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 11.67°, 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

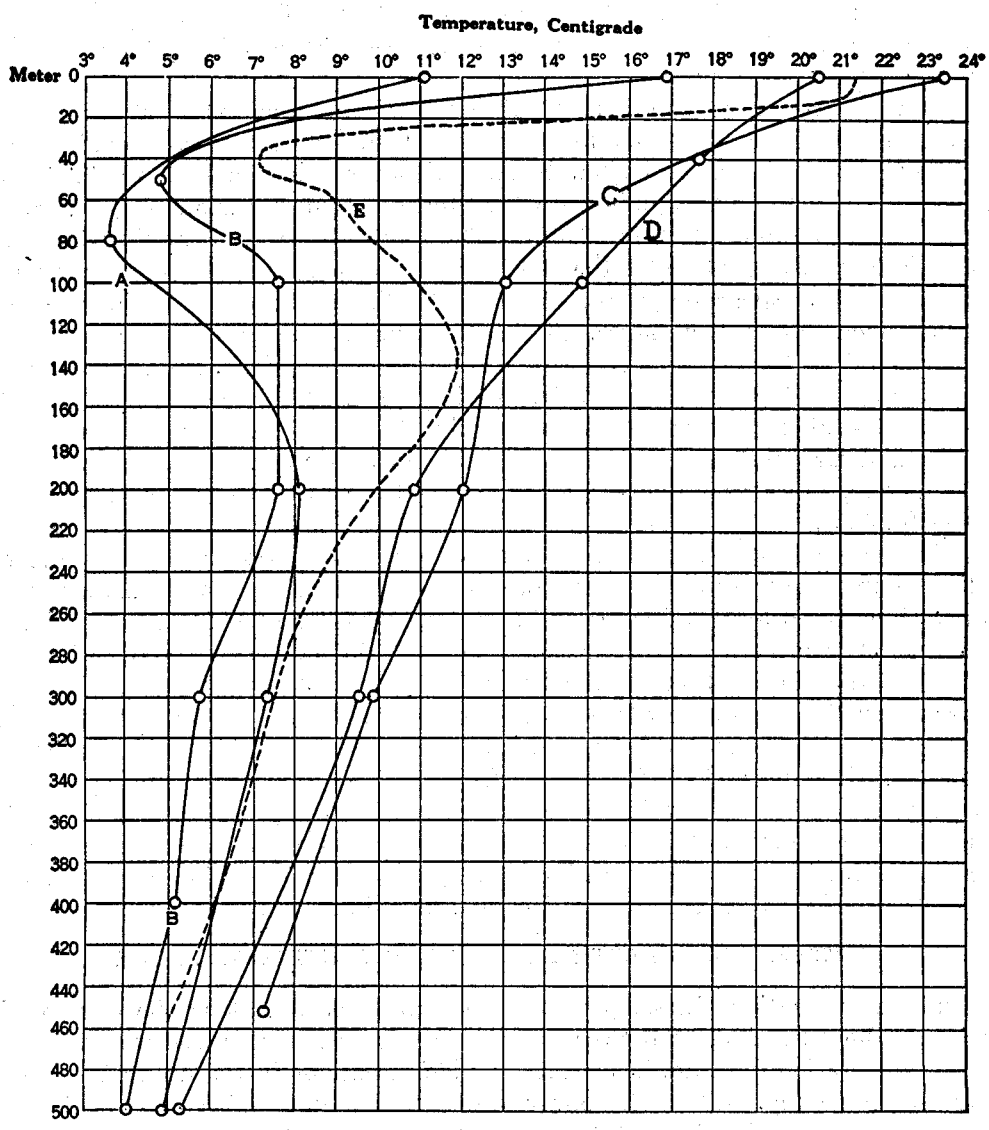

FIG. 51.—Vertical distribution of temperature on the continental slope in summer. A, abreast of Shelburne, Nova Scotia, June 24, 1915 (station 10295); B, on the southwestern slope of Georges Bank, July 24, 1916 (station 10352); C, on the southwest slope of Georges Bank, July 21, 1914 (station 10218); 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

