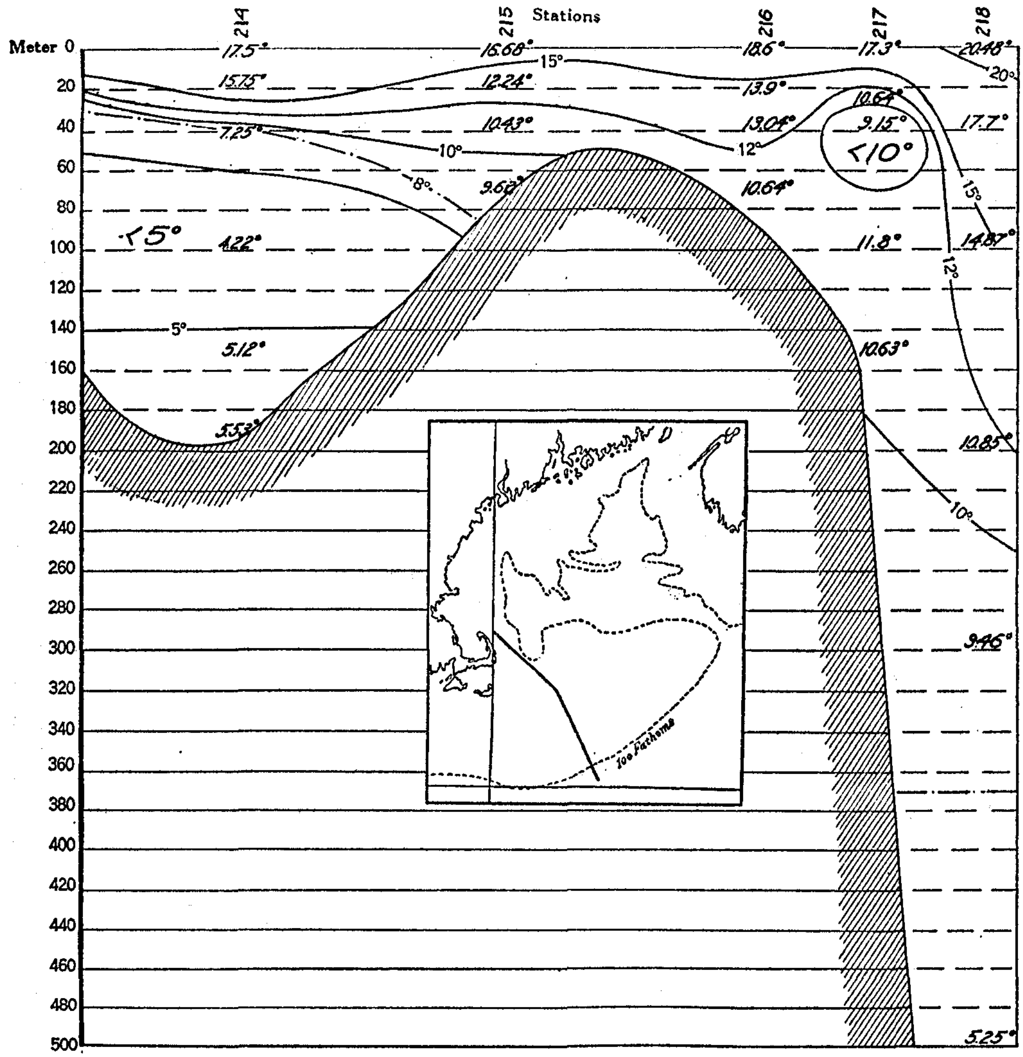

FIG. 58.—Temperature profile running from a point off northern Cape Cod, southeastward across Georges Bank to the continental slope, for July 19 to 21, 1914 (stations 10213 to 10218)

the basin to the north of the banks is warmer and where a cool wedge intervenes between ocean water and continental edge, a July profile (fig. 59) shows a contrast of only about 1° between the gulf, on the one hand, and the continental slope, on the other, at depths greater than 120 meters.

These two profiles of Georges Bank are further interesting for outlining the band of cool water that then extended along the bank from northeast to southwest, as just described. On the western member of the pair (fig. 58) this appears as a core (10°) over the offshore edge at a depth of 30 to 80 meters, but as a body of cold bottom water (8°) well in on the bank on the eastern profile (fig. 59), with the column of water nearly homogeneous in temperature from surface to bottom (inclosed by isotherms for 10° and 12°, evidence of active tidal mixing) on the northeastern part.

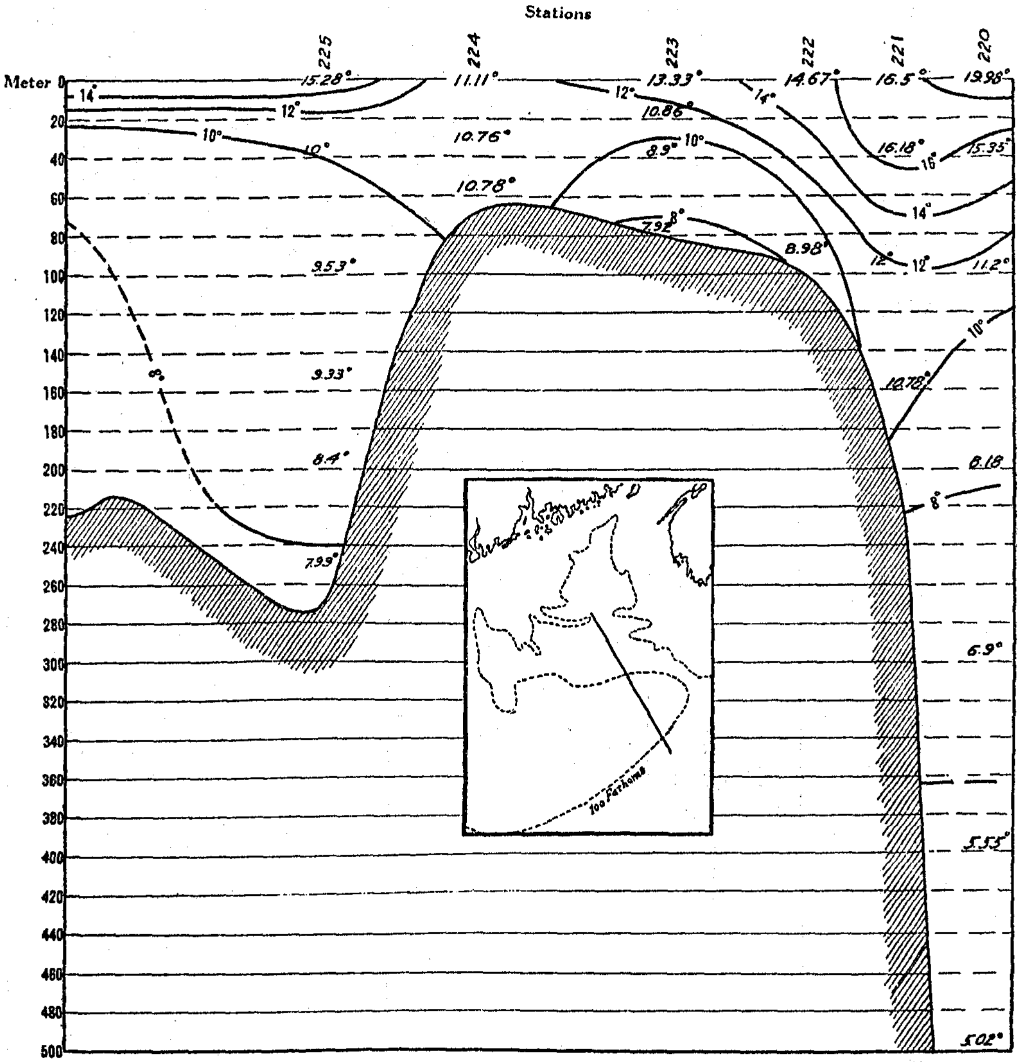

FIG. 59.—Temperature profile running from the eastern side of the basin, southeastward across the eastern end of Georges Bank to the continental slope, July 22 to 23, 1914 (stations 10220 to 10225)

With the August profile crossing the shelf off Marthas Vineyard (fig. 60), they also afford an instructive demonstration of the continuity of the zone of warm bottom water (10°) all along the offshore slope of Georges Bank at the 100 to 150 meter level in summer (though not farther east), with lower temperatures on the shoaler bottom of the bank, on the one hand, as well as deeper down the slope, on the other.

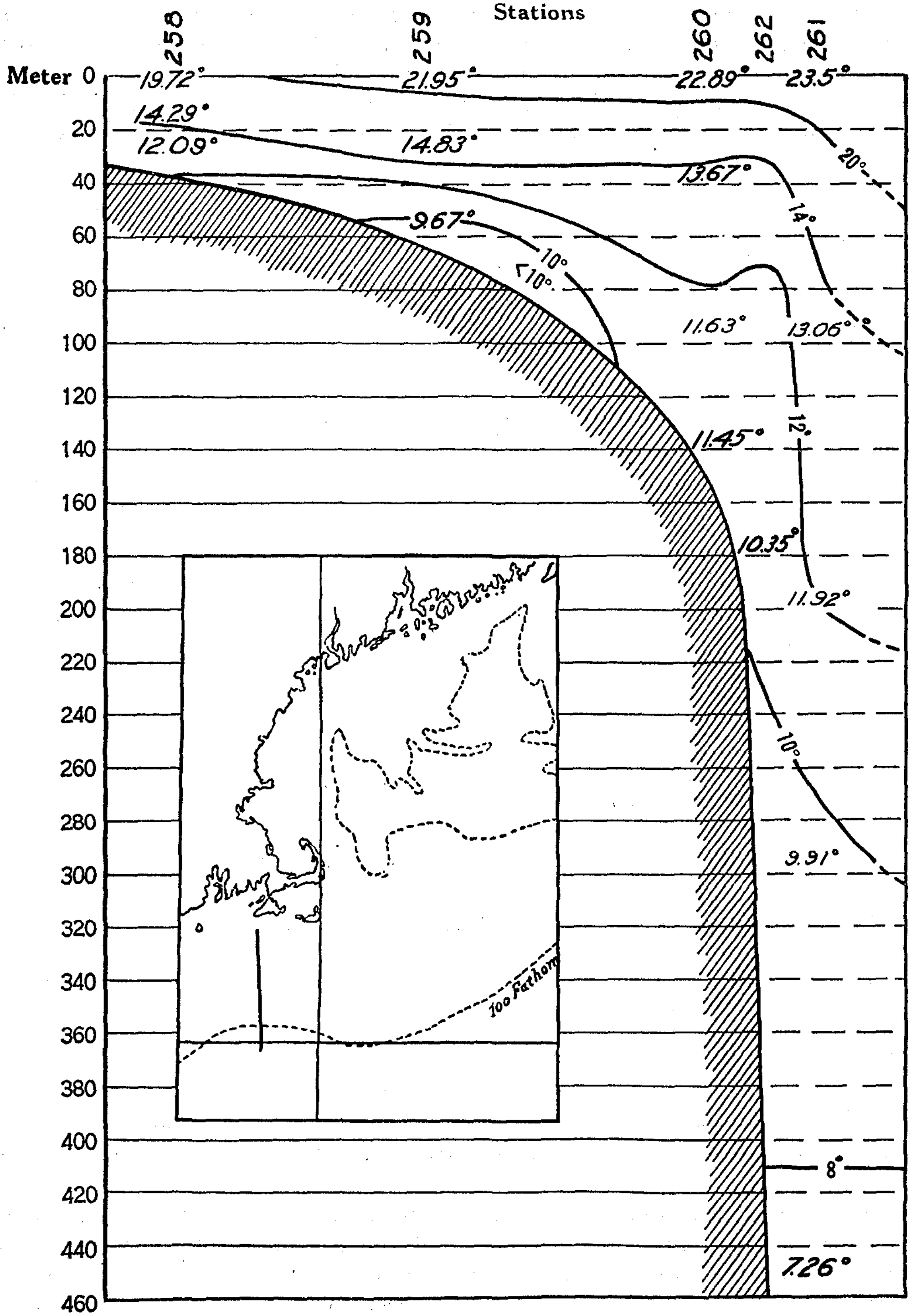

FIG. 60.—Temperature profile running southward from the offing of Marthas Vineyard to the continental slope, August 25 to 26, 1914 (stations 10258 to 10262)

The spacial relationship which the comparatively warm bottom water of the gulf bears to the colder mid stratum, to the still colder Nova Scotian water, and to the warm surface water, in summer, may best be illustrated by profiles crossing the Eastern Channel (fig. 61), crossing the gulf from west to east (figs. 62 and 63), and running out normal to the general trend of the eastern coast line of Maine (fig. 64).

The first of these, in conjunction with the corresponding profile for March (fig. 19), is especially interesting for its demonstration that it coincided with a slack period when a counter drift out of the gulf had filled the western side of the channel with colder and less saline water, but followed an inward pulse that had overflowed Browns Bank, raising the temperature of the whole column there to the high figure (8.5° to 14.7°) stated on the profile (station 10228). This, however, had spread no

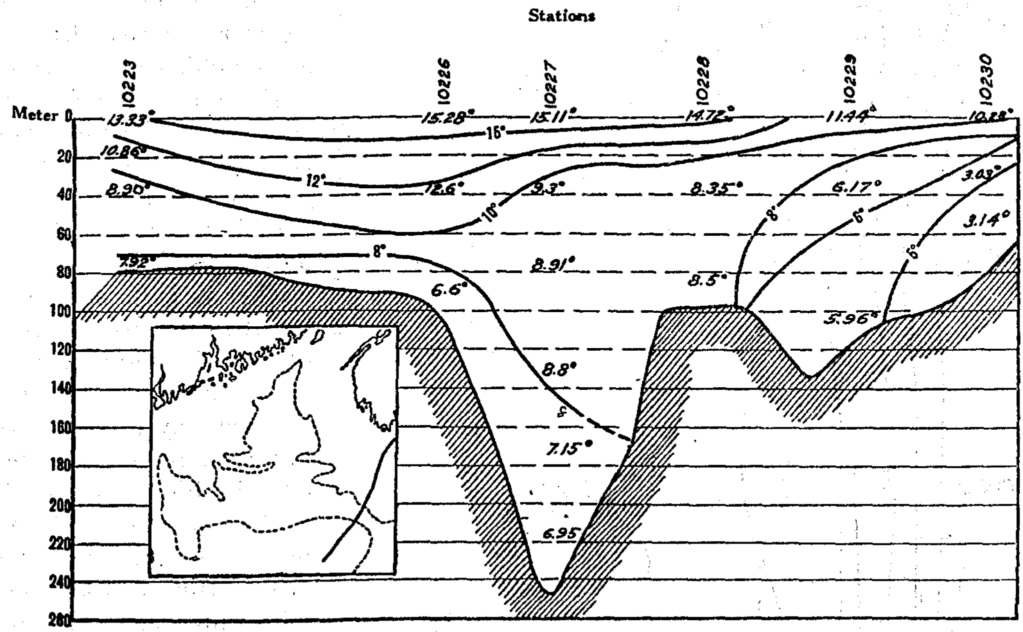

FIG. 61.—Temperature profile running from the eastern end of Georges Bank, across the Eastern Channel, Browns Bank, and the Northern Channel, to the offing of Cape Sable, July 23 to 25, 1914

farther north—witness the lower values in the Northern Channel (station 10229) and the still colder water (3° to 10°) at the Cape Sable end of the profile (station 10230).

Our summer cruise of 1914 does not afford a satisfactory profile across the gulf for July or August, lacking serial observations along the eastern slope of the basin, where the axis of warm bottom water, drifting into the gulf, is to be expected. One running eastward from the mouth of Massachusetts Bay toward Cape Sable for August 31 to September 2, 1915 (fig. 62), however, will represent the late summer state equally well for the gulf as a whole in a moderately warm year. The spacial relationship there shown between the warm surface water in the western side of the gulf (>16°), the cold mid stratum centering at about 100 meters (close to 5.5°), the warmer slope water (>6°) banked up against the eastern slope of the basin at depths greater than 140 meters, and the homogeneous column (9° to 10°) on German Bank in the

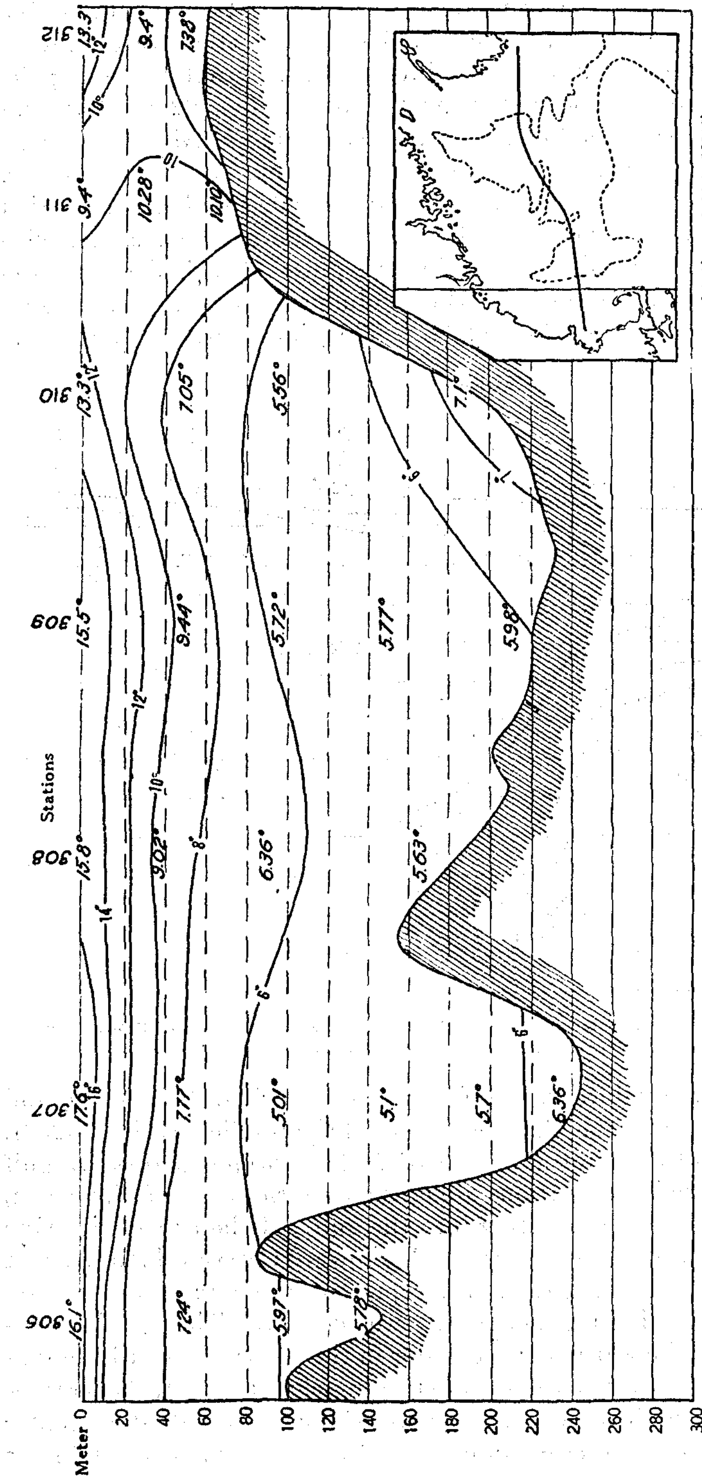

FIG. 62.—Temperature profile from the mouth of Massachusetts Bay to the offing of Cape Sable, August 31 to September 2, 1915 (stations 10306 to 10312)

eastern side of the picture (station 10311), resulting from the active tidal stirring, is characteristic of late summer.[35]

The low surface reading of 9.4° on German Bank was unexpected, because the whole underlying column and the surface water to the east as well as to the west of the station were slightly warmer. Probably this local chilling had its source in some upwelling from the still colder bottom water close in to Cape Sable.

In summers following periods when the inflowing bottom current has been weaker, or at least less regular (1913, for instance), cross profiles of the gulf bring out the cold mid layer even more clearly (fig. 63), with minimum readings of about 5.2° in both sides of the gulf at depths of 75 to 90 meters in this particular year. But, contrasting with this same month of 1914 and of 1915, the profile for 1913 shows only a fractional warming with increasing depth, from this level downward toward the bottom, with no apparent banking up of the warmer bottom water against the eastern slope.[36]

[35] The isotherm for 10° for this region, on my earlier representation of this profile, is incorrect (Bigelow, 1917, fig. 71).

[36] Highest value at 175 meters 6.6° off Cashes Ledge (station 10090); lowest 5.9° in the eastern side of the basin (station 10093).

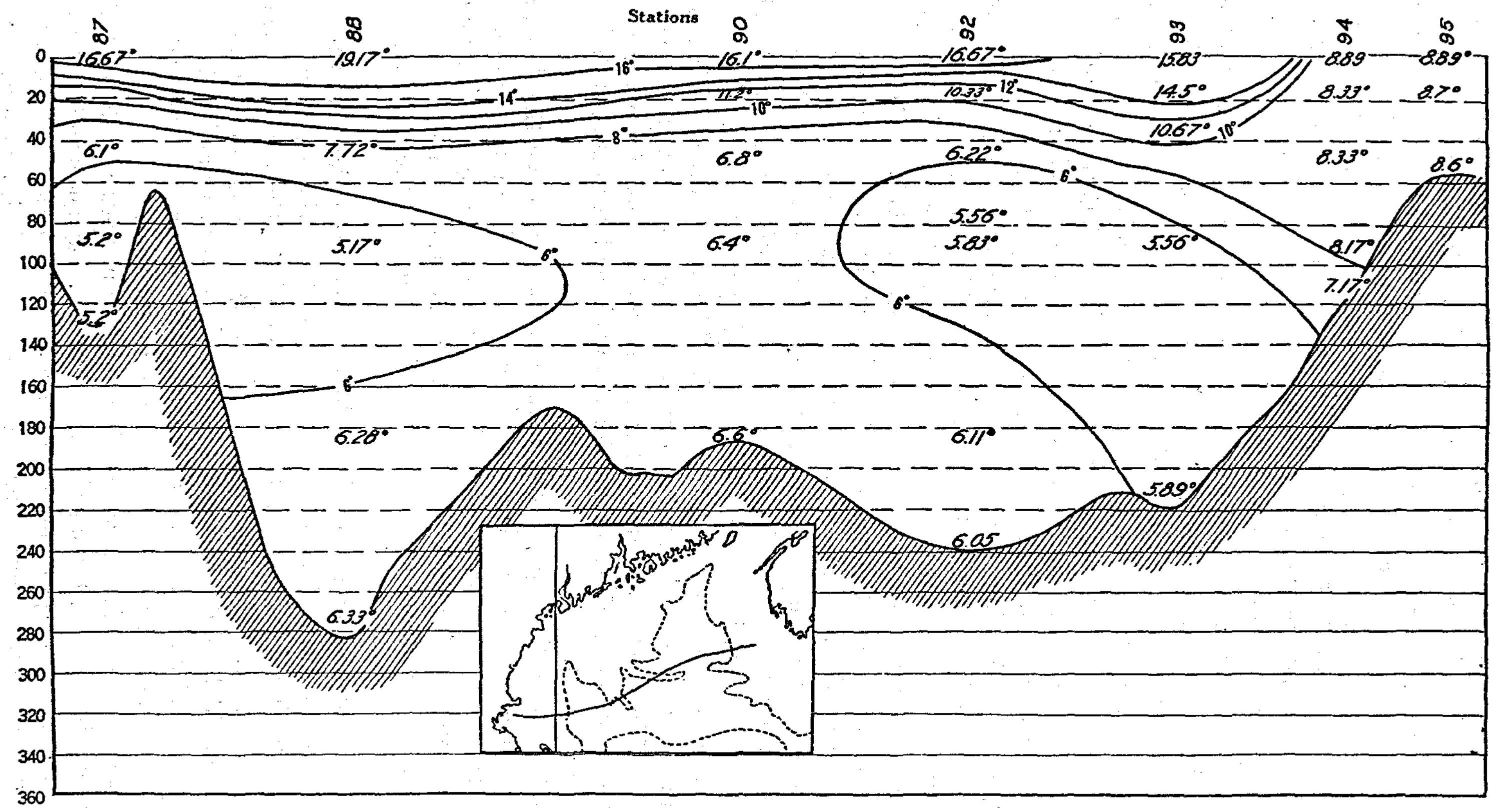

FIG. 63.—Temperature profile from the mouth of Massachusetts Bay to German Bank, August 9 to 20, 1913 (stations 10087, 10088, 10090, 10092 to 10095, and 10106)

The upper layers of the gulf thus present much the same picture from summer to summer when studied in west-east cross section, with isotherms closely crowded in the western side but spreading over the eastern coastal bank, and the uppermost stratum cooling from west to east as already described (p. 588). Invariably, too, the gulf has proved at least as cool at 100 meters as at any level in July and August, and usually coolest there in the form of a definite layer of minimum temperature spreading seaward, centripetally, from the western and northern shores. However, the spacial distribution of temperature at depths greater than 150 to 175 meters varies from summer to summer, depending on the volume and velocity of the bottom current drifting in through the Eastern Channel at the time or shortly previous (p. 613), as well as on the precise route followed by this water within the gulf. When this current has been in large volume shortly previous, it tends northward and westward around the eastern and northern slopes of the basin, so that the conditions described for 1914 and 1915 prevail (fig. 62). Following a long slack period, a reproduction of the temperatures of 1912 or of 1913 may be expected.

A composite profile (fig. 64), based on observations taken in the summers of 1913, 1914, and 1915, illustrates the relationship which the western extension of the warm bottom current bears to the shoaler water along the coast of Maine, on the one hand, and to the central part of the basin, on the other. When this drift is active, it hugs the northern slope of the basin as it eddies around to the westward, a statement supported by the evidence of salinity as well as of temperature.

The much lower surface temperature (12°) at the inshore end of this profile than over the basin offshore (16°) is simply the result of active vertical circulation along the coast; so, too, is the reverse relationship prevailing at the 60 to 100 meter level. I may also point out that this profile, like those already discussed, shows the cold mid-layer (of 5.3° to 6.04° at 100 to 150 meters) characteristic of the inner parts of the gulf in most summers, and which is reminiscent of the low temperature to which the whole mass of water shoaler than this had been chilled during the preceding winter (p. 689).

The maintenance of comparatively high temperatures down the slope, at depths greater than 30 meters, which is probably characteristic of the summer season in this part of the gulf, may have some biologic importance by making an especially favorable environment for such bottom animals as prefer a moderate temperature within narrow limits where they would find no sudden thermal bar to vertical migration.

Profiles crossing the mouth of Massachusetts Bay fron Cape Ann to Cape Cod, for the cold July of 1916 (fig. 65) and for August 22 of the warm summer of 1922 (fig. 66), are introduced for graphic demonstration of the thermal stratification that develops there by the end of the summer. It is surely worth emphasis that the bottom temperature should be only between 4° and 5° in water as shoal as 75 meters in as low a latitude as 42° N. at the end of August, with a surface temperature as high as 18°, as was the case in 1922—and this in a warm year.

The presence of a surface stratum of homogeneous water (18.6° to 18.7°) nearly 10 meters thick, blanketing the northern part of the August profile (station 10633), is rather contrary to our previous experience in this part of Massachusetts Bay, where low surface temperature usually has been recorded, reflecting upwellings or tidal mixings; but a temperature gradient of this type would result from active stirring of the upper stratum, if there be little interchange of water between the latter and the deep strata. In Cape Cod Bay, where partial inclosure and shoal water make local warming more effective than in any other part of the gulf, this state is probably typical of midsummer, judging from the state of the upper 14

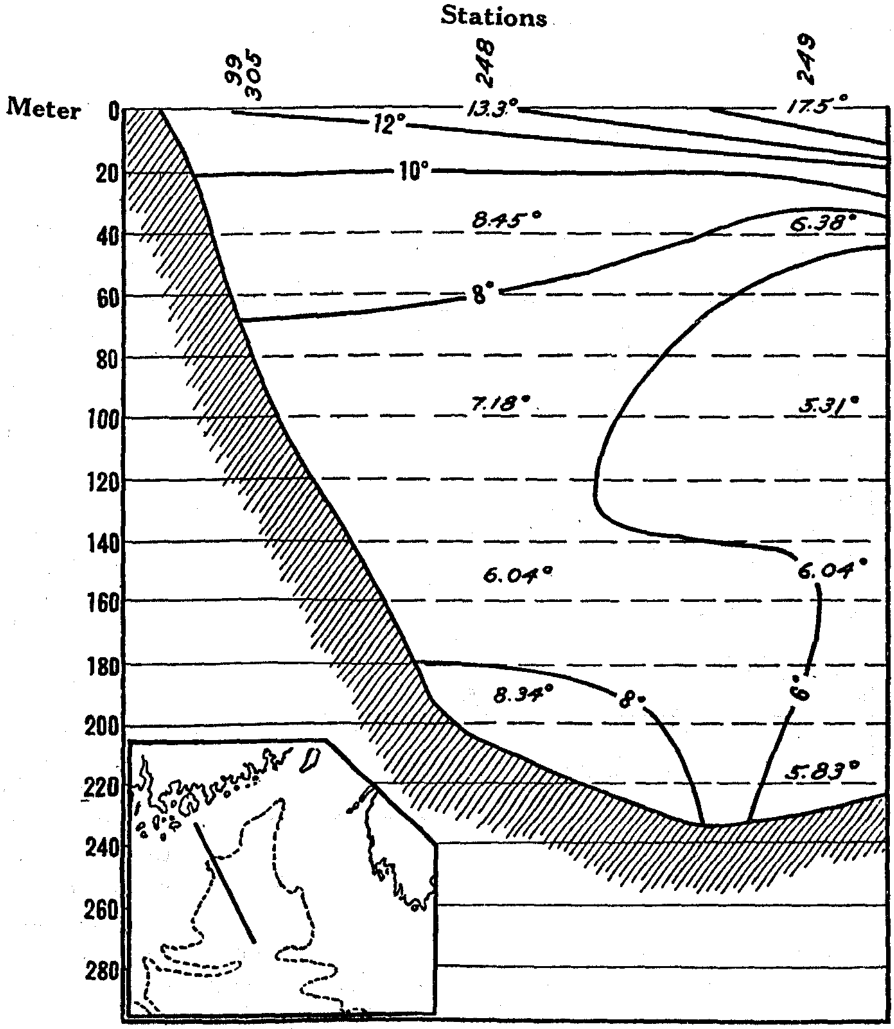

FIG. 64.—Temperature profile running southward from Mount Desert to the basin for August, from the data for the years 1913, 1914, and 1915, combined (stations 10099, 10248, 10249, and 10305)

meters of water there (18.3° to 17.9°) on August 24, 1922 (station 10644 and 10645, p. 995). The fact that the superficial stratum of water warmer than 12° was considerably thicker near Cape Cod than in the center of the bay that August corroborates the station data for May and June, 1925, to the effect that Cape Cod Bay is an important center of production of warm water during the summer months. Had the profile been run a few miles farther west, water warmer than 18° probably would have occupied the upper 10 meters from end to end, instead of showing the chilling effect of the strong tides, which actually characterize its Cape Cod end.

In the July profile (fig. 65) the cold bottom water is banked up against the southern side of the bay, but against the northern side on the profile for August (fig. 66). A difference of this sort probably reflects a corresponding difference in the movements of the deep water around Stellwagen Bank. Judging from experience in other years, the state illustrated by these August stations is the more usual in summer.

BOTTOM TEMPERATURE

The bottom temperature of the gulf in summer is governed chiefly by the depths, but also to some extent by locality. At this season the bottom is coldest (3° to 5°) in the troughs off the western shore of the gulf, irrespective of depth, and in the offing of Cape Sable in the opposite side, with the whole deep basin 1° to 3° warmer outside the 150-meter contour (5° to 8°). For example, an animal living in the trough off the Isles of Shoals might actually suffer lower temperatures during some summers than in some winters or springs, according as the years be cold or warm in the gulf. The annual differences in the basins at depths greater than 175 to 200 meters consequent on irregular pulses in the bottom current may so overshadow the regular seasonal cycle as to make the latter negligible, biologically, up to the end of the summer. Bottom dwellers in the coastal zone, however, must be inured to a wide range of temperature if they are to survive; as, indeed, they must in shallow boreal waters in general.

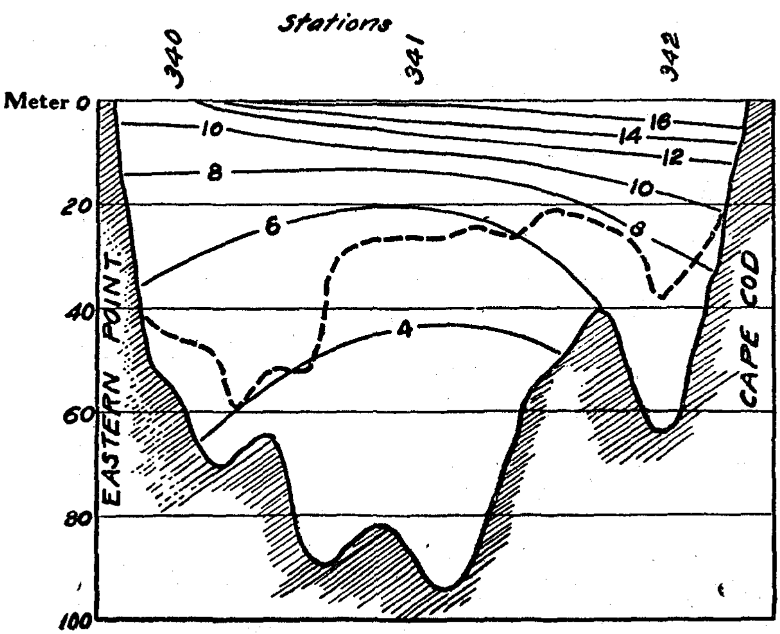

FIG. 65.—Temperature profile crossing the mouth of Massachusetts Bay just west of Stellwagen Bank, July 19, 1916 (stations 10340 to 10342). The contour of the bank is represented by the broken curve

Cape Cod Bay experiences a wider fluctuation in bottom temperature, with the succession of the seasons, than any other part of the open gulf outside the estuaries and islands. In order to exist there, without bathic migration, in water shoaler than 5 to 10 meters, any animal must be indifferent to temperatures as high as 18° to 19° in midsummer (p. 623). A bottom temperature of 17.9° was even recorded as deep as 13 meters off Barnstable on August 24, 1922 (station 10644)—an extreme for which the exposure of the neighboring flats to the sun at low tide is no doubt responsible—with 13.2° at 18 meters off Plymouth (station 10642). In winter these same regions cool to 0° or even fractionally colder. Around the more exposed shores of Massachusetts Bay, however, we have found the bottom temperature 12° to 9.8° in 15 to 18 meters depth; 7° to 9.8° at 25 to 30 meters; 7.2° to 5.6° at 40 to 50 meters; and 4.5° to 6.2° at 65 to 75 meters in August.

Compare this with the Bay of Fundy, where even the littoral zone warms only slightly above 10° to 12° off open shores, but where the bottom in 40 to 50 meters is almost equally warm by the end of the summer (p. 599). Under these conditions cool-water animals, at home in temperatures up to 10°, find no limit to their bathic dispersal short of the surface, instead of being confined to depths greater than 12 to 15 meters, as they are in Massachusetts Bay in summer. On the other

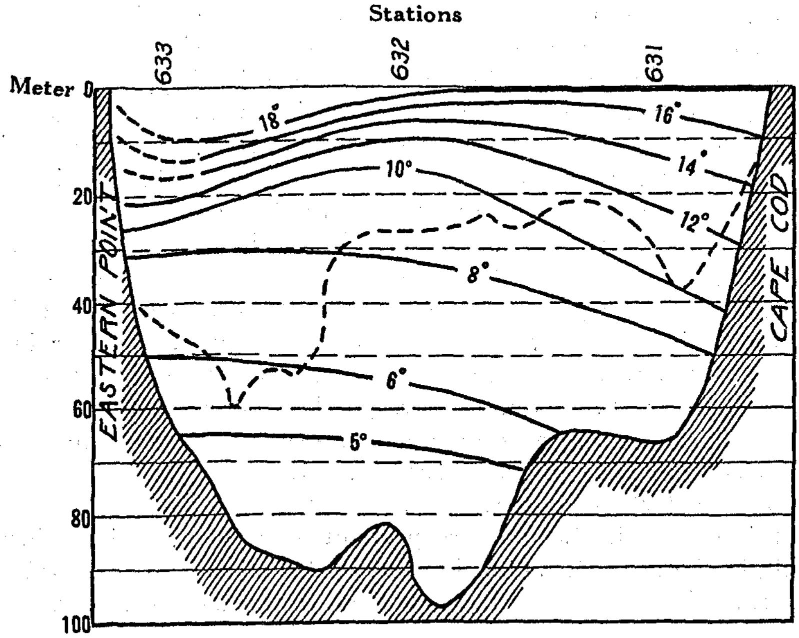

FIG. 66.—Temperature profile crossing the mouth of Massachusetts Bay from Gloucester to Cape Cod, August 22, 1922 (stations 10631 to 10633). The broken curve represents the shoalest contour of the bottom along the rim formed by Stellwagen Bank

hand, any animal restricted physiologically to truly Arctic temperatures would find a more favorable habitat in the deeper parts of Massachusetts Bay and in the still colder trough off the Isles of Shoals than in the Bay of Fundy at any depth.

The studies on the life history of the cod, on which the Bureau of Fisheries is now engaged, lend special interest to the bottom temperatures on the grounds where most of the fish have been tagged—Nantucket Shoals, Platts Bank, and the vicinity of Mount Desert Island.

In August, 1925, the *Halcyon* had bottom readings of 11.2° to 15.56° on the shoals in depths of 20 to 30 meters (p. 1012), and probably this is about the maximum to be expected there in an average summer. On the other hand, the bottom water cools to about 3° to 4° there at the end of winter, so that any fish (or other animals) remaining the year round on the shoals may experience a difference of 11° to 12° with the change of the seasons.

The bottom temperature usually has ranged from 9° to 10° in about the same depth of water off Mount Desert Island in August, but in the cold summer of 1923 it was probably about 2° colder there, judging from a temperature of 7.5° at the 30-meter level a few miles farther out from shore on August 5 (p. 599). On Platts Bank the bottom water had warmed only to about 6° at a depth of 71 meters by September 3, in 1925, with 4.5° at 80 meters on the 20th of July (p. 1012); but I may anticipate by pointing out that the temperature there does not reach its maximum for the year until October or even later at depths so great.

ANNUAL VARIATIONS IN SUMMER TEMPERATURE

Although the temperature of the gulf shows wide fluctuations with the change of the seasons, our data for seven summers, together with earlier records (p. 514), prove that as a rule there is little difference at a given locality, from year to year, for a given month. However, the period of observation has included the notably cold summers of 1916 and 1923; such also was that of 1882. Conversely, it is to be expected that unusually warm summers do also occur from time to time, though no definite record of such has yet been obtained in the temperature of the gulf.

On the whole, the bottom of the western side of the gulf had virtually the same temperature in July and August of 1872 (Verrill, 1874 and 1875) as when deep readings were first taken there[37] in these same months of 1912. Verrill's readings for the northeast corner of the gulf were consistently 0.5° to 1.5° colder in 1873 and 1874 than in 1912, but correspond very closely with the state of that region in 1913. The surface values for 1873 likewise correspond as closely with those for 1912 as could be expected, except that autumnal cooling seems to have commenced earlier in the season in the latter year (Bigelow, 1914, p. 92).

The summer of 1882 (the year that saw the oft-quoted destruction of the tilefish) was colder than normal in the southern parts of the Gulf of Maine, where the *Fish Hawk* (Verrill, 1882 and 1884, p. 654; Tanner, 1884b) obtained the following readings, with reliable reversing thermometers, on bottom to the eastward of Cape Cod:

Depth, meters	Temperture	Depth, meters	Temperature
	°C.		°C.
51	4.4	111	2.8
60	3.9	152	3.3
80	3.9	166	3.3
100	2.8	201	3.6

Turning now to the more recent records, we find the August temperatures for 1912, 1913, 1914, and 1923 differing so little, one from another, at any level that they may be taken as typical for that month.

The slight differences between the first three of these years have been discussed in earlier reports (Bigelow, 1915, p. 246; 1917, p. 231). Briefly, the eastern part

[37] These early readings and the allowance that must be made for the inaccuracies inherent in the type of thermometer used are discussed in detail in an earlier report (Bigelow, 1914, p. 92).

of the gulf was slightly colder, the western half slightly warmer, in the summer of 1913 than in 1912, though the greatest annual difference was nowhere greater than 2.5° for sets of observations taken at nearly the same date. Thus we found the August stations in Massachusetts Bay agreeing very closely for these two years (stations 10044, 10045, and 10106). The water a few miles north of Cape Ann was about 1° to 2.5° warmer in August, 1913 (stations 10104 and 10105) than in July, 1912 (stations 10011 and 10012b), a difference that may have been due chiefly to a difference in the dates at which the readings were taken.

The surface of the western side of the basin was about 1° warmer, the 100-meter level about 0.5° warmer, and the 200-meter level about 1.5° warmer on August 9, 1913 (station 10088), than on July 15, 1912 (station 10007); and while this difference was seasonal in the shoal strata, it probably reflected an annual fluctuation at depths greater than 100 meters. Off Platts Bank, a few miles to the northward, observations taken within three days of the same date (7th of August in 1912, station 10023; August 10 in 1913, station 10091) showed the immediate surface about 1° colder in 1913 than in 1912. However, this may have been due to a difference in the stage of the tide, which runs strong over the bank. The bottom temperatures there were almost precisely alike for the two years. In the eastern side of the basin 1913 was slightly the warmer year down to 70-odd meters, but about 1.5° the colder from that level down to bottom at stations only a few days apart in date.

The fact that the water was more than 2.5° warmer on the surface near Monhegan Island on August 14, 1913 (station 10102), than on August 2, 1912 (station 10021), though with virtually no difference below the 30-meter level, can hardly be accounted for on a seasonal basis. The mean temperature for the whole column of water was also about 0.7° higher on Jeffreys Bank, off Penobscot Bay, on August 2, 1913 (station 10091, about 10°), than on the 8th in 1912 (station 10025, about 9.3°), with less active vertical circulation, as evidenced by a wider vertical range of temperature. The 1913 temperatures, however, were about 0.75° to 1.5° the lower a few miles farther east on August 14 (station 10038, 1912; station 10101, 1913). The August temperatures for 1913 were likewise 1° to 1.5° the colder along the eastern coast of Maine and over the coastal bank west of Nova Scotia, where the observations for the two years were taken within a few days of the same dates. For example, the station off Lurcher Shoal was about 1° colder at the surface and in the mid levels, about 2° to 3° colder near bottom at 120 to 140 meters depth, in 1913 (station 10096) than in 1912 (station 10031); German Bank was also about 2° colder at all levels.

Except for the immediate surface, so subject to seasonal change, the upper 100 meters of the western basin was warmer in 1915 than in any previous summer of record; below that depth the readings for that year were fractionally cooler than those for 1913 or 1914, but warmer than for 1912, with an extreme annual variation of about 2.4°.

The surface stratum of the center of the gulf near Cashes Ledge was 2° to 3° warmer in 1914 than in 1913, but the water deeper than 40 meters was as much colder, with temperatures for 1915 intermediate between these two years at depths greater than 80 meters. These differences may have been due to differences in vertical circulation around Cashes Ledge, however, as may the fact that the water was coldest here on bottom in 1915.

In the western side of the eastern arm of the basin the differences in temperature between the four summers were less than 1°. On German Bank the temperature was about 1° higher in 1914 than in 1913, but about the same as in 1915 (allowing for seasonal differences, due to the difference in date of the observations).

The temperature along the northeastern coast of Maine, in the one side of the gulf, and in the deep bowl off Gloucester, in the other, have varied but little from summer to summer; but the deep water was 1° to 2° colder next the land west of Penobscot Bay and off Cape Elizabeth in 1914 than either in 1912 or in 1913. This also applies at depths greater than about 75 meters to the trough between Jeffreys Ledge and the coast.

In the deep strata of the Bay of Fundy the bottom water ranged about 2° warmer in August, 1914 (Craigie, 1916a), than in the summers of 1915 (Craigie and Chase, 1918) or 1916 (Vachon, 1918), and slightly warmer than Mavor (1923) records it for 1917 or 1919.

These annual differences may be summarized as follows: Except for the immediate surface, the upper 150 meters was slightly colder in the western, central, and northern parts of the gulf in 1914 than in either of the two preceding years, but the bottom water of the western, northern, and eastern parts of the basin were warmer, with still higher temperatures in the western side in 1915.

More or less fluctuation in summer temperature is to be expected in any partially inclosed basin as subject to violent climatic changes as is the Gulf of Maine, and where waters of different temperatures meet. What really deserves emphasis is that the yearly changes have been very small during the period of record; certainly not enough seriously to affect the waters of the gulf as a biologic environment, except perhaps in 1916.

During that year vernal warming proceeded so slowly in the sea, after an almost Arctic winter and a tardy spring, that the temperature of the central part of Massachusetts Bay was only 3.67° to 3.9° at 50 to 80 meters depth on July 19 (station 10341), though the immediate surface was about as warm as the expectation for that date (16° to 17°). In fact, the deep readings were hardly warmer than readings taken in May of the preceding year, only about 1.5° warmer than the winter minimum for that level during 1913, and 2° warmer than the early March temperature of 1920 (p. 522). The water off Northern Cape Cod (stations 10344 and 10345) [38] was likewise decidedly colder in 1916 than in the summers of 1913 to 1915, with the 20 to 40 meter lever 2° to 3° colder than in 1913 and 6° to 9° colder than in the same month of 1914. The suprisingly low surface temperatures of 10° off Chatham and 7.2° in the southwestern part of the basin on July 22, 1916, contrast with 16° to 17° for this part of the gulf as a whole at about that same date in 1913 and 1914. It is clear that such cold surface water reflected some temporarily and locally active vertical circulation, because the vertical range of temperature was less than 1° between the surface and 30 meters at the coldest of these two stations (10346), instead of a range of about 9°, which previous experience suggests as normal for the western side

[38] About 4.1° at 50 meters, 3.85° at 100 meters, and warming fractionally below that level to 4.06 at 150 meters.

of the gulf in July. But even allowing for this factor, a considerable annual difference in surface temperature remains to be accounted for between the cold July of 1916 and the warmer years, 1913 to 1915.

Furthermore, the vertical warming below 100 meters, so characteristic of this side of the gulf in 1914 and 1915 (Bigelow, 1917), was hardly appreciable in 1916. During the interval, July 22 to August 29, the mid layers off northern Cape Cod warmed by about 1° or 2° (stations 10344 and 10398). Even then, however, the temperature did not equal that of 1912 on the same date (station 10043, August 29), or of 1913 three weeks earlier (station 10086, August 5; Bigelow, 1922, p. 91).

The surface water on the northwestern part of Georges Bank was also about 2° colder in July, 1916, than in that month of 1913 or of 1914, as appears from the following table:

Depth	July 9, 1913, station 10059	July 20, 1914, station 10215	July 23, 1916, station 10347	Depth	July 9, 1913, station 10059	July 20, 1914, station 10215	July 23, 1916, station 10347
	°C.	°C.	°C.		°C.	°C.	°C.
Surface	13.33	16.68	11.39	40 meters		10.43	
20 meters		12.24		55 meters	12.60		
27 meters	12.60			60 meters			9.61
30 meters			10.91	70 meters		9.62	

The difference in temperature between July of 1916, on the one hand, and of 1913 and 1914, on the other, was even wider along the southern edge of the bank. Violent annual, even day by day, fluctuations are to be expected there (Bigelow, 1922, p. 10), but nothing in our previous experience foreshadowed summer temperatures as low as those of 1916, when the bottom water was 4° colder there than in 1914, though the stations for the two years were close together in location and the surface temperatures (17° to 18°) were almost alike. The surface near the continental edge south of Nantucket lightship and the depths greater than 50 meters were likewise 3° to 4° colder in July, 1916 (station 10351), than in that month in 1913 (station 10061); and the cold band just outside the edge was 4° to 5° (fig. 67) instead of 9° to 10°, as we had found it in 1914 (fig. 58).

There is nothing unprecedented in a vertical distribution of temperature of the type shown on this 1916 profile (fig. 67) over this part of the slope; indeed, its repeated occurrence suggests that something of the sort is to be expected except when obscured by encroachments from the warm water of the so-called "Gulf Stream" (p. 608). The surprising feature of the summer of 1916 is that the temperature of the coldest layer should have been so low and that water so cold lay so close to the surface of the open sea in July at this latitude. In fact, as I have elsewhere noted (Bigelow, 1922, p. 103), this July temperature very closely paralleled the temperature taken at the same relative position on the slope off Cape Sable, about 200 miles to the northeastward, on June 24 of the year previous (station 10295).

The *Grampus* did not visit the eastern side of the gulf in the summer of 1916, where the water was also unusually cold during that summer, as Dr. A. G. Huntsman writes:[39]

[39] Quoted from a letter from Doctor Huntsman.

The temperature of the water in the Fundy region was unusually low during the summer of 1916. The data given me by Craigie (1916a, 1916b), Craigie and Chase (1918), and by Vachon (1918) show that in the St. Croix River, near St. Andrews, and in Passamaquoddy Bay the

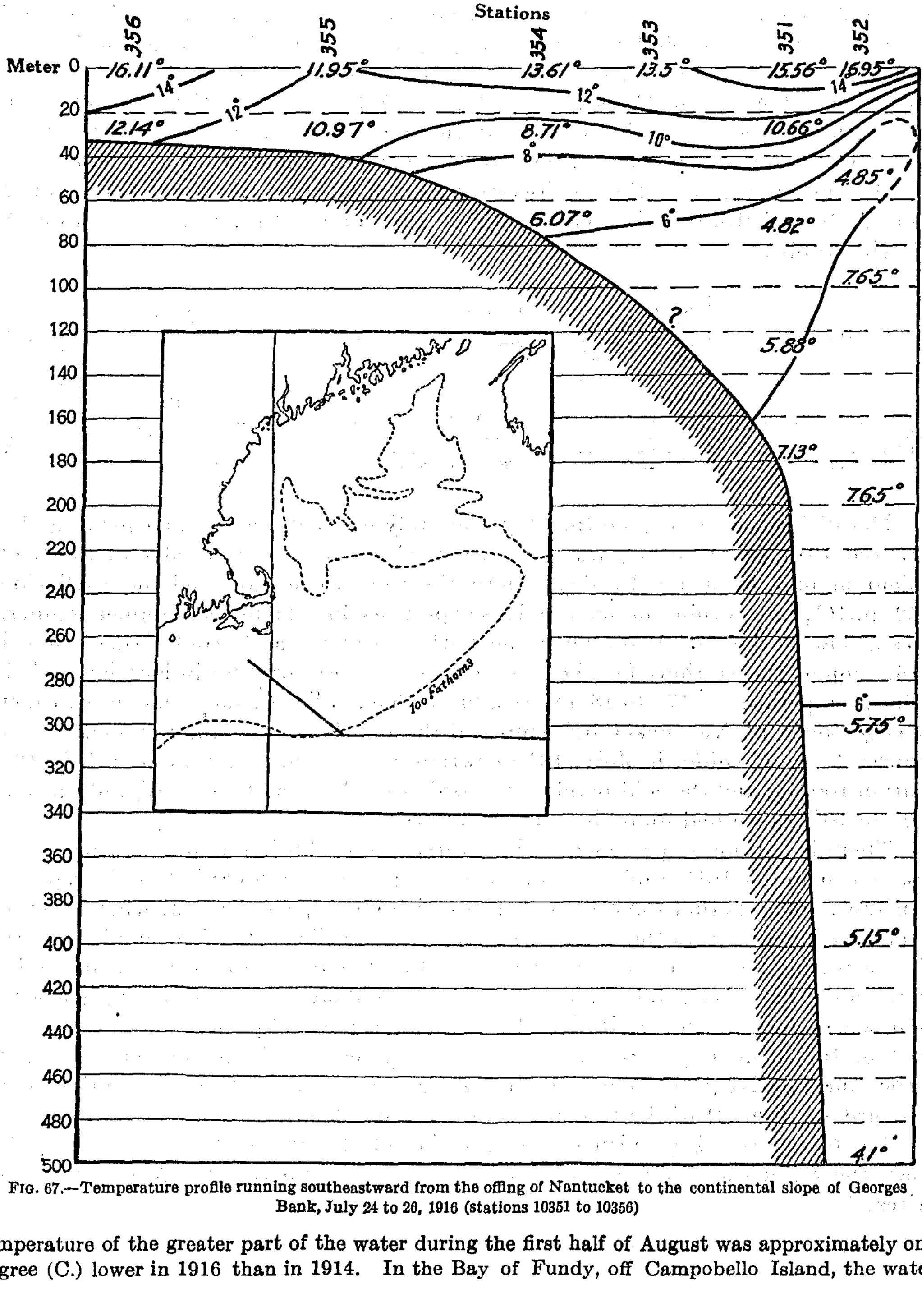

FIG. 67.—Temperature profile running southeastward from the offing of Nantucket to the continental slope of Georges Bank, July 24 to 26, 1916 (stations 10351 to 10356)

temperature of the greater part of the water during the first half of August was approximately one degree (C.) lower in 1916 than in 1914. In the Bay of Fundy, off Campobello Island, the water was slightly colder on July 25, 1916, than it had been on July 14, 1915, and nearly two degrees (C.) colder on August 16, 1916, than it had been on August 27, 1914. Also, in the Bay of Fundy, east of Grand Manan, the temperature of the body of the water was nearly one degree (C.) lower on July 24, 1916, than on July 15, 1915, and more than two degrees (C.) lower on August 16, 1916, than on August 27, 1914. This shows that in the Bay of Fundy the water was colder in the summer of 1915 than in that of 1914, and still colder in that of 1916.

Enough data have thus been gathered to class 1916 definitely as an abnormally cold year in the gulf.

It is interesting to consider whether climatic conditions during the preceding months will account for this abnormality. Unfortunately, no observations were taken in the gulf during the preceding winter, but the deep temperature of the western side changes so little from February to June that its July state gives an indication of the temperatures that have prevailed there in spring. Judged from this viewpoint, the July temperatures of Massachusetts Bay and of the neighboring parts of the gulf for 1916 do not suggest that the sea temperatures of the preceding winter were abnormally low.

This conclusion is corroborated by meteorological conditions, for the early part of the winter of 1915–16 was warmer than usual (mean temperature for January about 6.7° F. higher than normal at Boston, 2.7° F. higher than normal at Provincetown); but the temperature was about 2.5° F. below normal at Boston in February, 4.4° F. below normal in March, with unusually heavy snowfall in both these months (30.3 and 33.3 inches, respectively). Consequently, there is every reason to suppose that the temperature of the water of Massachusetts Bay did not commence to rise until a month or even two months later than usual that spring, and that vernal warming proceeded more slowly at first than in more normal years, because the weather continued abnormally cool and cloudy throughout May and June. Furthermore, it is in just such a spring as this, when the surface stratum warms very slowly at first, but then rapidly, that the deeper water is most effectively blanketed from the penetration of heat from above by the sudden development of a state of high stability. Indeed, a better illustration of how slowly the deeper water warms under such circumstances could hardly be found than by the very small rise in temperature that took place off Cape Cod from July 22 (station 10344) to August 29 of that year (10398) at 40 to 50 meters.

Thus the difference in temperature between the cold summer of 1916 and the warm summers of 1913, 1914, and 1915, in the western side of the gulf, was no wider than can be accounted for on the basis of the local weather.

I may point out that a cold winter and spring in 1916 were similarly followed by low summer temperatures in the coastal water all along the continental shelf, westward and southward to Chesapeake Bay during that same year (Bigelow, 1922), not alone in the Gulf of Maine.

It is possible that the low gulf temperatures of 1916 also reflected some unusual expansion of the Nova Scotian current, because even a temporary offshoot of that icy-cold stream crossing the gulf at any time during the spring would chill the surface of its western side 2° to 3° or more below normal (p. 680). Had the *Grampus* made a general survey of the gulf in 1916, as she did in 1914 and 1915, this question would have been cleared up; but the few stations for that cold year were all located close to the western shores. The salinity of the Nova Scotia current being considerably lower than that of the water it meets in the Gulf of Maine (p. 727), its presence causes low salinity as well as low temperature such, indeed, as prevailed at our few gulf stations for 1916. Salinity, however, is not a safe criterion for northern water in the western side of the gulf, because it is also dependent on the amount of run-off from the rivers, which was greater during the spring of 1916 (p. 837) than usual.

No serial observations were taken in the open gulf during the summers of 1917 to 1919, but Mavor's (1923) data for the Bay of Fundy classify 1917 and 1919 as normal seasons. Brooks (1920), however, points out that 1920 continued a "cold" year in the gulf through the summer, by the testimony of bathers along New England beaches. This was followed by a summer of at least average warmth in Massachusetts Bay, and probably over the gulf as a whole, in 1922 (p. 995). By contrast the summer of 1923, like that of 1916, was unusually cold in the deeper waters following a severe winter, with unusually heavy snowfall, and a tardy spring. Surface readings would not have suggested this more than a mile or two out from the land anywhere in the western side of the gulf. In fact, the coast sector between Cape Ann and Penobscot Bay was actually a degree or two warmer on the surface in 1923 than in 1912 at the end of the first week of August, as illustrated by the curves for 16° and 18° temperature on the charts for the two years (fig. 47), with readings of 16° and upwards right into the land off Cape Elizabeth in 1923, where we have usually found the coast skirted by a belt 1° to 3° cooler (p. 588).

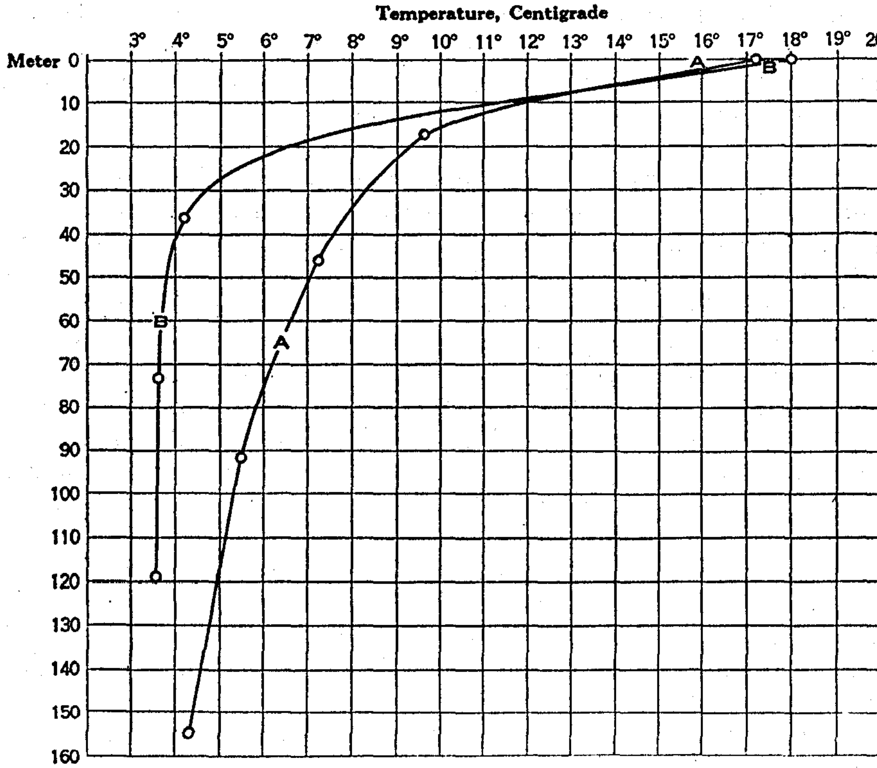

FIG. 68.—Vertical distribution of temperature off Cape Elizabeth on August 15, 1913 (A, station 10104), and on August 7, 1923 (B, latitude 43° 18', longitude 69° 44')

However, surface readings taken by the *Halcyon* to the eastward of Penobscot Bay early that August proved about 2° lower than the expectation. Bathers, too, reported the water unusually cold along the beaches throughout that summer, after offshore winds. This was corroborated by serial observations off Gloucester, which proved the whole column of water below the 30-meter level 1° to 3° colder in August, 1923, than it was three weeks earlier in the season even in the cold summer of 1916, although the difference in date would suggest just the reverse. Depths greater than 40 meters were also 1° to 3° colder off Cape Elizabeth in 1923 than in any previous August of record (fig. 68), notwithstanding the warm surface just mentioned. This statement would probably hold good for the inner part of the basin in general, also, as well as along the eastern coast of Maine, the relationship being similar near Mount Desert Island and off Mount Desert Rock (table, p. 635).

It is probable that a summer colder than those of 1916 or 1923 comes very seldom in the Gulf of Maine, because winters so severe, and with so heavy a snowfall, are exceptional (p. 697).

The possibility that cyclic changes of temperature may take place in the gulf, with warmer or colder periods enduring over many years, must not be ignored; but nothing of this sort has been recorded there within historic times.

The following comparative tables for representative localities will show in detail the annual differences in temperature summarized in the preceding pages.[40]

Annual differences in temperature

MOUTH OF MASSACHUSETTS BAY

Depth, meters	1912 10002 July 10	1913 10087 Aug. 9	1914 10253 Aug. 22	1915 10306 Aug. 31	1916 10343 July 19	1922 10632 Aug. 22	1923 Aug. 9
0	18.3	16.7	18.0	16.1	16.4	18.1	17.2
20	9.4	10.6	11.2	10.5	6.0	9.1	9.0
40	6.6	6.7	6.5	8.0	4.1	7.4	5.5
60	5.0	5.4	5.4	6.7	3.8	5.6	4.4
80	4.6	5.3	4.8	6.3	3.7	----------	3.3
100	4.6	5.2	4.6	6.2	----------	----------	3.2
120	----------	5.2	4.5	6.0	----------	----------	3.1
140	----------	----------	4.5	5.9	----------	----------	3.1

WESTERN BASIN

Depth, meters	1912 10007 July 15	1913 10088 Aug. 9	1914 10259 Aug. 22	1915 10307 Aug. 21
0	17.8	19.2	20.0	17.2
20	11.7	12.6	11.5	12.5
40	8.0	8.7	5.8	9.0
60	6.0	6.4	4.9	7.0
80	5.0	5.4	4.5	5.7
100	4.7	5.2	4.4	5.2
120	4.6	5.6	4.7	5.2
140	4.6	5.9	5.3	5.3
160	4.6	6.2	5.9	5.7
180	4.6	6.3	6.5	5.8
200	4.6	6.3	6.8	5.9
220	4.6	6.3	7.0	6.2
240	----------	6.3	7.0	6.4
260	----------	6.3	7.1	----------

[40] As the readings were not taken at the same levels at all the stations, or at as many levels as it is desirable to show here, it has been necessary in many cases to derive most of the values by interpolation. The temperatures are approximate, therefore, and are given only to the nearest tenth of a degree, Centigrade.

Annual differences in temperature—Continued

CENTER OF GULF NEAR CASHES LEDGE

Depth, meters	1913 10090 Aug. 10	1914 10255 Aug. 23	1915 10308 Sept. 1
0	16.1	19.2	15.8
20	11.1	12.2	11.2
40	7.2	7.8	9.1
60	6.6	5.7	7.7
80	6.4	4.3	6.8
100	6.4	3.1	6.3
120	6.4	4.1	6.0
140	6.4	4.7	5.8
160	6.5	5.5	5.7
180	6.6	6.3	----------
200	6.6	----------	----------

TROUGH BETWEEN JEFFREYS LEDGE AND COAST

Depth, meters	1912 10011-12b July 17-23	1913 10104 Aug. 15	1914 10252 Aug. 15
0	15.0	17.2	16.2
20	8.3	9.6	12.0
40	6.1	7.8	7.8
60	4.8	6.6	6.2
80	4.6	5.8	5.0
100	4.6	5.2	4.3
120	4.6	4.8	3.8
140	----------	4.5	[2]3.7
160	4.1	4.3	----------
180	----------	----------	----------

[2] At 130 meters.

OFF CAPE ELIZABETH

Depth, meters	1912 10019 July 29	1913 10103 Aug. 12	1914 10251 Aug. 14	1923 Aug. 7
0	13.9	16.1	16.6	18.1
20	11.1	11.3	----------	----------
40	8.3	8.7	5.7	4.3
60	6.9	7.4	----------	3.9
80	5.8	6.1	----------	----------
100	5.7	6.7	4.4	3.6
120	----------	----------	----------	3.5
140	----------	----------	4.9	----------

OFF PENOBSCOT BAY

Depth, meters	1912 10039 Aug. 22	1913 10101 Aug. 14	1914 10250 Aug. 14
0	13.3	11.1	13.1
20	11.3	10.1	10.2
40	9.3	9.4	8.6
60	8.9	8.1	7.9
80	8.7	8.7	7.4
100	8.3	8.4	7.1
120	7.9	----------	6.6
140	7.3	----------	6.2

Annual differences in temperature—Continued

CLOSE IN TO BAKERS ISLAND, OFF MOUNT DESERT ISLAND

Depth, meters	1913 10099 Aug. 13	1915 10305 Aug. 18	1923 Aug. 5
0	12.8	10.8	11.7
25	10.0	9.4	7.6
40	9.3		
50		8.8	7.0

OFF MOUNT DESERT ROCK

Depth, meters	1913 10100 Aug. 13	1914 10248 Aug. 13	1923 Aug. 6
0	12.8	13.3	12.8
40	8.7	8.5	7.1
100	7.7	7.2	4.5
150	6.8	6.0	5.1
190	6.0	8.3	

OFF THE NORTHEAST COAST OF MAINE

Depth, meters	1912 10033 Aug. 16	1913 10098 Aug. 13
0	10.6	10.8
20	10.1	9.6
40	9.7	9.3
60	9.6	9.1

NORTHEAST CORNER OF GULF

Depth, meters	1912, 10036	1913, 10097	1914, 10246
0	10.6	12.8	14.4
20	10.2	11.7	10.0
40	9.3	10.4	8.4
60	8.9	9.2	7.3
80	8.6	8.4	6.6
100	8.3	7.7	6.3
120	8.0	7.3	6.6
140	7.6	6.7	7.3
160	7.4	6.5	7.8
180	7.4	6.2	8.0
200		6.0	[1] 8.2

[1] At 190 meters.

"PRINCE" STATION 3

[In the center of the Bay of Fundy, between Grand Manan and Nova Scotia, from data by Craigie (1916a), Vachon (1918), and Mavor (1923).]

Depth, meters	1914 Aug. 27	1916 Aug. 25	1918 Sept. 4	1919 Aug. 26
Surface	11.2	10.1	12.2	11.3
10	10.4	9.9	11.2	11.1
25	9.5	9.1	9.2±	9.1
50	9.2	7.4	7.7	7.9
75	9.2	6.5	6.7	7.4±
100	8.8	6.1	6.1	7.1
150	8.5	5.8	6.2	7.0
175	8.4	5.8	6.1	6.7

Annual differences in temperature—Continued

WEST SIDE OF EASTERN BASIN

Depth, meters	1912 10027 Aug. 14	1913 10092 Aug. 11	1914 10249 Aug. 12	1915 10309 Sept. 1
0	15.0	16.7	17.5	15.6
20	9.2	8.1	9.1	12.5
40	7.8	6.7	6.4	10.3
60	7.4	5.8	5.7	8.5
80	7.2	5.6	5.3	6.8
100	6.1	5.9	5.3	5.9
120	6.6	6.1	5.5	5.8
140	6.2	6.1	5.9	5.9
160	6.1	6.1	6.1	5.9
180	6.0	6.1	6.0	6.0
200		6.1	5.9	6.1
220		6.1	5.8	
240		6.1		

OFF LURCHER SHOAL

Depth, meters	1912 10031 Aug. 15	1913 10196 Aug. 12	1914 10245 Aug. 12	1915 10315 Sept. 7
0	13.3	12.1	14.4	12.2
25	11.8	10.5	10.3	11.3
50	10.7	9.4	9.2	10.1
75	10.1	8.6	8.8	9.9
100	8.5	7.4	8.6	

AUTUMNAL COOLING

SURFACE

The surface is at its warmest at some time during August in all those parts of the Gulf of Maine where the surface temperature rises much above that of the deep water in summer.[41] This includes the whole open area, except for the northeastern part, and the sites of active tidal mixing on the banks, the precise date of maximum surface temperature for any given summer depending on the prevailing weather. Our recent studies have not been sufficiently intensive precisely to locate this critical date for any one year or for any given locality in the gulf, but the records collected by Rathbun (1887) for the years 1881 to 1885 show that it may fall at any time between the first and last of August for the western and northern shores of the gulf between Nantucket Shoals and Penobscot Bay. After the first of September the surface of this subdivision cools as the autumn advances.

Experience in the summers of 1912, 1913, and 1914 suggests that the temperature of the upper layers of the western and deeper parts of the gulf generally (i. e., where vertical circulation is only moderately active) probably had passed its midsummer maximum, and that autumnal cooling had commenced there by the date of our late August and early September cruise of 1915. Thus, the highest reading recorded on August 31 and September 2 of that year, on the run eastward from Gloucester toward Cape Sable, was only 17.6°, contrasting with a probable maximum of about 19° to 20° over the western side of the basin during mid August. The seasonal schedule seems to have been about the same in 1925, also, when the *Halcyon* had surface readings of 16.6° a few miles north of Cape Ann, 15.2° on Platts Bank, and 14.7 between the latter and Portland on September 3.

[41] The temperature of inclosed harbors is highest in July, mirroring the summer maximum for the air (p. 585).

The more tide-swept waters along and among the islands east of Casco Bay where the whole column of water continues nearly homogeneous in temperature through the summer and the surface warms only to about 11° to 13° instead of 16° to 18°, do not commence to chill until a month or more later in the season. In 1925, for example, the surface temperature near the Duck Islands, off Mount Desert, was almost exactly the same on September 9 and 10 (11.1° and 10.8°) as it had been there on August 11 (10.9°), 10° on September 15, and still 10.3° to 10.8° on October 15 to 16. Readings of 10.28° off Machias and of 11.6° near Mount Desert on September 15 and 16, 1915, are in line with this.

This same rule holds good for the Bay of Fundy, where no appreciable cooling takes place until after the first of October—a month later than in Massachusetts Bay or off Cape Ann. Thus, Vachon (1918) had surface readings of 9.21° to 11.07° in the central parts of the bay on September 27 and October 4, 1916, with 9° to 10.6° at various localities in Passamaquoddy Bay between October 3 and 17, showing a cooling of only about 1° to 2° from the summer maximum. Mavor (1923) likewise records surface temperatures of 11.07° between Grand Manan and the Nova Scotian shore on October 4, 1916, and 9.77° on October 2, 1918. However, the 10-day averages for Lubec Narrows (fig. 31) show that considerable variation is to be expected from year to year in the date after which the surface of this part of the coast water commences to chill, for a steady though slight cooling was recorded through September, 1920, whereas the mean surface temperature at Eastport averaged highest at the last week of September for the 10-year period, 1878 to 1887.

Surface readings of 9.4° on German Bank (station 10311) and 13.3° near Cape Sable (station 10312) on September 2, 1915, suggest that the temperature was then about stationary at its summer maximum in this side of the gulf.

With the surface along the western shores of the gulf, from Massachusetts Bay northward, chilling rapidly during the early autumn, but with the northeastern and eastern margin of the gulf cooling only very slowly at first, there comes a time when the whole peripheral belt of the gulf outside of the outer headlands is nearly uniform in surface temperature (close to 9.5° to 10.5° in most years), varying only a couple of degrees, at most, from place to place. In 1915 this state was apparently attained sometime between the first and middle of October, the surface of Massachusetts Bay having chilled to 10.5°–13.4° by the last week of September (stations 10320 to 10324), with 11.6° off the Isles of Shoals and 11.9° off Cape Elizabeth on October 4 (stations 10325 and 10326), 10° at the mouth of Penobscot Bay (station 10329), and 9.4° near Mount Desert and off Machias on the 9th (stations 10327 and 10328). The surface of Massachusetts Bay continued virtually constant at about 11° throughout October.

The following tabulation (p. 638) of Rathbun's (1887) graphs for the years 1881 to 1885 likewise shows extremely uniform averages of 11.67° to 9.44° on October 1 for Boon Island, Seguin Island, Matinicus Rock, Mount Desert Rock, and Petit Manan Island, localities where the midsummer temperatures for the same years would show a range of at least 6°.[42]

[42] The average surface temperature at Thatchers Island, at the tip of Cape Ann, was somewhat higher (14.17°) for the two years, 1881 and 1882, at the beginning of October.

Unfortunately, it is not known whether autumnal cooling proceeds at as rapid a rate during October out over the basin of the gulf in general as it does along the western shore, nor are data available for Georges or Browns banks during that month; but Rathbun's (1887) tabulations show the surface almost as cool at Pollock Rip, off the southern angle of Cape Cod, on October 1 (11° to 13.5°) as it is in Massachusetts Bay at that same date. This applies also to the whole region of Nantucket Shoals, where the *Halcyon* had surface temperatures of 11.6° to 12.2° on October 1, 1925, showing that a decided regional equalization had taken place since midsummer, when surface readings in the same region have ranged from 11.6° to 16.4° (p. 1012).

The autumnal cycle of temperature to the southward of Marthas Vineyard lags several weeks behind that of the waters to the north and east of Cape Cod. Thus, the surface was 13.3° to 14.4° across the whole breadth of the continental shelf off Marthas Vineyard on October 22, 1915 (stations 10331 to 10333), with 15.5° a few miles outside the continental edge, while the *Halcyon* had 13.3° near No Mans Land on the 28th of the month in 1925. This corresponds closely with Rathbun's averages of 15° for October 1 and 11.7° for November 1, 1881 to 1885, 22 miles off Nantucket (the old situation of Nantucket South Shoals lightship, which has since been relocated).

Average and extreme surface temperature, ° C., 1881 to 1885, from Rathbun's (1887) graphs, to the nearest half degree only

Date	22 miles SSE. of Nantucket, lat. 40° 54′, long. 69° 49′		Pollock Rip Lightship		Boon Island Light		Seguin Light		Matinicus Rock		Mount Desert Rock		Petit Manan Island [1]	
	Av.	Ex.	Av.	Ex.	Av.	Ex.	Av.	Ex.	Av.	Ex.	Av.	Ex.	Av.	Ex.
Oct. 1	15.0	14.5–15.5	13.0	11.0–13.5	11.0	9.5–12.0	11.0	9.5–12.0	10.5	10.0–11.5	9.5	9.0–10.5	11.5	11.0–12.0
Nov. 1	11.5	11.0–12.0	10.0	9.5–10.5	9.0	7.0–10.5	9.0	8.0– 9.5	9.5	8.5–10.0	8.5	8.0– 9.5	9.5	9.5
Dec. 1	7.5	6.5– 8.5	6.5	4.5– 8.5	[2] 6.0	5.5– 6.0	5.5	5.0–6.25	7.0	6.0– 8.5	5.5	2.0– 7.0	6.5	5.5– 8.0
Dec. 16	6.0	5.0– 6.5	5.5	3.5– 6.5	5.0	4.0– 6.0	4.0	3.0– 5.0	5.5	4.5– 6.5	5.0	3.0– 6.5	4.5	3.0– 6.0

[1] For years 1884 and 1885 only, the readings for 1881 and 1882 being omitted because so irregular that their reliability is doubtful.

[2] Omitting one reading of 0.56°, which was obviously an error.

SUBSURFACE

At first the autumnal cooling of the surface, which accompanies the cooling of the air, is due not only to an actual loss of heat by radiation (p. 692) but reflects mixture with the cooler underlying water, a process that correspondingly warms the latter. The result is that the annual maximum is attained later and later in the year as the depth of observation increases down to about 100 to 150 meters, or to the lower boundary of the stratum, the temperature of which is controlled by solar warming alternating with winter chilling. Consequently the wide vertical range of temperature that characterizes most parts of the gulf in summer gradually gives place to a state of vertical homogeneity as the autumn progresses. In 1915 (a typical year) autumnal cooling had affected only the uppermost stratum of Massachusetts Bay up to the end of September, the 20 to 25 meter temperature having continued virtually stationary at the midsummer value (11° to 12°) up to that date, with a rise of 2° to 3° at greater depths, resulting, no doubt, from the constant tendency toward vertical equalization by tidal mixing.

The profile for this date (fig. 69) shows that cooling had proceeded less rapidly in the southern side of the bay next to Cape Cod, which receives warm water from Cape Cod Bay, than in the central and northern parts, making the regional variation wider than it is in summer (fig. 66). Temperature of the upper 40 meters of Massachusetts Bay, however, was virtually equalized at 9.5° to 11.5° by the last week of that October (stations 10237 to 10239). On the other hand, vertical stirring had been active enough to raise the temperature of the 80 to 150 meter stratum of the bowl off Cape Ann from 5.8° on August 31, 1915, to 6.8° to 7° on October 1 (stations 10306 and 10324).

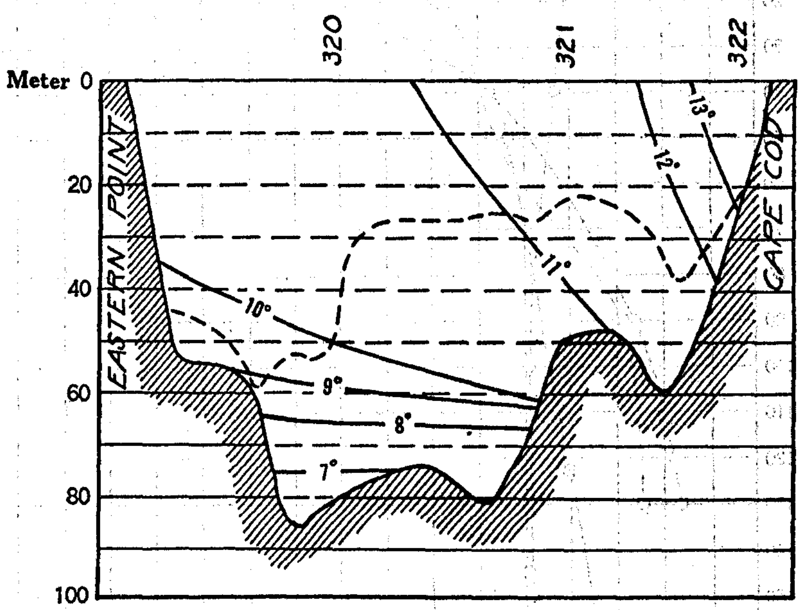

FIG. 69.—Temperature profile at the mouth of Massachusetts Bay, inside Stellwagen Bank, September 29 to October 1, 1915 (stations 10320 to 10322). The broken curve shows the contour of the bank

The thermal cycle was essentially similar in the cold year of 1916, when the 80 to 90 meter level was nearly 2° warmer at the mouth of the bay on October 31 (station 10399, 5.43° at 90 meters) than it had been on July 19 (station 10341, 3.67° at 80 meters), although the surface had cooled from 16.4° to 10° during the same interval, or to about the temperature normal for the outer part of the bay at that season.

Graphs for temperature off the Isles of Shoals and off Cape Elizabeth on October 4, 1915 (stations 10225 and 10226), and at various dates in August (fig. 70.) show much the same seasonal change as Massachusetts Bay, characterized by considerable cooling at the surface, but at a decreasing rate, down to about 30 to 40 meters, contrasted with a slight warming at greater depths down to bottom in 145 to 175 meters. However, it is impossible to state the precise rate of change for any given level for any one year from the data at hand.

The entire column of water down to 30 meters had cooled to about 10° at the mouth of Penobscot Bay by October 9, 1915, with about 9° at 60 meters, corresponding to a decrease of 3° at the surface, but a rise of about 1° at depths greater than 20 to 25 meters (fig. 71).

The surface (9.4°) was about 0.7° colder than the bottom near Mount Desert Island in 60 meters depth (10.1°) on October 9, 1915 (station 10328), the bottom

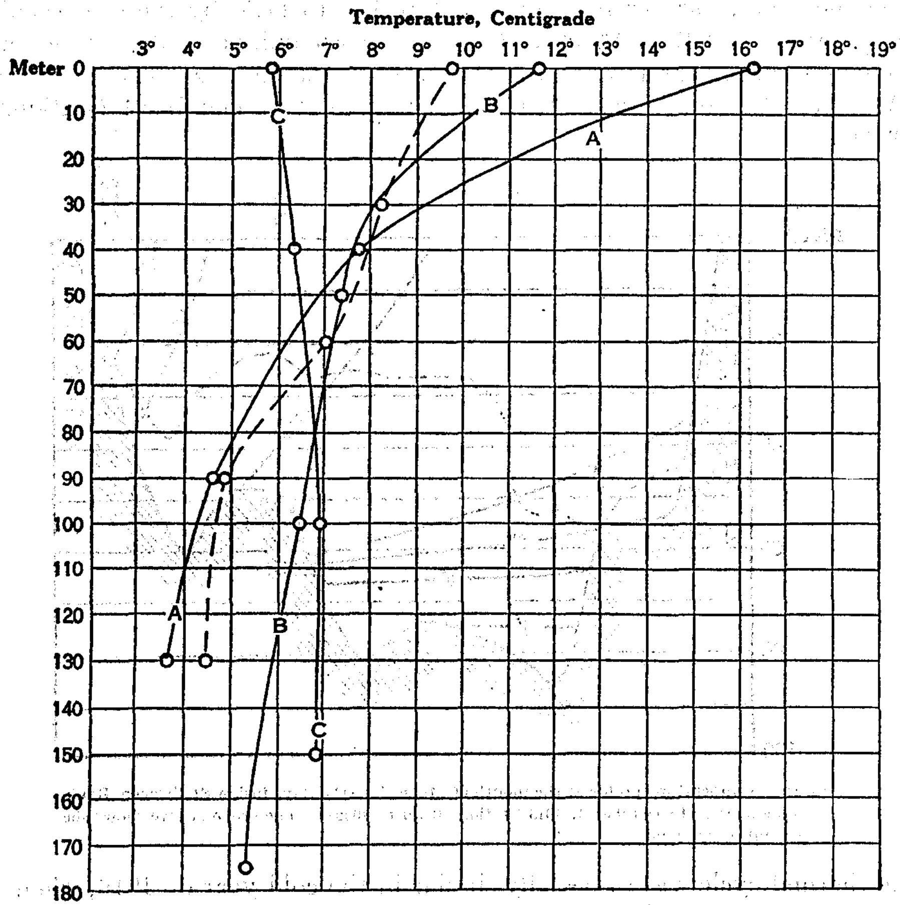

FIG. 70.—Vertical distribution of temperature in the trough between the Isles of Shoals and Jeffreys Ledge, to show the progress of autumnal cooling. A, August 15, 1914 (station 10252); B, October 4, 1915 (station 10325); C, December 30, 1920 (station 10493). The broken curve is for November 1 of the cold year 1916 (station 10400)

having warmed since August about as rapidly as the surface had cooled. Probably the temperature would have been found homogeneous there from surface to bottom at about 9.5° a week or so earlier in the season, as it was off Machias, Me., on that same date (station 10327), with a reading of 9.4° at the surface and 9.83° close in to the bottom.

The whole column of water warms slowly in the deeper parts of the Bay of Fundy throughout the summer, and at a more nearly uniform rate vertically than is the case in the deeps of the open gulf. Probably this process continues into September every year, sometimes into October, as happened in 1916 (Vachon, 1918, tables, p. 309), with the bottom water continuing to warm for some time after the surface has commenced to cool. Judging from Mavor's (1923) tables, the depths greater than about 60 meters in the trough between Grand Manan and the Nova Scotian shore of the bay may be expected to warm by about 1° after the date when the surface reading is highest and before the deep layers also commence to show the chilling effect of autumn. In 1917 the temperature of the mid-stratum rose from about 6° to 7° there on September 4 to 7°–8° on October 2, but the maximum (6° to 7°) was not attained at depths greater than 60 meters until some weeks later in 1916.

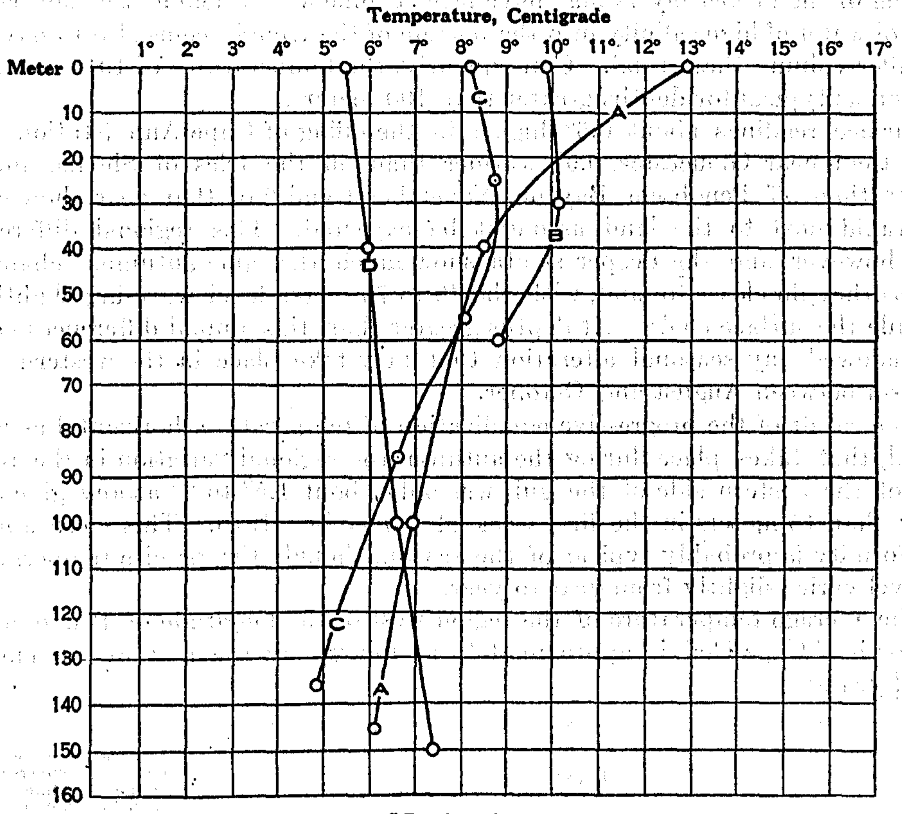

FIG 71.—Vertical distribution of temperature off Penobscot Bay at successive dates, to show the progress of autumnal cooling. A, August 14, 1914 (station 10250); B, October 9, 1915 (station 10329); C, November 2, 1916 (station 10402); D, January 1, 1921 (station 10496)

In the lower part of Passamaquoddy Bay, Vachon (1918; *Prince* station 4) found the whole column in 30 meters depth cooling after October 3 as follows:

Depth	Oct. 3, 1916[1]	Oct. 16, 1916[1]	Oct. 21, 1916[1]	Oct. 27, 1916[1]
	°C.	°C.	°C.	°C.
Surface	10.60	9.35	9.32	8.51
20 meters	9.83	9.14	9.08	8.81
30 meters	9.82	8.98	[2]8.88	8.80

[1] From Vachon's (1918) tables. [2] 26 meters.

In 1916 the temperature of the upper 30 meters was about the same a few miles off Cape Ann on October 31 (station 10399, surface 10°, 30 meters 9.18°) as it was on the 3d to the 16th in Passamaquoddy Bay, showing a regional difference of about two weeks in the autumnal schedule between the southwestern and the northeastern parts of the gulf. This corresponds both to the land climate and to the difference in latitude.

Our only records of autumnal temperatures for the offshore parts of the gulf later than the first week of September are for its western and southwestern parts, where serial readings were taken on November 1, 1916 (station 10401), and again on the 8th of the month (station 10404). In this very cold year the autumnal warming of the deeper layers may have lagged some weeks behind the normal; the inflow of water of high salinity into the bottom of the trough seems also to have been in smaller volume than usual. Consequently, the temperatures of 1916 can hardly be taken as typical for depths greater than 100 meters.

Surface readings about 0.5° higher in the offing of Cape Ann (station 10401, 10.6°) than near Gloucester, 0.9° warmer than off the Isles of Shoals, and 1.3° warmer than off Penobscot Bay on November 1 and 2 of that year show cooling most rapid next to the land, as might be expected. This regional difference is slight, however, and the deeper strata show much the same autumnal change offshore as they do closer to land, with the 40 to 70 meter level warming slightly (fig. 72) while the surface cools. At depths greater than this annual differences entirely overshadowed any seasonal alteration that may take place in the western side of the basin between August and October.

As a result of the progressive equalization of temperature, horizontal as well as vertical, that takes place during the autumn, the regional variation in the temperature of the western side of the gulf was only about 1.5° to 2° at any given level deeper than 15 meters in the first week of November, 1916. This close approach to uniformity is probably typical of the season, though the precise temperature at any level varies slightly from year to year.

The average temperature of the region west of the longitude of Penobscot Bay and north of Cape Cod is approximately as follows by the first of November in normal years:

Depth	Average temperature Aug. 15	Average temperature Nov. 1	Seasonal change
	°C.	°C.	°C.
Surface	15.0-18.0	10.0	−5.0-8.0
20 meters	11.5	9.5	−2.0
40 meters	7.2	8.9	+1.6
70 meters	5.6	7.0	+1.4
100 meters	4.7	5.0	+.3

No records of the subsurface temperatures have been taken on Georges Bank in autumn. In the shallow water of Nantucket Shoals autumnal cooling may at first reduce the temperature of the surface slightly below that of the bottom, the *Halcyon* having recorded surface readings of 11.6° to 12.2° on October 1, 1925, on the shoal, when the bottom water was 12° to 13.5° in a depth of about 25 meters (p. 1013).

The whole column, however, cools nearly uniformly on the shoals during October, whether the surface be slightly cooler than the bottom or slightly warmer at this season depending on the wind as the latter moves the surface water in or offshore.

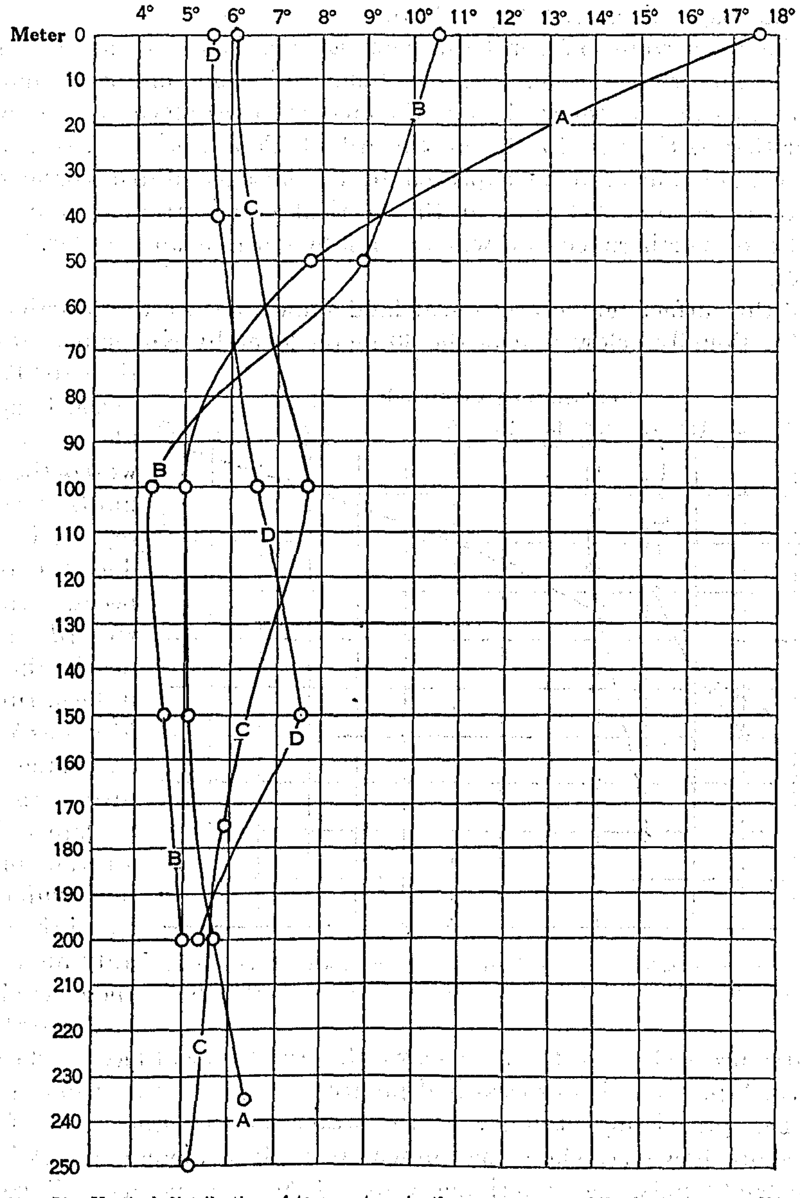

FIG. 72.—Vertical distribution of temperature in the western arm of the basin of the gulf in autumn and winter. A, August 31, 1915 (station 10307); B, November 1, 1916 (station 10401); C, December 29, 1920 (station 10490); D, January 9, 1921 (station 10503)

The upper 40 meters of water over the continental shelf, south of Marthas Vineyard and out to the edge of the continent, was vertically homogeneous in temperature at 13° to 14.5° by October 22, 1915 (stations 10331 to 10333, fig. 73).

We again found the superficial stratum over this part of the shelf equally homogeneous in temperature in November, 1916. While the bottom water then showed slight vertical cooling at depths greater than 30 to 40 meters, it was considerably warmer then than it had been there in August—a state obtaining as far southward as Chesapeake Bay (Bigelow, 1922, p. 123).

Thus, the coast water off southern New England corresponds to the Gulf of Maine in the fact that the temperature tends to become uniformly homogeneous during September and October, though the change takes place at a temperature 3° to 4° higher than is the case to the northward of Cape Cod. "A seasonal change of this sort was, of course, to be expected in the absence of disturbances by extra-limital currents, as the first step in the vertical equalization of temperature so characteristic of northern coastal waters in late autumn and winter." (Bigelow, 1922, p. 123.)

In 1916 the surface temperature near land a few miles west of Marthas Vineyard had fallen fractionally below that of the 30-meter level by November 10 to 11 (stations 10405 to 10408); and although this profile lies a few miles west of the geographic limits covered by this report, it is reproduced here (fig. 74) because the readings would have been nearly the same had it been run out from Marthas Vineyard on the same date. Its most instructive feature is its demonstration of the fact, now sufficiently established, that autumnal cooling in the coastal waters off the northeastern United States proceeds from the land seaward. In 1916, as I have earlier remarked (Bigelow, 1922, p. 123), this process had progressed so far by that date as to nearly obliterate the preexisting stability of the water on the inner half of the shelf. Farther offshore, however, where the immediate surface alone had yet been chilled by the cool land winds, the underlying water at 20 to 50 meters still continued 1° to 2° warmer than the superficial stratum above or the bottom water below. As a result the curves for 12° and 13° might suggest a landward intrusion of water from offshore if taken by themselves. However, the salinities forbid this interpretation, proving this apparent tongue merely reminiscent of the maximum temperature to which this level had warmed during the preceding summer (Bigelow, 1922, p. 123).

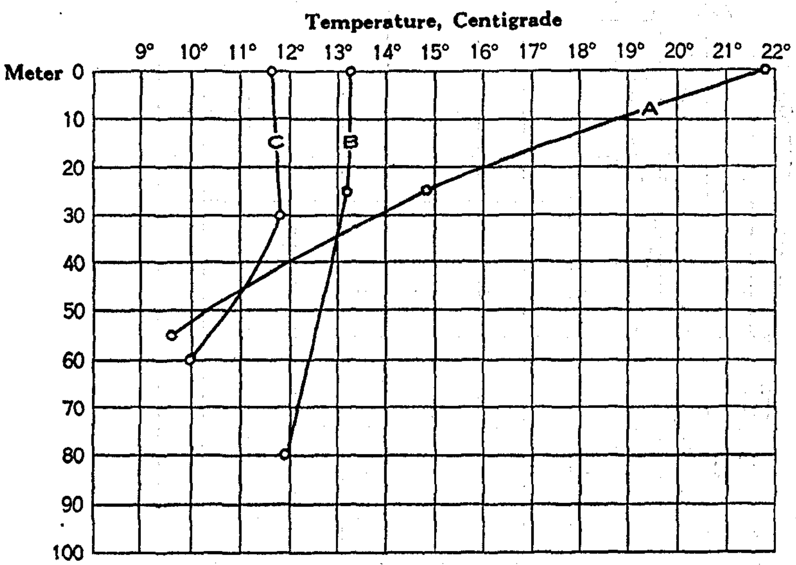

FIG. 73.—Vertical distribution of temperature off Marthas Vineyard to show autumnal cooling. A, August 25, 1914 (station 10259); B, October 22, 1915 (station 10333); C, November 1, 1916 (station 10406)

A thermal distribution of the opposite sort, with a shelf of cold water projecting seaward, has been recorded repeatedly off this part of the slope at the end of the summer.

NOVEMBER AND DECEMBER

In 1912 the whole column of water off Gloucester had become vertically homogeneous in temperature (about 9°) by November 20 (fig. 75), suggesting that autumnal cooling had proceeded at about the same rate there as it did in 1915 and 1916 (p. 638), while the whole column, 70 meters deep, had cooled to about 7.8° to 8.1° by December 4 (station 10048). It is interesting that the immediate surface was 0.1° to 0.3° warmer there than the deeper levels on both these dates, which may have reflected irregularities and setbacks in the progress of cooling from day to day, because both these stations were occupied after one or two warm days, though on

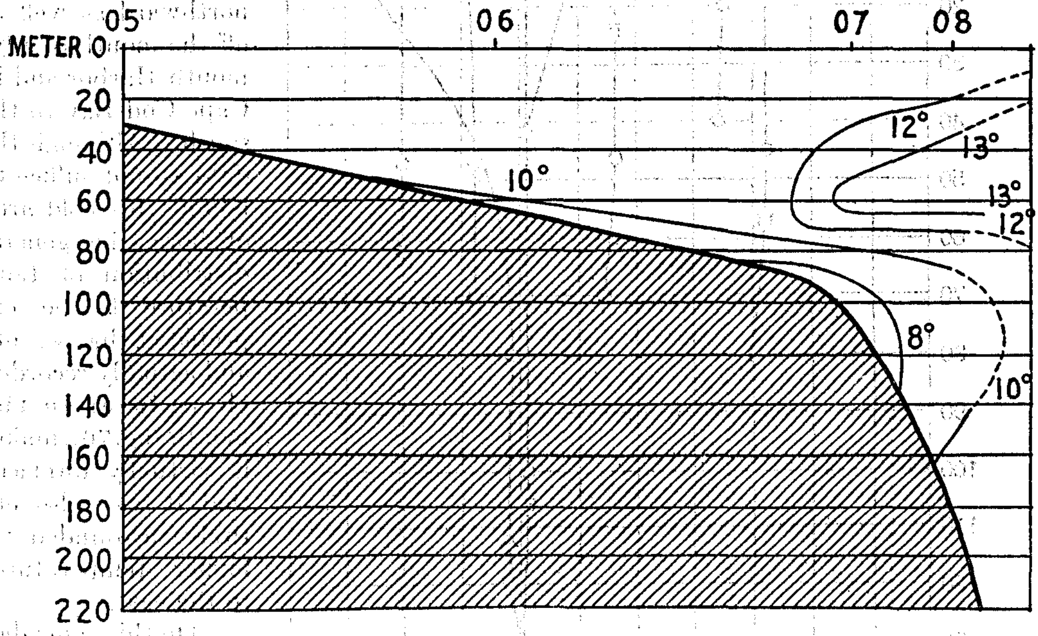

FIG. 74.—Temperature profile crossing the continental shelf off Narragansett Bay, November 10 and 11, 1916 (stations 10405 to 10508)

both occasions the air temperature was a degree or so colder than the water at the times the readings were taken.

The *Fish Hawk* again found the temperature virtually uniform vertically, from surface to bottom, all along the southern side of Massachusetts Bay on Decmber 3, 1925, in depths of 25 to 40 meters; in fact, the surface reading did not differ by more than 0.2° from the intermediate or bottom reading at any of the 10 stations. The progress of autumnal cooling also was made evident by a mean temperature of about 6.2° for this side of the bay. Although the preceding autumn had been unusually mild (suggesting that in most years the sea temperature is a degree or two lower by that date), one station off Plymouth Harbor (No. 10) and two at the head of the bay (Nos. 16 and 17) were then fractionally cooler at the surface than deeper—evidence that the water had been rapidly losing heat from the surface for some days previous, which can be associated with a cold northwest gale on November 23. No great horizontal variation in temperature was to be expected over so small an area; in fact, all the readings for this cruise fell within the limits of 4.80° and 6.93°.

The slight differences recorded from station to station on this cruise prove unexpectedly instructive, because the coldest water (4.8° to 5.8°) then formed a more or less definite pool close inshore, a few miles north of Plymouth, with appreciably higher temperatures (6.8° to 6.9°) to the northward as well as off the mouth of Plymouth Harbor and in Cape Cod Bay to the south. Although the data do not suffice to bound this cold area offshore, the general distribution of temperature to be expected at that season, and actually recorded there later in the month (fig. 76), makes it virtually certain that it was also entirely surrounded by higher temperatures to the east.

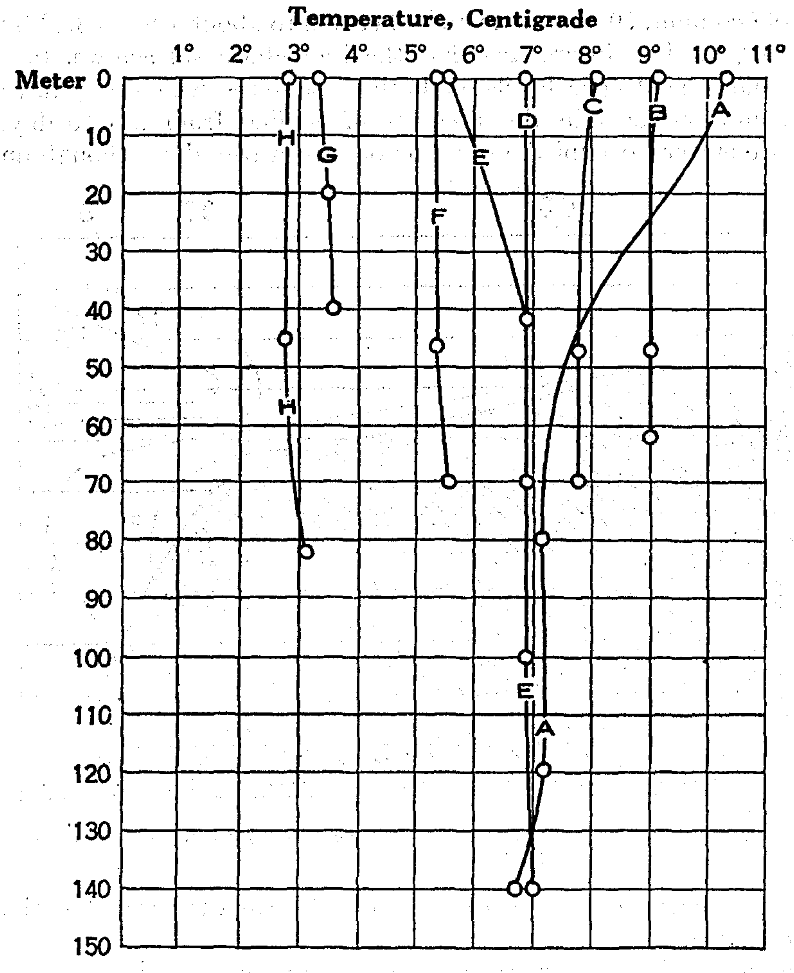

FIG. 75.—Vertical distribution of temperature in the offing of Gloucester on successive dates of the autumn and winter. A, October 1, 1915 (station 10324); B, November 20, 1912 (station 10047); C, December 4, 1912 (station 10048); D, December 23, 1912 (station 10049); E, December 29, 1921 (station 10489); F, January 16, 1913 (station 10050); G, February 9, 1921; H, February 13, 1913 (station 10053)

On this same day (December 3), C. G. Corliss, superintendent of the Gloucester hatchery, found the surface water 4.4° in Gloucester Harbor and 5.6° at a locality 1 to 2 miles off its mouth, a gradation that illustrates the progression of winter cooling from the land out to sea, but does not suggest any considerable thermal difference between the two sides of the bay at the time. Unfortunately, no corresponding readings were taken in the central part; but the water was about 2° warmer 7 miles off Gloucester on December 4, 1913[43] (also a mild year), than in the coastal belt on that same day in 1923. Temperatures of about 5° to 7° may therefore be expected around the shores of Massachusetts Bay, with about 8° in its center, by the first week in December in average years, with the water virtually homogeneous from surface to bottom.

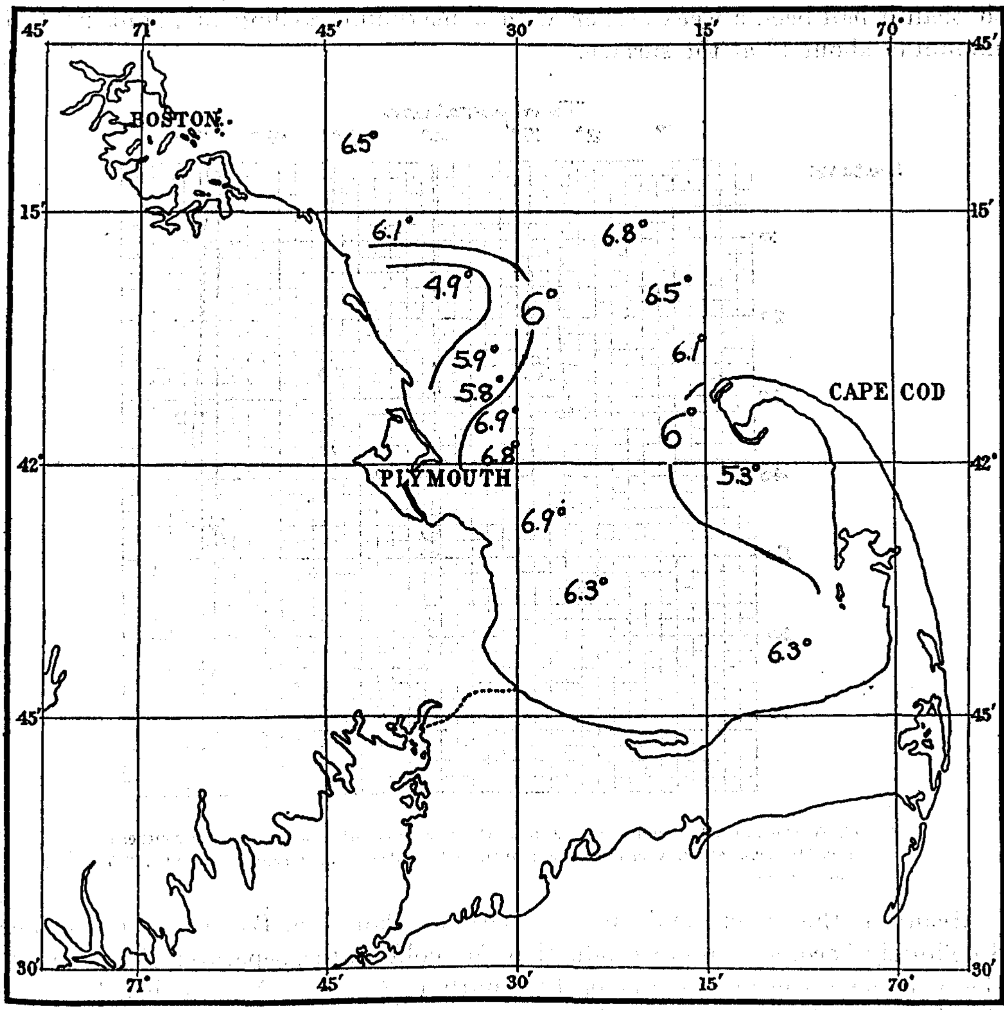

FIG. 76.—Surface temperature of Massachusetts Bay, December 9 to 11, 1924

The data for the *Fish Hawk* stations show that almost no change took place either in the actual temperature of Massachusetts Bay or in its vertical distribution during the first two weeks of December, 1925, the readings being fractionally higher for the second cruise than for the first at some stations, lower at others. The regional distribution remained unaltered, with the coldest water (5° to 6°) taking

[43] Station 10048; 8.1° at the surface, 7.8° at 46 meters and 70 meters.

the form of an isolated pool near the western shore, surrounded by slightly higher temperatures (fig. 76). Equally cold water (about 5.3°, surface to bottom) off the mouth of Provincetown Harbor (station 5) now marked the shallows of the latter as a second center for local cooling.

After cold west winds on December 13, 14, and 15, the whole column of water averaged about 1 degree colder in the southern half of the bay on the 16th and 17th than it had been a week earlier, with a maximum cooling of about 2° and a minimum of about 1° at the surface.

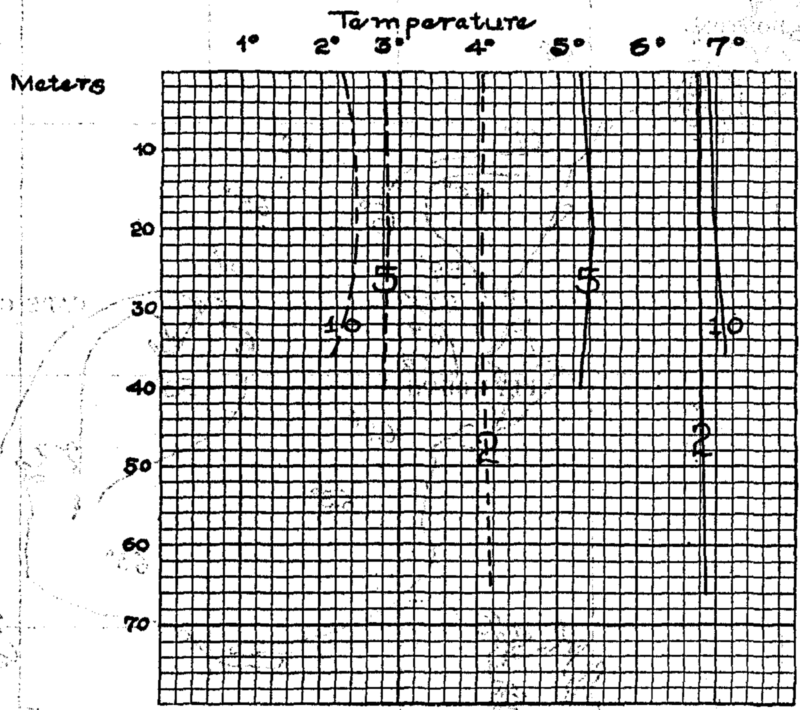

FIG. 77.—Vertical distribution of temperature at three representative stations in the southern side of Massachusetts Bay on December 9 to 11, 1924 (solid curves), and January 6 and 7, 1925 (broken curves).

Meantime the eastern and southern parts of Cape Cod Bay (5° at the surface) had definitely become a site of production for cold water, separated from the still colder pool next the land north of Plymouth (3.8° to 4.5°) by a slightly warmer wedge (5° to 6°) in the center of the bay. At this season the water of the bay is so nearly homogeneous, surface to bottom (fig 77), that a chart of the minimum temperature, irrespective of depth (fig. 78), illustrates this regional distribution better than a surface chart can.

When the temperature varies more widely between stations a few miles apart than between surface and bottom at any one station, as is the case in the southern

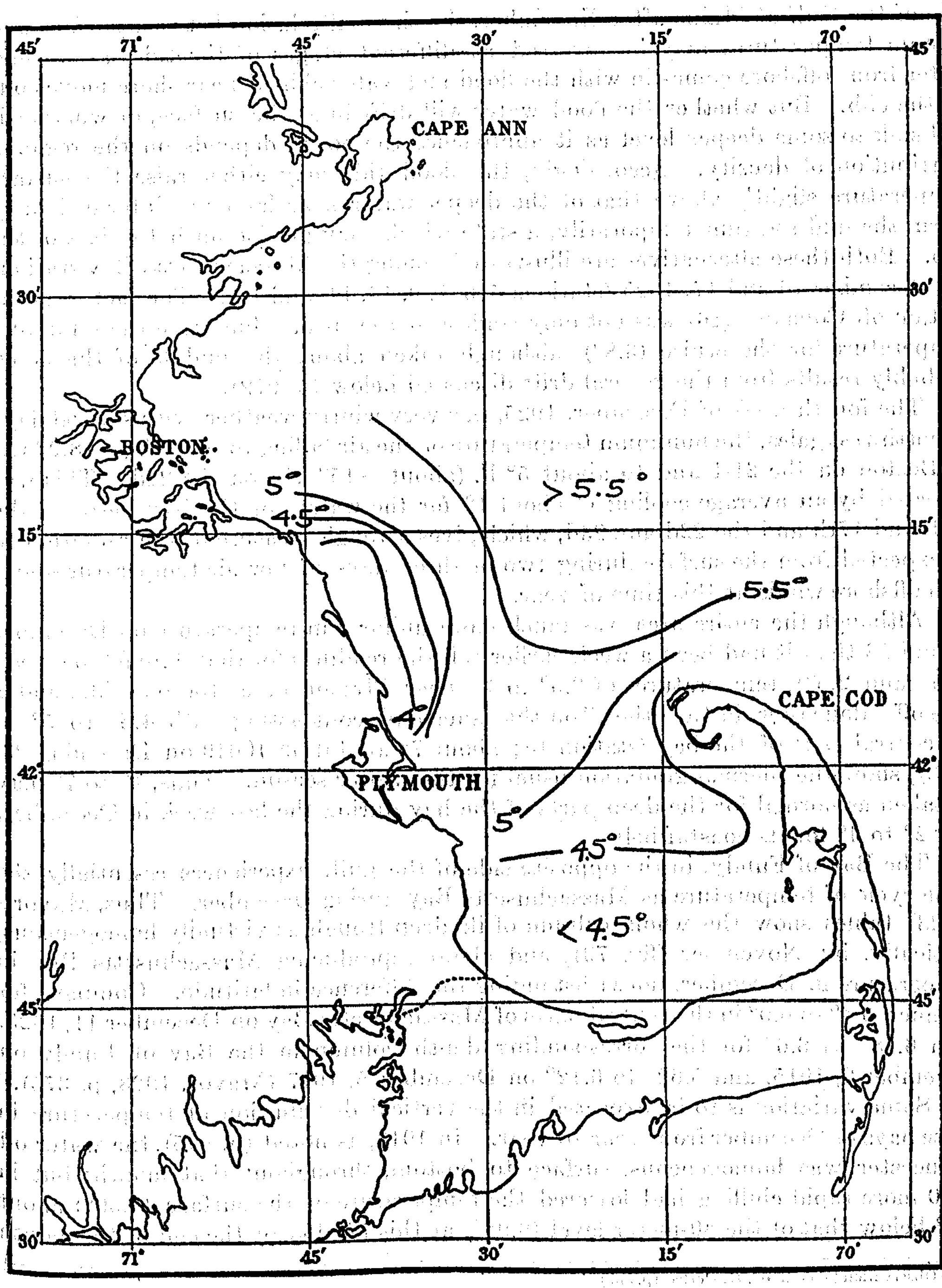

FIG. 78.—Minimum temperature of the southern side of Massachusetts Bay, irrespective of depth, December 16 and 17, 1924

side of the Gulf of Maine after November, the thermal relation between surface and bottom temperatures may be reversed at different stages of the tide, as warmer water from offshore comes in with the flood and water chilled near shore moves out on the ebb. But whether the flood water will drift in at the surface, or whether it will sink to some deeper level as it approaches the coast, depends on the regional distribution of density. Accordingly, the flood tide may either raise the surface temperature slightly above that of the deeper water near land in winter or it may warm the mid stratum temporarily, a state which may persist until the last of the ebb. Both these alternatives are illustrated among the Massachusetts Bay stations for December 16 and 17, 1925 (stations 5, 6, 7, 9, 13, 14, and 17). The fact that the station off Cohasset (16) was not only coldest at the surface but gave the minimum temperature for the cruise (3.8°), although taken about the middle of the flood, probably results from the general drift discussed below (p. 972).

The fourth week of December, 1925, saw very wintry weather, with several days of northwest gales, the minimum temperature of the air falling to −1° F. (−18.2° C.) at Boston on the 21st and to about 5° F. (about −15° C.) on the 22d. This was reflected by an average cooling of about 1° for the waters of the bay between the 16th and 17th and the 22d and 23d, which gives a rough measure of the radiation to be expected from the surface during two or three days of low air temperatures and high offshore winds at this time of year.

Although the entire area was much more uniform in temperature on December 22 and 23 than it had been a week earlier (all the readings for that date fell between 4.95° and 2.5°), temperatures of 2.5° to 3° near Plymouth, in the one side, and a mile off Gloucester, in the other,[44] on the same day, contrasting with 4.5° to 5° in the central part of the bay (station 18; about 7° at station 10049 on December 23, 1913), show the thermal gradation usual for the winter season. Thus, 4° to 7° may be taken as normal for the deep parts of the bay during the last week in December, and 2° to 4° for its coastal belt.

The Bay of Fundy, in the opposite side of the gulf, experiences essentially the same cycle of temperature as Massachusetts Bay during December. Thus, Mavor's (1923) tables show the whole column of its deep trough as virtually homogeneous, vertically, by November (fig. 79), and about reproducing Massachusetts Bay in temperature in December, notwithstanding the difference in latitude. Compare, for instance, 6.4° to 6.9° in the central parts of Massachusetts Bay on December 11, 1925, with 6.18° to 6.6° for the corresponding depth column in the Bay of Fundy on December 2, 1915, and 5.62° to 6.12° on December 5, 1917 (Mavor, 1923, p. 375).[45]

Some variation is to be expected in the vertical distribution of temperature in these bays in December from year to year. In 1913, as noted (p. 645), the water off Gloucester was homogeneous, surface to bottom, throughout that month; but in 1920 more rapid chilling had lowered the temperature of the surface (5.56°) about 1.5° below that of the 40-meter level (6.94°) at this locality by the end of the month

[44] Observation taken by C. G. Corliss (p. 513.)

[45] Mavor (1923) records 6.11° for the surface, 6.42° at 50 meters, and 6.6° at 175 meters on Dec. 2, 1916; 5.62° at the surface, 5.72° at 50 meters, 6.16° at 100 meters, and 6.18° at 175 meters on Dec. 5, 1917.

(station 10489), and the Bay of Fundy was also fractionally colder at the surface than a few meters down at this season in 1916 and 1917.

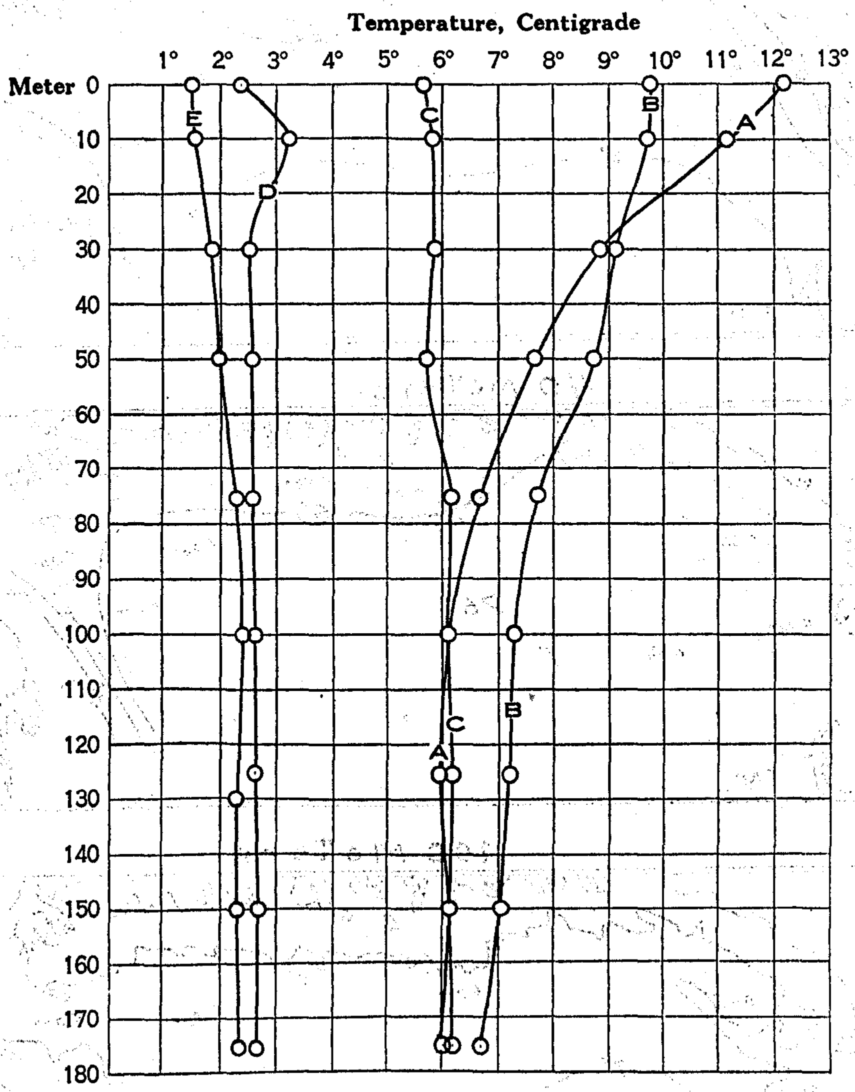

FIG. 79.—Vertical distributions of temperature at *Prince* station 3, in the Bay of Fundy, in autumn and winter, from Mavor's (1923) data. A, September 4, 1917; B, October 2, 1917; C, December 5, 1917; D, January 19, 1918; E, February 28, 1917.

MIDWINTER

The records obtained by the *Halcyon* during the last days of December, 1920, and first half of January, 1921 (stations 10488 to 10503), represent the distribution of temperature in the inner part of the open gulf for a midwinter neither unusually cold nor unusually mild.

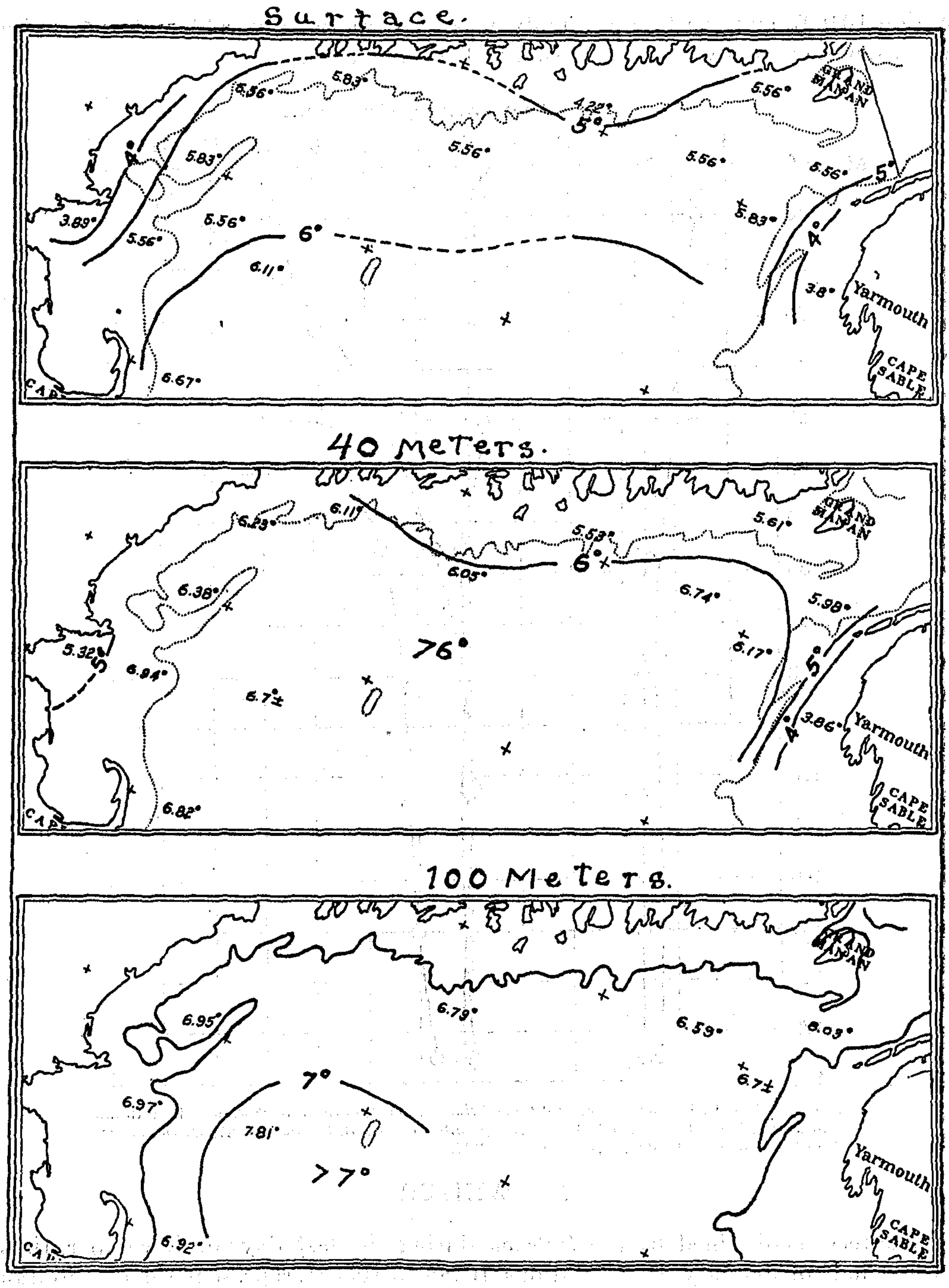

FIG. 80.—Temperature of the northern part of the gulf on the surface (upper chart), at 40 meters (middle chart), and at 100 meters (lower chart), December 29, 1920, to January 9, 1921.

These several midwinter stations (fig. 80), combined, show that at this season any line run normal to the coast of the gulf would lead from lower surface temperatures out into slightly warmer water, with the surface then coldest (below 1°), locally, close in to the land between Boston and Cape Elizabeth on the one side of the gulf, and along Nova Scotia on the other; slightly warmer than 4° along the intervening coast sector, outside the outer islands, and about 6° on the central and southern parts of the basin (fig. 80); but the temperature may fall as low as 1° among the islands by the end of December, as happened at Boothbay and in Lubec Channel in 1919 (figs. 30 and 31).

These local differences result from the topography of the coast line, from the local winter climate, and from differences in the activity of vertical stirring by the tides. Thus, the surface chills more rapidly at the head of Massachusetts Bay than along the open coast of Maine because less actively mixed by the tides with warmer water from offshore and from deeper levels. Chilling takes place most rapidly of all in the sounds and harbors, because their enclosure prevents free interchange with the water outside.

In midwinter the surface is, as a whole, the coldest level, though differing by less than 1° from the warmest stratum at most of the stations. Thus, the inner part of Massachusetts Bay (station 10488) had cooled to 3.89° at the surface on December 29, with 5.86° on the bottom in 60 meters. In the bowl off Gloucester the readings were 5.56° at the surface and 6.9° to 7° from 40 meters down to the bottom in 150 meters, the latter almost precisely reproducing the temperature recorded there on December 23, 1912 (fig. 75). The surface was about 0.5° warmer 15 miles off the northern end of Cape Cod (station 10491), but the 100-meter level was about 0.1° cooler. The vertical distribution of temperature was the same near the land, off the mouth of the Merrimac River (station 10492), as near the head of Massachusetts Bay, and with the actual values nearly alike, while the trough off the Isles of Shoals (station 10493, fig. 70) agreed equally with the sink station off Gloucester just mentioned.

The vertical range of temperature was only about 0.2° off Seguin in about 80 meters depth on December 31, 1920 (station 10495, 5.83° on the surface, 6.1° at 40 meters, and 6.1° at 75 meters); but a few miles farther out from the influence of the land off the mouth of Penobscot Bay, the next day (station 10496), where the water is less subject to tidal stirring, the temperature curve closely paralled that for the Isle of Shoals station 2 days previous in the upper 100 meters (5.6° at the surface, 6.05° at 40 meters, and 6.79° at 100 meters), but showed a slight vertical warming at greater depths to 7.5° on the bottom in 150 meters. Surface (4.7°) and 90-meter readings (5.7°) differed by about this same amount close in to Mount Desert Island (station 10497). However, the temperature was uniform, surface to bottom, a few miles off Machias (station 10498, 5.56° to 5.61°), a state approximated here throughout the year.

In the Fundy deep the *Halcyon* found the whole column about 1° to 2° warmer on January 4, 1921 (station 10499), than Mavor (1923) records it for January 3, 1916; in fact, agreeing more closely with his temperatures for December 5, 1918, in spite of the difference in date, as follows:

Depth	Station 10499	Prince station 3, Jan. 3, 1917[1]
	°C.	°C.
Surface	5.56	3.69
50 meters	[2]6.00	4.56
100 meters	6.03	5.30
175 meters	[2]6.80	4.59

[1] From Mavor, 1923. [2] Approximate.

Apparently the waters along the western shores of Nova Scotia are about as cold as the inner part of Massachusetts Bay in the first week in January, judging from 1921, when the temperature was uniformly 3.8° to 3.9°, surface to bottom, a few miles off Yarmouth (station 10501) on the 4th; or about the same at the surface as the reading off the mouth of Boston Harbor 5 days previous, with no wider difference at 20 to 40 meters than can be accounted for by more active vertical circulation and by this difference in date.

In the northeastern part of the trough, on January 5 (station 10502), the surface was coldest (5.56°) overlying a uniform stratum (6.6° to 6.7°) at 40 to 100 meters, with slightly warmer water (6.9° to 7.2°) at still greater depths; but readings taken in the western side of the basin for January 9 showed the water about 2° warmer at 100 to 150 meters than either the surface or the bottom (station 10503).

Thus, the level that is coldest in the western side of the basin in summer is warmest in midwinter—about 2.5° warmer, in fact (7.5° to 7.8°), than we have ever found it in August. A serial for late November is required for a correct picture of the autumnal change there; but the fact that the salinity of the 100-meter level was higher at this locality in December, 1920, than we have ever found it in August, September, or October (fig. 138), suggests that the temperature of its warm stratum had been maintained at about the November value (about 8°) throughout December by additions of warmer and more saline water from the southeastern part of the gulf, while the surface stratum had cooled. This reconstruction is corroborated, also, by the fact that while the surface continued to chill (about 0.5°) during the interval between December 29 (station 10490) and January 9 (station 10503), the 100-meter level warmed by about 0.5°, the 150-meter temperature rose by about 1.5° during the interval, with no corresponding increase in salinity (p. 994).

In horizontal projection the midwinter serials just discussed show the 40-meter level coldest (3.86°) in the eastern side of the gulf, off Yarmouth, Nova Scotia; 4° to 6° in Massachusetts Bay, along the coast of Maine east of Penobscot Bay, and at the mouth of the Bay of Fundy; 6° to 7° elsewhere (fig. 80). The temperature was regionally as uniform at 100 meters, also, varying only from 6.03° to 7.81° over the whole area—coldest in the mouth of the Bay of Fundy. At 200 meters, however, the regional distribution of temperature (also of salinity—p. 804), was just the reverse, being warmest (6.9° to 7°) in the northeastern branch of the basin and the Bay of Fundy and coldest in the western side of the basin off Cape Ann (5.3° to 5.6°).

No serial temperatures have been taken in the open basin of the gulf during the last half of January or the first three weeks of February, but records for the vicinity of Gloucester in 1913, for the southern side of the Massachusetts Bay region in 1925 and for the Bay of Fundy region show that the water continues to cool during these months. In 1924–25 cold weather at about Christmas was reflected in the southern half of Massachusetts Bay by temperatures about 2.5° lower on January 6 and 7 than they had been on December 22 and 23, the mean temperature having fallen to about 2.5° to 2.6°, surface to bottom.[46]

Large amounts of ice formed in the southeastern side of Cape Cod Bay during the low temperatures and northwest gales of the last week of that December, until it was packed several feet high on the flats and along the beaches south of Wellfleet, reaching for a mile or more offshore as I saw it on the 29th. Its chilling effect is reflected in the fact that the temperature of the water was much lower (0.3° on the surface, 0.25° on bottom in 13 meters) off Billingsgate Shoal on January 7 (*Fish Hawk* cruise 5, station 7) than at the other stations for that cruise.

The surface temperatures for this January cruise (fig. 81) are also instructive as an illustration of the gradation from lowest readings of 0.5° to 2.5°, close in to the shore, to warmer water (4° to 5°) in the center of the bay, characteristic of the season. A reading of 2.78° a mile off the mouth of Gloucester Harbor on this same date shows that the coldest band was continuous right around the coast line of the bay, as it had been the month before (p. 650).

Probably the mouth of the bay, generally, and the open basin in its offing are usually about 5° to 5.5° in temperature at the second week of January at all depths, judging from readings of 5.3° to 5.6°, surface to bottom, in 70 meters off Gloucester on the 16th of the month in 1913 (station 10050).

On January 6 and 7, 1925, the surface (fig. 81) was slightly cooler than the bottom at the four stations in the central part of Massachusetts Bay (*Fish Hawk* cruise 5, stations 19, 18, 2, and 4) and in the eastern side of Cape Cod Bay (station 6), fractionally warmer than the bottom in the southern part of the latter and along the Plymouth shore. Nor is the cause for this slight regional difference clear, for most of the stations of the second group, as well as of the first, were occupied on the ebb tide.

On January 9, 1920, Gloucester Harbor was between 0° and 1° (fig. 29), Boothbay Harbor fractionally colder than 0° (fig. 30), and Lubec Narrows about 0° (fig. 31), showing that the temperature falls about equally fast in such situations all around the western and northern shores of the gulf in spite of the difference in latitude.[47] The water is also about as cold at Woods Hole at this season (Sumner, Osburn, and Cole, 1913; Fish, 1925).

Massachusetts Bay is coldest during the first half of February; and this probably applies to the gulf as a whole. The precise date when the temperature fell to its minimum can not be stated for any of the years of record (no doubt this varies from year to year, as well as regionally), but the readings taken in the bay on February 6 and 7, 1925 (*Fish Hawk* cruise 6), were close to the coldest for that particular winter.

On this date the surface of the southern side of the bay (mean temperature about 0.75°) averaged about 2° colder than it had on January 6 and 7, though the regional distribution of temperature (fig. 82) continued reminiscent of the late December

[46] The mean temperature of the air had been below normal at Boston on every day save three since Dec. 19.

[47] Gloucester Harbor, 42° 35′ N; Lubec Narrows, 44° 49′ N.

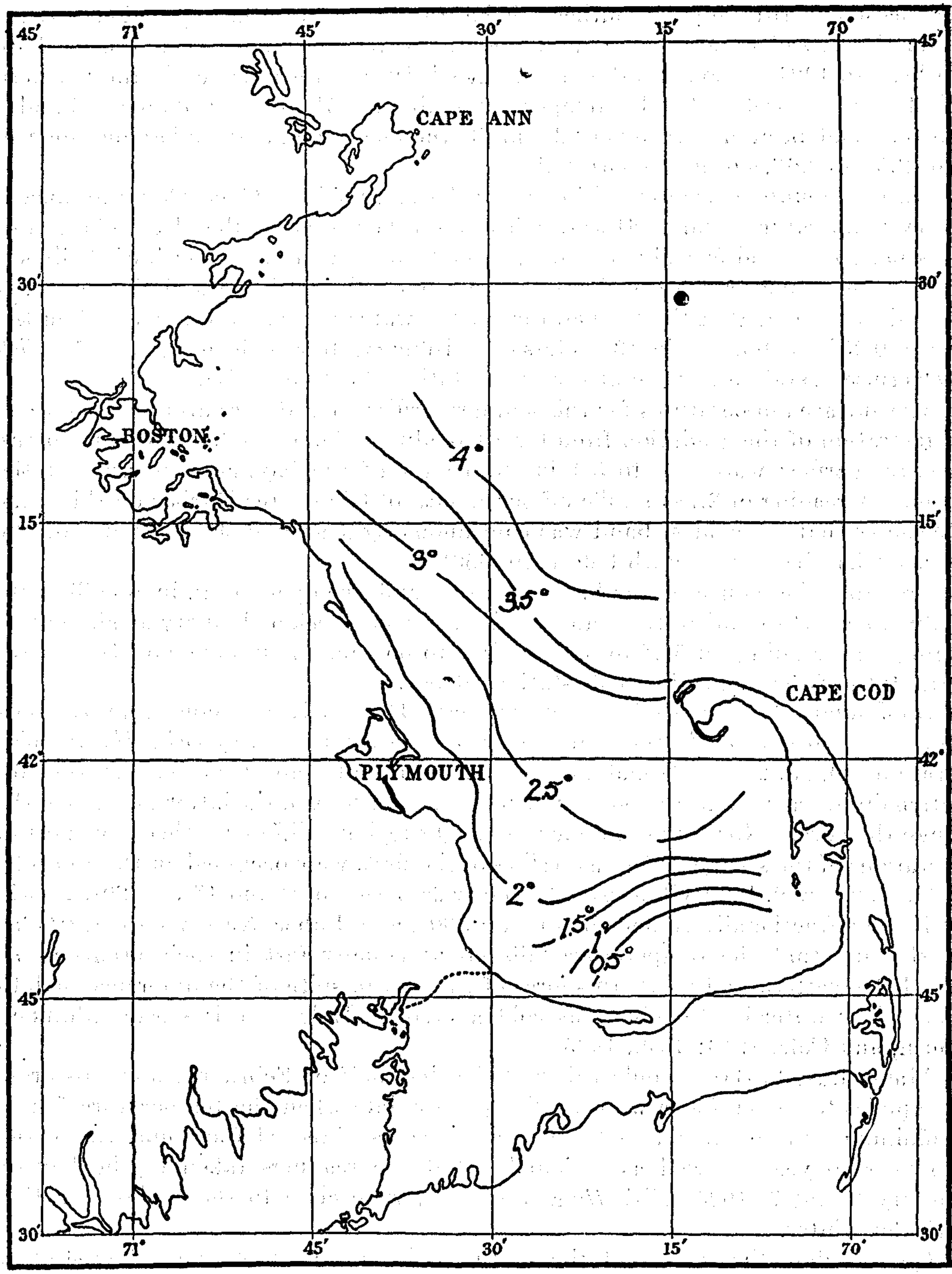

FIG. 81.—Surface temperature of the southern side of Massachusetts Bay, January 6 and 7, 1925

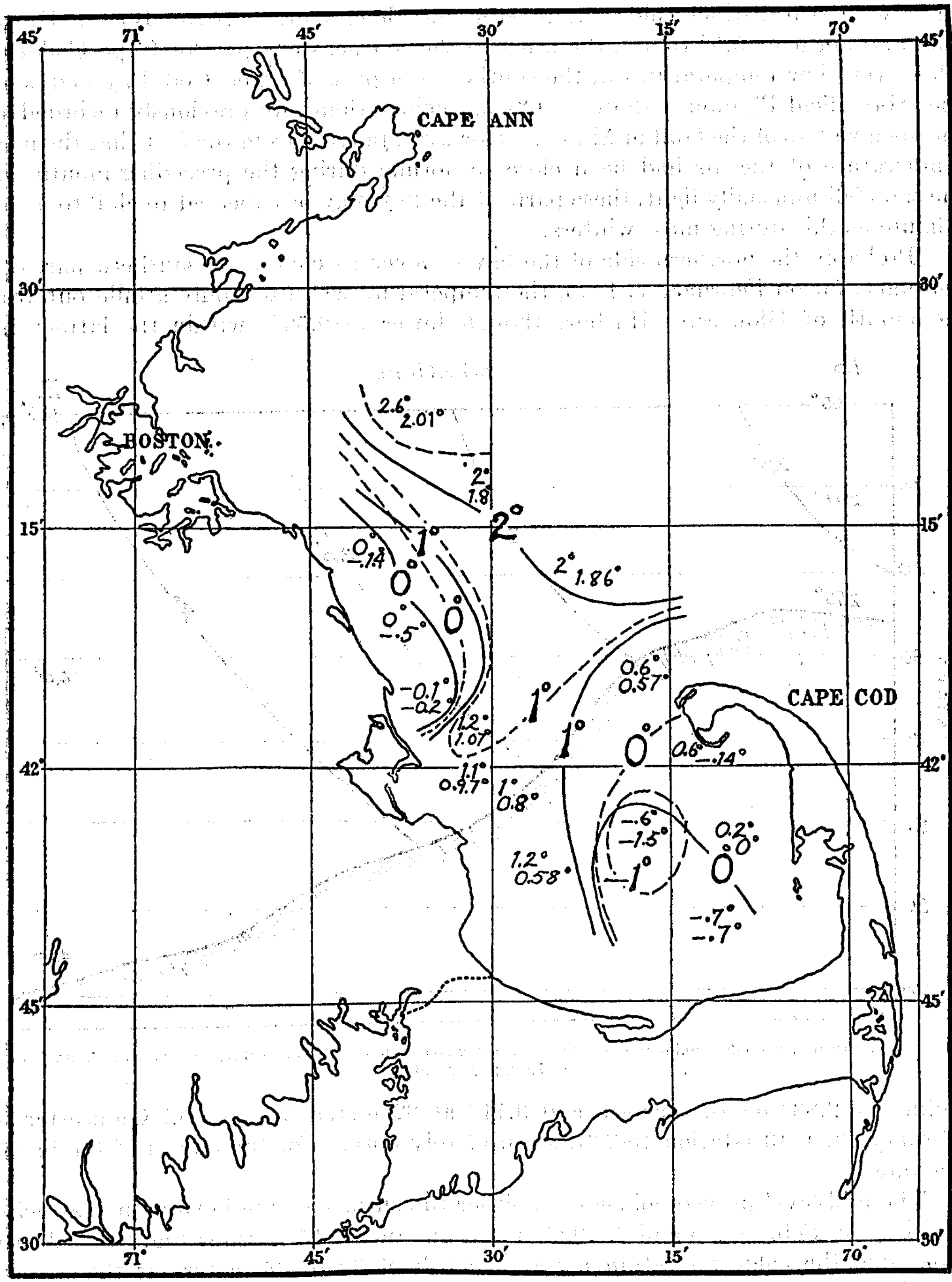

FIG. 82.—Surface temperature (solid curves) and minimum temperature (broken curves) of the southern side of Massachusetts Bay, February 6 and 7, 1925

state, with two distinct cold centers—the one along shore between Boston Harbor and Plymouth (−0.5° to 0°), the other in the southeastern part of Cape Cod Bay. These very low temperatures in the southeastern part of Cape Cod Bay and along the Marshfield-Plymouth shore (<0°) are colder than any previously recorded for the open waters of the Gulf of Maine. However, judging from the fact that the mean temperature of the air had been close to normal during the preceding month, and the snowfall unusually light, these parts of the bay may be expected to chill to as low a figure as this during most winters.

Probably the northern side of the bay is never as cold as its southern part is in February, for on February 7, 1925, the temperature was 1.67° only a mile out from the mouth of Gloucester Harbor, though lower (−0.56°) within the latter; and

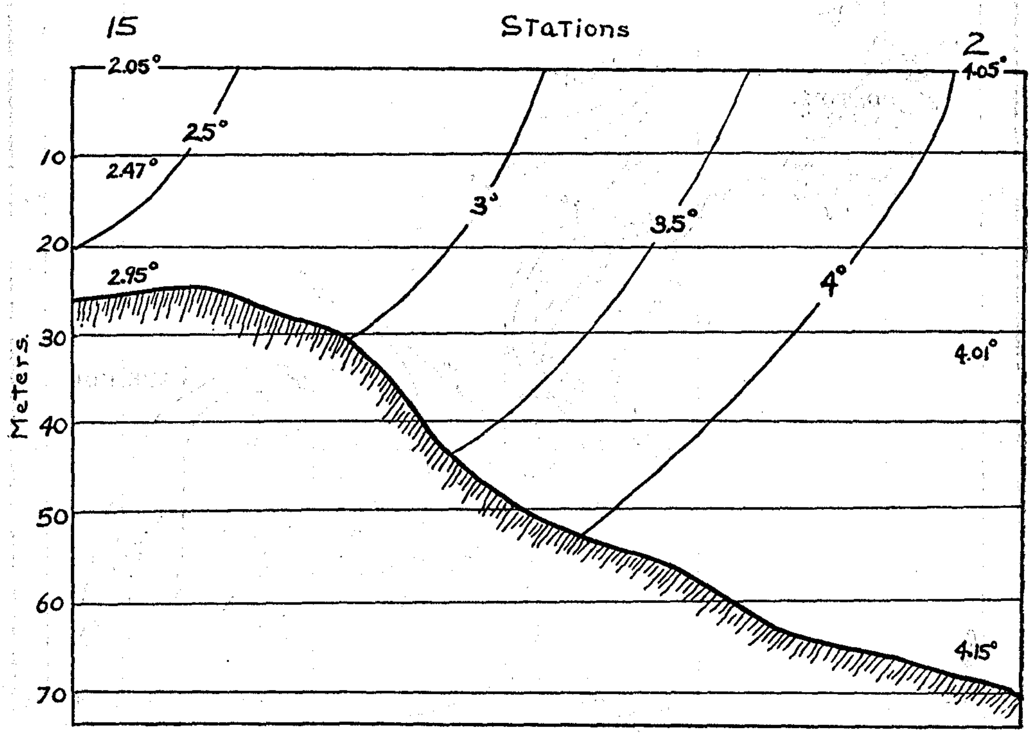

FIG. 83.—Temperature profile running from the Marshfield shore out into Massachusetts Bay, January 6 and 7, 2925 (*Fish Hawk* stations 2 and 15)

readings of 2.83° on the surface and 3.11° at 82 meters 7 miles off Gloucester on February 13, 1913 (station 10053), are probably normal for the mouth of the bay at this date.

The mid-level proved colder than either the surface or the bottom in Massachusetts Bay on February 6 and 7, 1925, at 12 out of the 15 stations (fig. 82). At the same time the coldest stratum lay at a depth of 30 to 35 meters at the offshore line (*Fish Hawk* cruise 6, stations 19, 18, 2, and 4) but within 10 to 15 meters of the surface near the Plymouth-Marshfield shore.

Profiles running out from the land off Marshfield for January 6 and 7 (fig. 83) and for February 6 and 7 (fig. 84) show a very interesting succession, with the water that had been cooled near shore moving out from the land and at the same time sinking, to develop a shelflike intrusion into the warmer water of the center of the bay. The profiles also suggest that the coldest water was produced even closer in to the coast line than the innermost of the two stations, and that the whole column was colder than 0° next this sector of the coast at about the end of January, down to a depth of 10 to 15 meters.

In 1925 the southern side of Massachusetts Bay had experienced its minimum temperature for the winter and had commenced to warm again by the last week in February, when the mean temperature of the surface (1.65°) was nearly 1° higher than it had been two weeks earlier, with a corresponding rise in mean bottom

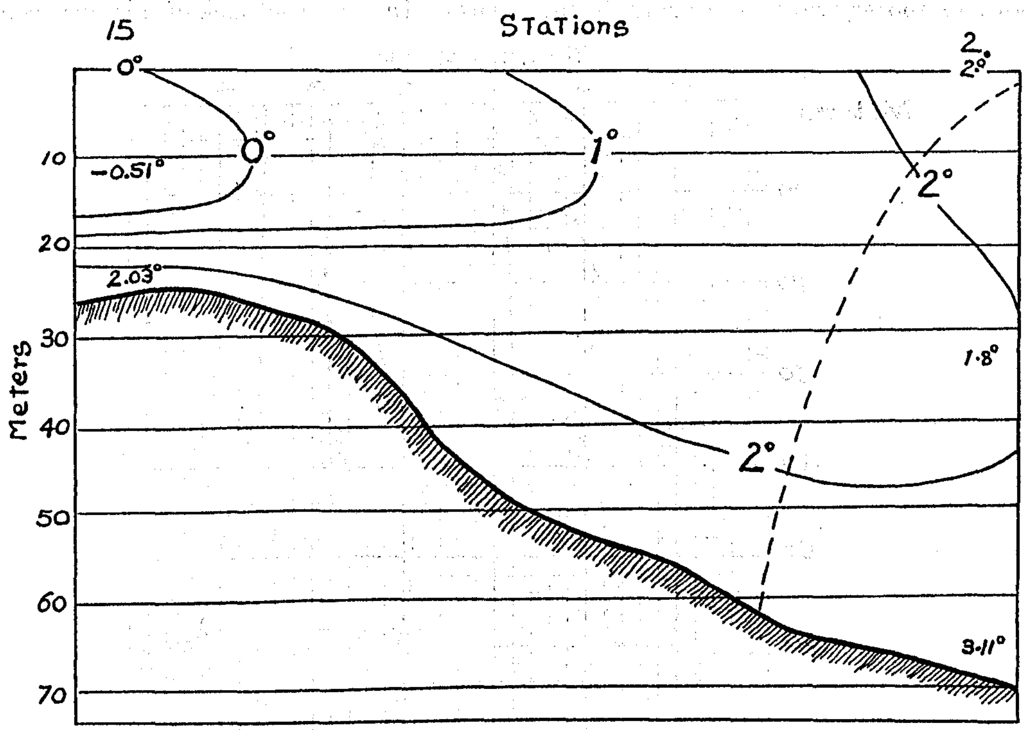

FIG. 84.—Temperature profile running from the Marshfield shore out into Massachusetts Bay, February 6, 7, and 27, 1925. The broken curve is the isotherm for 2° on February 24

temperature from 0.95° to 1.68°. On the 24th the whole surface of the bay was close to 2° in temperature, a regional uniformity illustrated by readings of 2.2° a mile or two off Gloucester, in the one side of the bay, with 2° to 2.1° in the central parts and 2.3° near Provincetown (station 5) in the other side. The offshore drift of water, chilled next the Plymouth shore, had also slackened, if not entirely ceased (fig. 84).

The vertical distribution of temperature off Provincetown (*Fish Hawk* station 5) on February 24 is interesting because the bottom reading was the highest (2.34°) recorded for any level at any of these late February stations. A 40-meter salinity of about 33 per mille at 40 meters there, contrasted with 32.7 to 32.8 per mille in the central part of the bay, shows that some inflow through the bottom of the channel that separates Cape Cod from Stellwagen Bank was responsible for this unexpected warmth of the bottom water at the tip of the cape.

The facts that the inshore stations for the last week of February were slightly warmer at all levels than they had been three weeks previous, and that the water was slightly warmer inside Gloucester Harbor (2.78°) than a mile or two off the mouth (2.2°), instead of the reverse, are sufficient evidence that the coastal belt had begun to gain heat from the sun faster than it was losing heat by radiation from its surface. This gain was not yet rapid enough, however, to have produced any general differentiation in temperature between surface and underlying water in the moderate depths of Massachusetts Bay; and periods of severely cold weather may be expected to cause temporary reversals during the first weeks. In fact, a setback of this sort seems

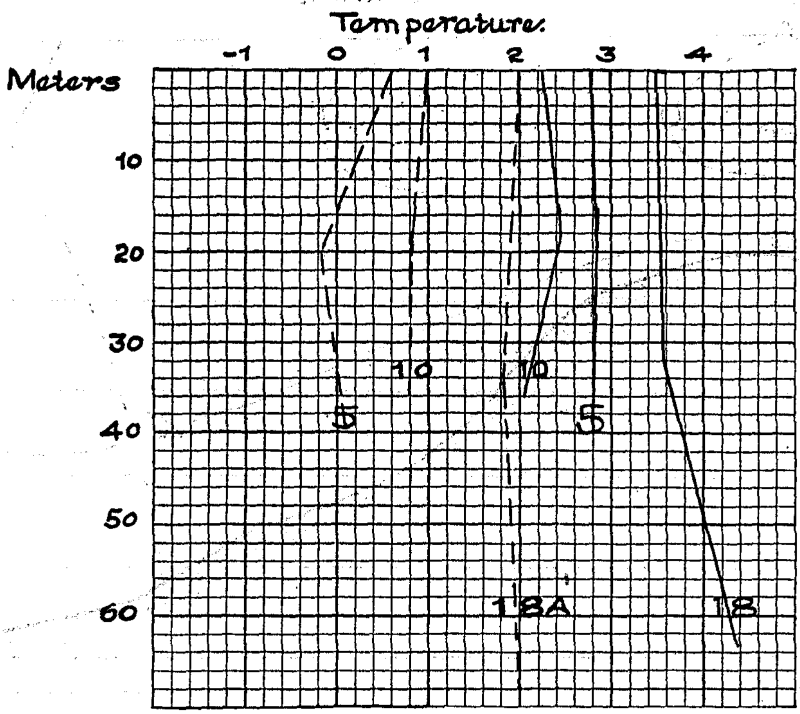

FIG. 85.—Temperature at three representative stations (5, 10, and 18 to 18A) in the southern side of Massachusetts Bay on January 6 and 7, 1925 (solid curves), and on February 6 and 7 (broken curves), to show change in one month

to have occurred between the 25th and 27th of that February, because the *Fish Hawk* once more found the water off the mouth of Plymouth Harbor coldest at the surface on the latter date, after three days of severe cold accompanied by a northwest gale. Thus, the shoals seem to have acted as a temporary center for cooling there, as might be expected.

The winter of 1912–13 seems to have been about as cool as 1924–25 in Massachusetts Bay, minimum temperatures slightly higher (2.8° at surface and at 46 meters, 3.11° at 82 meters, February 13, 1913) being associated with the situation of the standard station well out in the mouth of the bay. February, 1921, was measurably warmer, with 3.3° at the surface, 3.52° at 20 meters, and 3.63° at 40 meters 1½ miles off Gloucester Harbor on the 9th (p. 994), where the surface reading was 1.67° on the 6th in 1925. After the almost Arctic February of 1920, the *Albatross* found the surface about 1.1° on March 1 on the run from Boston out to station 20050 at the mouth of the bay, and the open gulf correspondingly low in temperature, as described above (p. 522).[48]

It is also probable that the temperature of the water did not begin to rise in 1920 until after the first of March, instead of gaining heat from the middle of February, as happened in 1913 and in 1925; but rising temperatures may be expected in Massachusetts Bay by the last of February in all but the tardiest seasons.

It would be interesting to compare the midwinter temperature of Massachusetts Bay with that of the Bay of Fundy in the opposite side of the gulf. Unfortunately, the winter data so far available do not sufficiently establish the relationship between the two regions because they are for different years, except that there is no great difference between them at the coldest season.

Depth	Massachusetts Bay Feb. 6 and 7, 1925		Feb. 13, 1913, off Gloucester, station 10053	Feb. 7, 1917, Bay of Fundy (Mavor, 1923)
	Fish Hawk Station 18A	Fish Hawk Station 2		
	°C.	°C.	°C.	°C.
Surface	2.00	2.00	2.83	1.46
30 meters				1.99
30–34 meters	1.85	1.81		
46 meters			2.78	
50 meters				2.44
64–68 meters	2.00	3.10		
75 meters				3.12
82 meters			3.11	

Passamaquoddy Bay, tributary to the Bay of Fundy, seems also to correspond closely to Cape Cod Bay in minimum temperature, its inclosed situation so exposing it to climatic chilling that its surface falls close to the freezing point. Thus, Doctor McMurrich's notes (p. 513) record a temperature of about −1.7° at St. Andrews from February 16 to March 3 in the very cold winter of 1916, compared with a minimum of −1.55° in Cape Cod Bay on February 6 and 7 of the more moderate season of 1925 (*Fish Hawk* cruise 6, station 6A). Willey (1921) also records −0.77° at 20 meters depth in Passamaquoddy Bay on February 23 1917, which is about the expectation for Boston Harbor and probably for the inner parts of Casco Bay and of Penobscot Bay.

Neither is the difference of latitude between the Bay of Fundy and Massachusetts Bay accompanied by more than a week's difference, or so, between the dates when vernal warming becomes effective in the two regions. Thus, the trough of the Bay of Fundy commenced to warm about the first of March in 1917 (Mavor, 1923), and while Doctor McMurrich's plankton notes for St. Andrews do not show a rise in temperature until the end of that month in 1916, this was even a more tardy spring than 1920.

[48] The surface of Massachusetts Bay is recorded as 3.3° on Feb. 24, 1920 (Bureau of Fisheries Document No. 897, p. 183); but this is simply the quartermaster's record.

During the winter of 1919–20 the water of Gloucester Harbor (fig. 29) chilled to about −1.5° and was colder than 0° from about January 12 to March 20; Boothbay Harbor (fig. 30) chilled nearly to −2° and was below 0° from January 5 to March 5; Lubec Narrows (fig. 31), where tidal mixture with the water outside is more active, chilled to about the same temperature as Gloucester and was colder than zero for a slightly longer period—January 5 to March 20. In such situations, then, the strength of the tides and the frequency with which the water is renewed from outside govern the minimum to which the temperature drops in winter more than the latitude does.

THERMAL SUMMARIES

Summaries of the thermal cyles for the following representative localities are given: (1) Mouth of Massachusetts Bay, off Gloucester; (2) the Fundy Deep, between Grand Manan and Nova Scotia; (3) near Mount Desert Island; and (4) the western side of the basin of the gulf in the offing of Cape Ann.

1. MOUTH OF MASSACHUSETTS BAY, OFF GLOUCESTER

Temperatures at various dates, to 0.1°, some by direct observation and others by interpolation

Depth	Mar. 1, 1920 20050	Mar. 4, 1913 10054	Mar. 19, 1924	Apr. 7, 1925, Fish Hawk station 31	Apr. 3, 1913 10055	Apr. 9, 1920 20090	May 4, 1920 20120
Surface	2.5	2.9	2.2	4.1	4.1	3.3	6.4
20 meters	1.9	2.9	1.9	3.4	4.1	2.5	4.7
40 meters	1.9	3.0	1.8	3.0	4.0	2.4	4.3
70 meters	1.7	3.4	1.8	2.8	4.0	2.4	2.7
100 meters	1.5	----------	----------	----------	----------	2.3	----------

Depth	May 4, 1915 10266	May 16, 1920 20124	May 26, 1915 10279	June 16–17, 1925 Fish Hawk station 31	July 10, 1912 10341	July 19, 1916 10341	Aug. 9, 1913 10087
Surface	6.1	9.7	10.0	12.9	18.3	16.4	16.7
20 meters	4.0	5.1	7.2	5.5	9.0	6.0	10.4
40 meters	3.6	2.9	5.2	4.0	6.6	4.1	6.7
70 meters	3.6	2.8	3.8	3.6	4.6	3.7	6.3
100 meters	3.6	2.7	----------	----------	4.6	----------	5.2

Depth	Aug. 22, 1914 10253	Aug. 22, 1922 10632	Aug. 22, 1922 10633	Aug. 31, 1915 10306	Sept. 29, 1915 10320	Oct. 1, 1915 10324	Oct. 27, 1915 10339
Surface	18.9	18.00	18.7	16.1	10.5	10.3	10.8
20 meters	12.0	9.10	12.3	12.0	10.6	10.0	----------
40 meters	6.5	7.40	7.0	8.3	10.1	9.0	----------
70 meters	5.3	4.70	----------	6.7	7.0	7.5	7.3
100 meters	4.6	----------	----------	6.0	----------	7.1	----------

Depth	Oct. 31, 1916 10399	Nov. 20, 1912 10047	Dec. 4, 1912 10048	Dec. 23, 1912 10049	Dec. 29, 1920 10489	Jan. 16, 1913 10050	Feb. 9, 1921 10504	Feb. 13, 1913 10053
Surface	10.0	9.2	8.1	6.9	5.6	5.4	3.3	2.8
20 meters	9.6	9.0	7.8	6.9	6.0	5.4	3.5	2.8
40 meters	8.2	9.0	7.8	6.9	6.9	5.3	3.6	2.8
70 meters	6.1	----------	7.8	6.9	6.9	5.6	----------	3.0
100 meters	5.4	----------	----------	----------	7.0	----------	----------	----------

In this region (fig. 86) the most obvious seasonal change is the very rapid warming of the surface, which takes place from the end of the winter until about the end of July, resulting (on the average) in a rise of nearly 17°. After the first month or so of vernal warming (March to April), during which the whole column warms nearly uniformly, the rate at which the temperature rises becomes inversely proportional to the depth; and it so continues throughout the spring and summer,

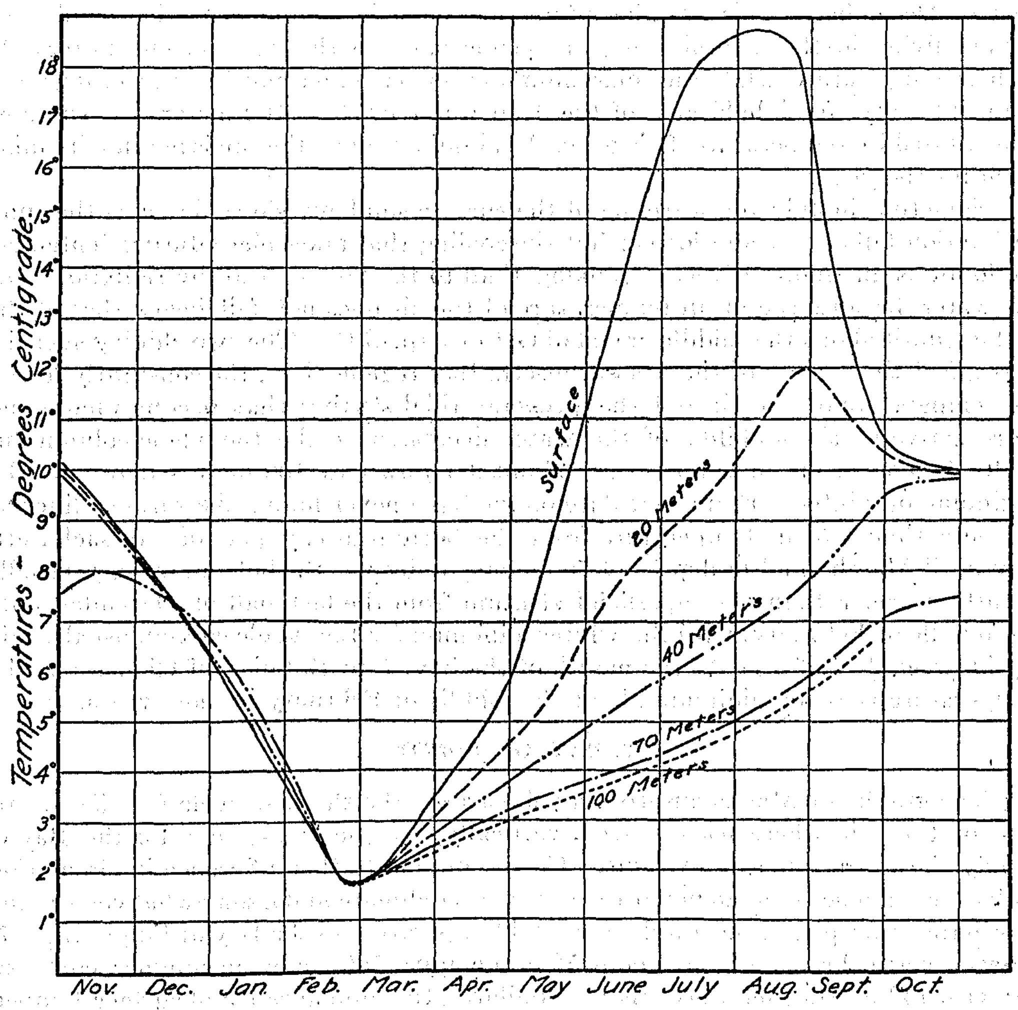

FIG. 86.—Composite diagram of the normal seasonal variation of temperature at the mouth of Massachusetts Bay, off Gloucester, at the surface, 20 meters, 40 meters, 70 meters, and 100 meters. The curves are smoothed. The station for August 9, 1923, is omitted because the water between the 20 and 150 meter levels was much colder that summer than usual, after an unusually cold winter

primarily because the source of heat is from above and secondarily because the vertical circulation is not sufficiently active to prevent a constant increase in vertical stability as the upper strata becomes warmer and warmer. The steadily widening spread between the curves for the surface and for the 20-meter level thus mirrors increasing stability. The result of this partial insulation of the deeper strata from the penetration of heat from above is that the maximum temperature for the year is reached later and later in the season, at greater and greater depths, with the water continuing to warm at any given level until the autumnal cooling of the surface brings the temperature of the overlying mass down nearly as low. Thus, the surface is warmest in August, the 20-meter level about the first week of September, the 40-meter level not until October, and the 70-meter level in November, while the 100-meter temperature probably does not reach the maximum for the year until the first part of December. This has the interesting biologic complement that while any animal living in the littoral zone, or pelagic close to the surface, encounters the highest temperature while the solar illumination has fallen but little from its maximum intensity, for inhabitants of the deep water in 70 to 100 meters the summer, as measured by temperature, falls when the illumination by the sun is nearing its minimum for the year.

Sometime in July the warming of the surface suddenly slows down as the sun's declination falls lower and lower; but the cooling that takes place during September no doubt is due more to vertical mixing than to the loss of heat by radiation from the water, because the mean temperature of the air does not fall below that of the surface until about the middle or end of October (p. 671). The two chilling agencies that affect the surface of the Massachusetts Bay region—i. e., the constantly lowering temperature of the air and the incessant tidal stirring that becomes more and more active as the stability of the water decreases—make the whole column virtually homogeneous in temperature (about 9°) down to 100 meters depth by the beginning of winter. From that date on we have never found the surface differing by more than 2.5° in temperature from the bottom in any part of Massachusetts Bay until March; and in depths of 70 meters, or deeper, the bottom water is usually slightly warmer than the superficial stratum from the last half of December until the middle of February, with the winter minimum for the whole column usually falling between 2° and 3°. At the mouth of the bay, 7 to 12 miles off Gloucester, the temperature is at its minimum about the middle of February in most years.

2. BAY OF FUNDY

The graph for Massachusetts Bay illustrates the thermal cycle for the coastal zone of the gulf where least stirred, vertically, by the tides; that for the Bay of Fundy shows the opposite extreme. Corresponding to this difference in circulation under the influence of a much more severe winter climate and a somewhat cooler summer in the atmosphere, the graph of annual temperature in the Bay of Fundy (fig. 87) shows a vertical range of only about 5° in the upper 100 meters in summer, contrasting with 14° in Massachusetts Bay. Similarly, the annual range of surface temperture is only about 10°; 17° or 18° at the mouth of Massachusetts Bay. At 100 meters, however, the annual range (approximately 5°) is about the same for the two localities. Although the Bay of Fundy is much less stratified, with regard to temperature, than is Massachusetts Bay during the warm months, it is more so during the winter, with the surface 1° to 1.5° colder than the 100-meter level between the dates when the whole column becomes homogeneous in temperature in autumn and again in early spring.

In normal years the surface of the Bay of Fundy reaches its highest temperature in August or early September (slightly later than the date when the surface of

Massachusetts Bay is warmest), the 20-meter level early in September, 40-meter level about the 1st of October, and the 70-meter and 100-meter levels during that month or the next.

3. NEAR MOUNT DESERT ISLAND

Off Mount Desert, where tidal stirring keeps the water thoroughly mixed, surface to bottom, throughout the year, the column cools nearly uniformly at all levels during the autumn and warms only slightly more rapidly at the surface than in the deeper strata during the spring (fig. 88), so that the period when the surface is more than 1.5° to 2° warmer than the 20 to 40 meter level averages 2 to 3 months instead of 5 to 6 months, as in Massachusetts Bay; and the 40-meter level warms to its

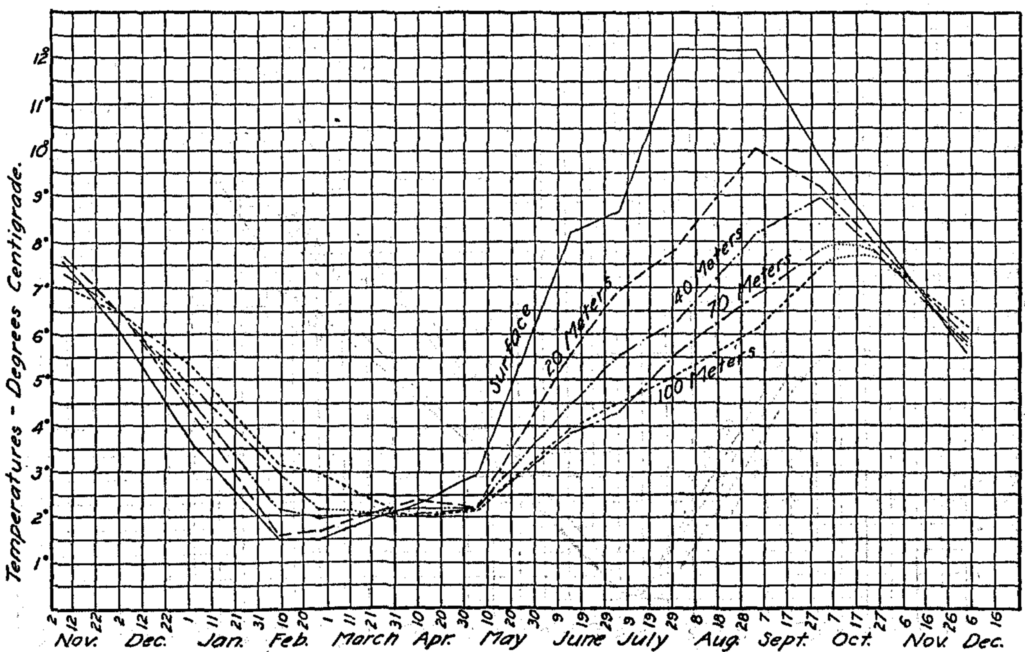

FIG. 87.—Composite diagram of the seasonal variations of temperature at *Prince* station 3, in the Bay of Fundy, between Grand Manan and Petite Passage, from November, 1916, to November, 1917, from Mavor's (1923) data

maximum for the year only a month or so later than the surface, instead of about 2 months later. The autumnal equalization of temperature also takes place by the first week of October near Mount Desert, a month earlier than in the deep part of the Bay of Fundy (fig. 87) but only a week or two earlier than in Massachusetts Bay (fig. 86).

4. WESTERN SIDE OF THE BASIN

Probably the western arm of the basin (fig. 89) is less subject to tidal stirring in its upper strata than any other part of the gulf. Therefore, it is not surprising to find the seasonal rise and fall of temperature of its superficial stratum (surface to 40 meters) closely reproducing that of Massachusetts Bay, except that the temperature does not fall quite as low in winter, being farther offshore. The date when the temperature rises to its maximum for the year is also about the same here as in the bay—mid-August for the surface, late August or early September for the 20-meter level—but in 1920 this part of the basin was not coldest until about the last week in March, whereas the surface in the neighborhood of Gloucester had begun to warm by the end of February, a difference corresponding to the difference in location (p. 694). Vernal warming is also generally parallel at these two locations down to the 40-meter level; but it can readily be appreciated that any upwelling of the much colder bottom water at any time from June to October would interrupt the orderly progression

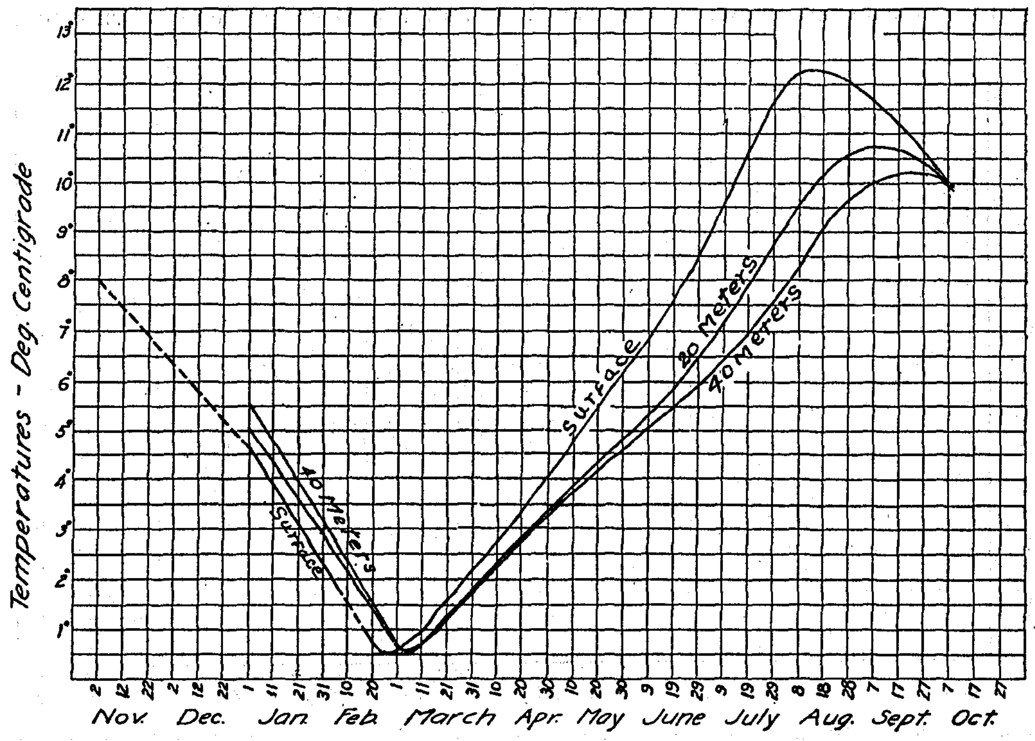

FIG. 88.—Composite diagram of the normal seasonal variations of temperature near Mount Desert Island, at the surface, 20 meters, and 40 meters, from data for the years 1915, 1920, 1921, and 1923. The curves are smoothed

of the 40-meter temperature, and it is probable that the very low 40-meter reading recorded off Cape Cod for August 22, 1914 (station 10254, 5.75°) is to be accounted for on this basis. Lacking data for late September or early October, I can not definitely state whether the 40-meter level of this side of the basin warms to its annual maximum at about the same date as in Massachusetts Bay (September).

The amplitude of the seasonal variation in temperature is nearly the same in the superficial stratum of the basin off the mouth of Massachusetts Bay as within the latter— i. e., a range of about 17° to 19° from summer to winter at the surface, about 10° to 11° at 20 meters, and about 7° to 8° at 40 meters. Unfortunately the only autumnal data for the deeper levels (100 and 150 meters) were for October and November of the very cold year 1916, when these underlying strata certainly had not warmed to the temperature usual for the date, although the superficial strata had (p. 642); but warming is probably to be expected here at 100 meters until some time in December. However, no rule can be laid down for depths greater than 100 to 150 meters in the basin. Thus, the lowest temperature so far recorded in the

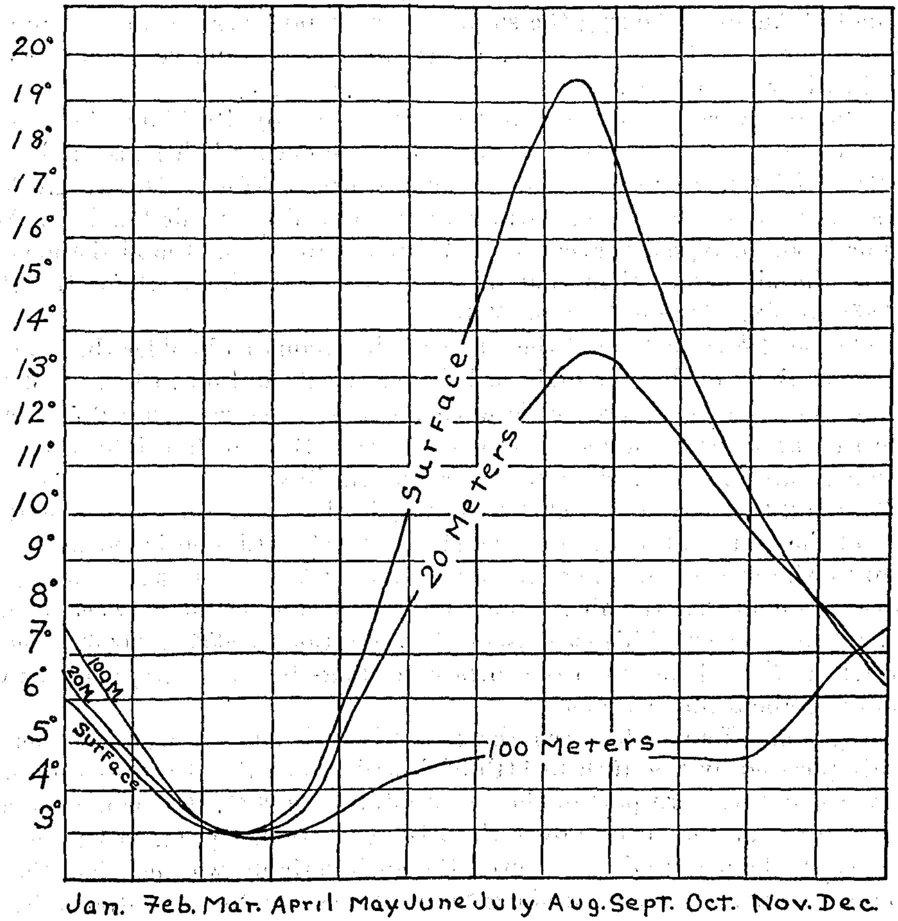

FIG. 89.—Normal seasonal variations in temperature at the surface, 20 meters, and 100 meters in the western side of the basin of the gulf, in the offing of Cape Ann, combined from the data for the several years and months. The curves are smoothed

western side of the basin at 150 meters was for midsummer (1912) instead of at the end of the winter, as is the case off Gloucester only 30 miles to the westward. This lack of conformity between the season of the year and the temperature is still more notable at 200 meters, for which level the lowest as well as the highest temperatures for this locality have been recorded in summer, the latter (6.3° and 6.8°) in August, 1914 and 1915, and the former (4.61°) on July 15, 1912.

RELATIONSHIP BETWEEN THE TEMPERATURE OF THE SURFACE AND OF THE AIR

The daily air and surface temperatures for Gloucester, Boothbay, and Lubec for the year 1919–20 (figs. 29 to 31) show the air constantly warmer than the water along the western and northern shores of the gulf from the middle of that March until late in October, a difference averaging greatest from some time in June until the last half of August. During the summer the 10-day averages for air and water frequently differ by 4° C.—occasionally by as much as 7°—and very hot days would show a still wider divergence.

The 10-day averages for air and water recorded by Rathbun (1887) for the years 1881 to 1885 are of the same tenure at the following lighthouses: Thatchers Island, Boon Island, Seguin Island, Matinicus Rock, Mount Desert Rock, and Petit Manan, with air averaging warmer than water after the first half of March. At Eastport, too, the Signal Service of the United States Army found the mean temperature of the air higher than that of the water after March 21 for the 10-year period, 1878 to 1887 (Moore, 1898, p. 409).

In 1920 the *Albatross* [49] found the air averaging about 1.7° colder than the water across Georges Bank during the night of February 22–23 and up to 1 p. m. of February 23, but the average difference between air and water was only 0.7° (day and night) on the run in from the bank to Massachusetts Bay on that date, with air and water temperatures precisely alike in Massachusetts Bay.

On March 2 to 4 (stations 10252 to 10260) in that year the surface of the central parts of the gulf (stations 20052, 20053, and 20054) still continued warmer than the air up to March 2 to 4 (average difference about 1.5° C.); but the air had warmed so fast over the land that the air readings for the coastal sector between Penobscot Bay and the inner part of Massachusetts Bay (stations 20055 to 20062) were consistently 1.1° to 5.6° higher than the surface readings by that date, night as well as day, averaging about 3.5° warmer.

This regional difference between the coastwise belt and the water farther out at sea had disappeared by the 10th to 11th of March, when the *Albatross* ran out from Boston to the southeastern part of the basin (station 20064), the air now being constantly warmer than the surface over the 24-hour period, 1 p. m. to 1 p. m. From that date on the hourly readings showed the air invariably warmer than the water, except on March 20, when we ran along the west coast of Nova Scotia to St. Marys Bay in a southeast storm with snow squalls.

Apart, then, from extremes of weather, the air averages warmer than the surface of the gulf from about March 10 on, though the precise date when this state is established varies from year to year and falls a week or more sooner near land than out in the central parts of the gulf.

[49] Hourly temperatures, United States Bureau of Fisheries (1921, p. 183).

Amount by which the air was warmer than surface water, April 6 to 20, 1920

General locality	Station	Date	Time	Amount by which air was warmer than water, °C.
Off Boston Harbor	20089	Apr. 6	3 p. m.	5.5
Off Gloucester	20090	Apr. 9	10.15 a. m.	1.0
Off Cape Ann	20091	do	1.50 p. m.	5.7
Off Ipswich Bay	20092	do	5 p. m.	2.5
Off Isles of Shoals	20093	do	10.30 p. m.	.8
Platts Bank	20094	Apr. 10	3 a. m.	1.1
Near Cape Elizabeth	20095	do	8 a. m.	1.9
Off Seguin Island	20096	do	12.20 p. m.	9.4
Off Penobscot Bay	20097	do	11 p. m.	1.0
Near Mount Desert Rock	20098	Apr. 11	4 p. m.	3.6
Near Mount Desert Island	20099	Apr. 12	1 p. m.	6.3
Northeast part of basin	20100	do	4.30 p. m.	3.9
Do	20101	do	9.30 p. m.	3.5
Off Yarmouth, Nova Scotia	20102	Apr. 13	2.15 a. m.	3.9
German Bank	20103	Apr. 15	1 p. m.	6.7
Off Seal Island, Nova Scotia	20104	do	6 p. m.	4.7
North Channel	20105	do	9.15 p. m.	4.1
Browns Bank	20106	Apr. 16	12.20 a. m.	3.5
Eastern Channel	20107	do	4.35 a. m.	5.5
East edge of Georges Bank	20108	do	8.50 a. m.	6.4
Southeast slope of Georges Bank	20109	do	5 p. m.	5.8
East part of Georges Bank	20110	do	8.30 p. m.	6.1
Do	20111	Apr. 17	1.15 a. m.	3.6
Southeast part of basin	20112	do	5.35 a. m.	.7
Center of basin	20113	do	1 p. m.	3.8
Near Cashes Ledge	20114	do	8 p. m.	3.3
Basin off Cape Ann	20115	Apr. 18	3.40 p. m.	2.0
Off Cape Cod	20116	do	9.55 a. m.	3.0
Do	20117	do	1 p. m.	4.6
Cape Cod Bay	20118	Apr. 20	10.50 a. m.	8.3
Mouth of Massachusetts Bay	20119	do	8.20 p. m.	6.9

The air averaged about 5° warmer than the water in Massachusetts Bay, along Cape Cod, and out across Georges Bank to the continental edge by May 16 to 17, 1920 (run from station 20123 to station 20129), with the difference greatest (10°) in Massachusetts Bay from 10 a. m. to 1 p. m., least (1.4°) at 9 p. m., but increasing again to 4° to 5.5° over Georges Bank during the daylight hours of the next day.

In any partially inclosed body of water, such as the Gulf of Maine, where the wind may blow either out from the land over the water or in from the open sea, the relation of water to air temperature depends largely on the strength and direction of the wind at any particular moment. For instance, the *Halcyon* recorded an air temperature of 23.3° C. and surface reading of 14.44° while fishing on Platts Bank on July 27, 1924, at 5 a. m. in a flat calm; but shortly afterward a breeze coming in from the south—from the open sea—lowered the temperature of the air to 15.6°, with no change in the water. On the whole, however, the difference between air and water during the part of the year when the air is the warmer certainly rules greatest by day, when the sun's heat pours down, and least by night. For instance, the air was 3° to 4° warmer than the water from 7 a. m. to 5 p. m. on the run out to the basin off Cape Ann on July 15 to 16, 1912, and only about 1.5° to 2° warmer than the water from 9 p. m. to 1 a. m.

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The hourly temperatures taken on our summer cruises have not yet been studied in detail, but preliminary examination shows that the spread between air and water continues of about this same order of magnitude over the open gulf from May until July, averaging about 0.3° to 5°.

Usually we have found the air at least 2° but seldom as much as 4° warmer than the water of the open gulf in August and September by day. This accords with Craigie and Chase's (1918, p. 130) and with Craigie's (1916a) records of air 2.2° to 6.24° warmer than surface over the Bay of Fundy generally during July, 1915, and air 2° to 3.8° warmer than water along a section of the bay from Grand Manan to Nova Scotia on August 27 to 29, 1914. Mavor's (1923) experience was also similar. (No night time records have been published for the Bay of Fundy.)

The only regional distinctions that I dare draw in this respect for the open gulf until the very considerable mass of material is more carefully analyzed, is that the difference between daytime temperatures of the air and of the water averages greatest near the shore, as was to be expected.

It is common knowledge that the air along our seaboard is often much warmer than the water that actually washes the coast during the warmest part of the summer. Thus, we find the air averaging 6° to 7° warmer than the water at Boothbay and Gloucester and in Lubec Channel about July 25, 1920 (figs. 29 to 31), with differences as wide as 10° C. (18° F.) on individual hot days.

Vachon (1918), too, found differences as great as 10° to 12° between the temperatures of air and water in Passamaquoddy Bay on individual days in July, August, and September, whereas the maximum difference between air and surface so far recorded for the open Bay of Fundy is only 7.34°; 8.3° for the Gulf of Maine outside the outer headlands (on August 16, 1912). The mean difference between air and surface temperatures for the Gulf of Maine as a whole will probably be found to fall between 2° and 5° for the summer.

We have occasionally found the surface slightly warmer than the air as early as the first week in August. In 1912, for example, the *Grampus*, running offshore from Cape Elizabeth in a flat calm and bright sun on August 7 and 8, found the water fractionally colder than the air early in the day, 1° to 1.5° warmer than the air from noon to 2 p. m., once more slightly colder than the air from 3 to 9 p. m., and then again fractionally warmer than the latter from 10 p. m. until 1 a. m.

A period is next to be expected when the air will be cooler than the water during some of the nights, though still warming by day to a temperature higher than that of the water, presaging the date (sometime in October) when the mean temperature of the air falls permanently below that of the surface of the gulf, so to continue throughout the winter. The following table of hourly differences will illustrate this for one 24-hour period (August 15, 1 a. m., to August 16, 1 a. m.), during which the *Grampus* ran eastward from the vicinity of Mount Desert Rock toward the Grand Manan Channel.

Difference between surface and air temperatures (° *C.*)

[− signifies that the air was colder, + that it was the warmer]

Hour	Difference	Hour	Difference
August 15:		August 15—Continued	
1 a.m.	+2.8	2 p.m.	+5.6
2 a.m.	+1.7	3 p.m.	+3.9
3 a.m.	+1.1	4 p.m.	+4.4
4 a.m.	+1.7	5 p.m.	+2.2
5 a.m.	−0.6	6 p.m.	+2.2
6 a.m.	−0.6	7 p.m.	+2.2
7 a.m.	+0.6	8 p.m.	+2.2
8 a.m.	+1.1	9 p.m.	−1.1
9 a.m.	+2.8	10 p.m.	−1.7
10 a.m.	+2.8	11 p.m.	−1.7
11 a.m.	+2.8	12 midnight	0.0
12 noon	+3.3	August 16: 1 a.m.	0.0
1 p.m.	+5.0		

It is to be noted that while the air temperature did not fall below that of the water until between 3 and 4 a. m. on the first night, this happened at 9 p. m. on the second.

In 1920 the air averaged colder than the water in the harbors of Gloucester, Boothbay, and Lubec after about the middle of October. According to the temperatures collected by Rathbun (1887), the surface was colder than the air at the several lighthouses after the following approximate dates of 1881 to 1883:

Locality	Year	Date
Pollock Rip	1882	After Nov. 16.
	1883	After Nov. 1.
Thatchers Island	1881	After Nov. 8.
	1882	Between Nov. 11 and 16.
Boon Island	1881	After Oct. 30.
	1882	After Nov. 1.
	1883	After Nov. 6.
Seguin Island	1881	After Nov. 1.
	1882	After Oct. 25.
	1883	Nov. 1 to 6.
Matinicus Rock	1881	After Oct. 17.
	1882	After Oct. 25.
	1883	Nov. 1 to 6.
Mount Desert Rock	1881	After Nov. 16, but with reversals.
	1882	After Nov. 16.
	1883	After Nov. 6.
Petit Manan	1881	After Nov. 8.
	1882	After Oct. 22.
	1883	After Nov. 26.

Thus the water in the coastal belt is constantly warmer than the air after the last week of October or the first week in November. From that time on the difference between air and water increases until the middle of January, when the air averages about as much colder than the water as it is warmer in summer (illustrated by the 10-day averages for Gloucester, Boothbay, and Lubec, figs. 29 to 31). During periods of extreme cold, such as come to New England and to the Maritime Provinces almost every winter, the spread between air and surface temperatures is even wider than the spread of the reverse order in summer. At Lubec, for example, the air averaged 10° the colder for 10 days in January, 9° the colder at Boothbay, and it may be more than 20° colder than the water in the western side of the gulf on the coldest days. Thus, on December 21, 1924, when the mean surface temperature of the southern side of Massachussetts Bay was about 4.3° (p. 650), the air temperature was −18° C. at Boston (p. 650). As another example I may cite December 17, 1919, when the air temperature was about −21.5° C. at Lubec (7° below zero F.), the temperature of the surface water being 0°.

In the winter of 1919–20 (a cold year) the air temperature averaged about 3.1° colder than the surface at Gloucester from December 2 to March 1 and about 5° colder than the water at Lubec. At Eastport the United States Army Signal Service found the mean water temperature to average about 6.6° warmer than that of the air for the period December to February during the 10 years 1878 to 1887.

The temperatures collected by Rathbun at lighthouses and lightships do not cover the months of January or February, and his statement (Rathbun, 1887, p. 166) that the reason for this omission is "the manifest errors of observation sometimes made during extremely cold weather" makes it doubtful how close an approximation to the truth is given by his averages for the last half of December. Consequently, it is necessary to turn to the observations taken on the *Halcyon* during December to January, 1920–21, for the relationship between the air and surface temperatures for the open gulf in midwinter; nor do these fairly represent its outer waters, all having been taken within 30 to 40 miles of land.

These *Halcyon* stations show the air 4.4° colder than the water off Boston Harbor (station 10488), but averaging about 2.5° colder than the water in the northeastern corner of the gulf and precisely the same as the water in the Fundy Deep (station 10499).

The records for this cruise would have been more fairly representative had it included any severely cold days, which it did not, for the obvious reason that when icy northwest gales sweep the gulf oceanographic research from a small ship becomes impossible. Nevertheless, the regional difference just sketched does illustrate the very important fact that the cold winds of winter are most effective as cooling agents close in to the land.

While no exact data are at hand for Georges Bank in early winter, general report has it that the temperature of the air is close to that of the water there in December and January, except when cold northwest gales blow out from the land or warm "southerlies" blow from the tropic water outside the edge of the continent.

From the oceanographic standpoint, the most instructive conclusion to be drawn from the relationship between the temperature of the air and that of the water is that the surface of the gulf follows the air in its seasonal changes (p. 699; Bigelow, 1915 and 1917). This, of course, is a corollary of its situation to leeward of the continent, with winds blowing from the land out over the sea for a much greater percentage of the time than vice versa, especially in winter. It follows from this, as I have emphasized in earlier publications, that the relation of sea climate to air climate is, on the whole, the reverse here of what applies to northwestern Europe, the surface of the sea responding rapidly in winter to the rigorous air climate.

How closely the winter temperature of the water of the harbors and bays tributary to the gulf depends on the influence of the land is illustrated by the fact that Gloucester

Harbor, which opens freely to the deeps off Massachusetts Bay, is 0.05° to 1° warmer than the more inclosed waters of Woods Hole in winter, although a degree of latitude farther north and bordering a colder ocean area (Bigelow, 1915, p. 257). Gloucester Harbor, in turn, is colder than the neighboring parts of Massachusetts Bay. For example, the surface temperature of the outer part of the harbor fell to about 0.5° to 1.1° during the winter of 1912–13, but the lowest reading a few miles outside was 2.78° (Bigelow, 1914a). Boothbay Harbor, 75 miles north of Gloucester and shut in by numerous islands, is likewise colder in winter than are the neighboring waters of the open gulf. On March 4, 1920, for instance, the temperature of the harbor was fractionally below 0° (fig. 30), at which date the *Albatross* had surface readings of 2.2° to 1.1° on the run in to the land there from a station some 35 miles offshore (20057). Information to the same effect results from an average March temperature of about 0.11° at the Bureau of Fisheries station at the head of Boothbay Harbor for March, 1881 to 1885, contrasting with 1.1° to 1.7° at Seguin Island (Rathbun, 1887). Finally, a graph (fig. 90) is offered to show the thermal progression of air and water in Massachusetts Bay during the winter of 1924 and 1925.

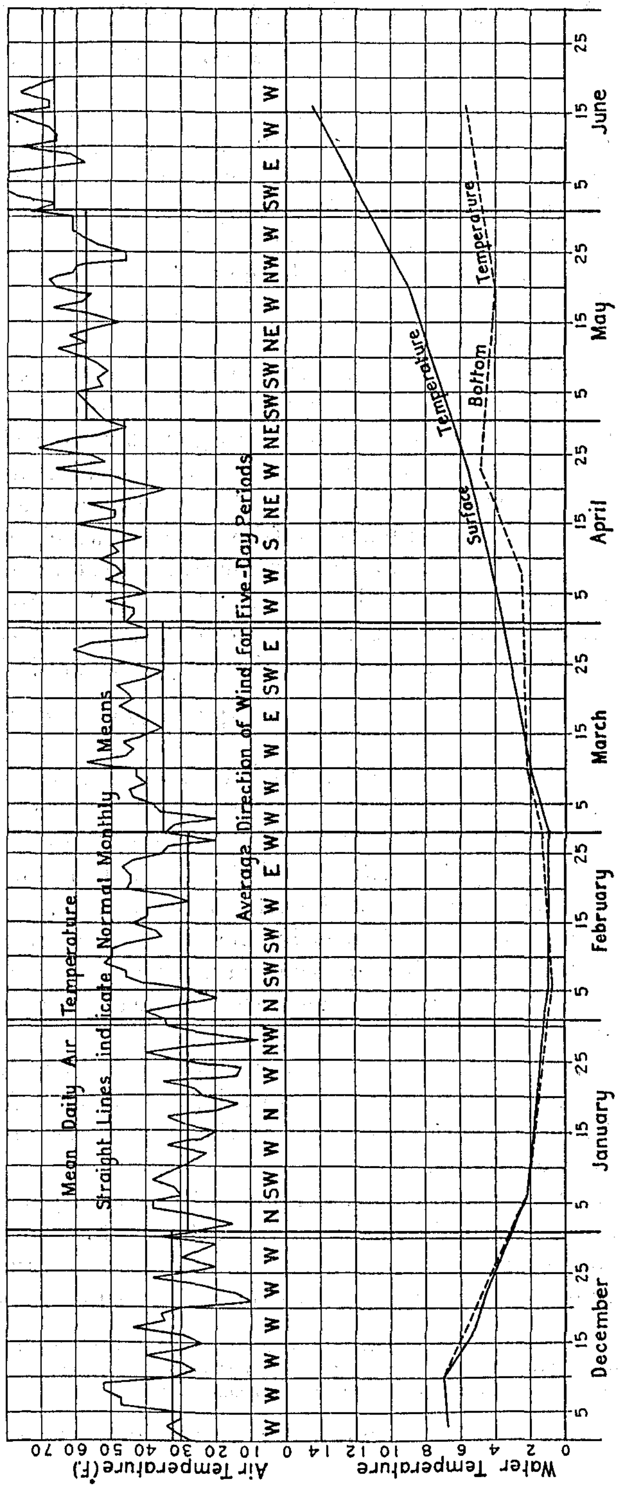

FIG. 90.—Surface and bottom temperatures off Plymouth, Mass. (*Fish Hawk* station 10, p. 1006); daily temperature of the air at Boston and direction of the prevailing wind from December 3, 1924, to June 17, 1925. Compiled by R. Parmenter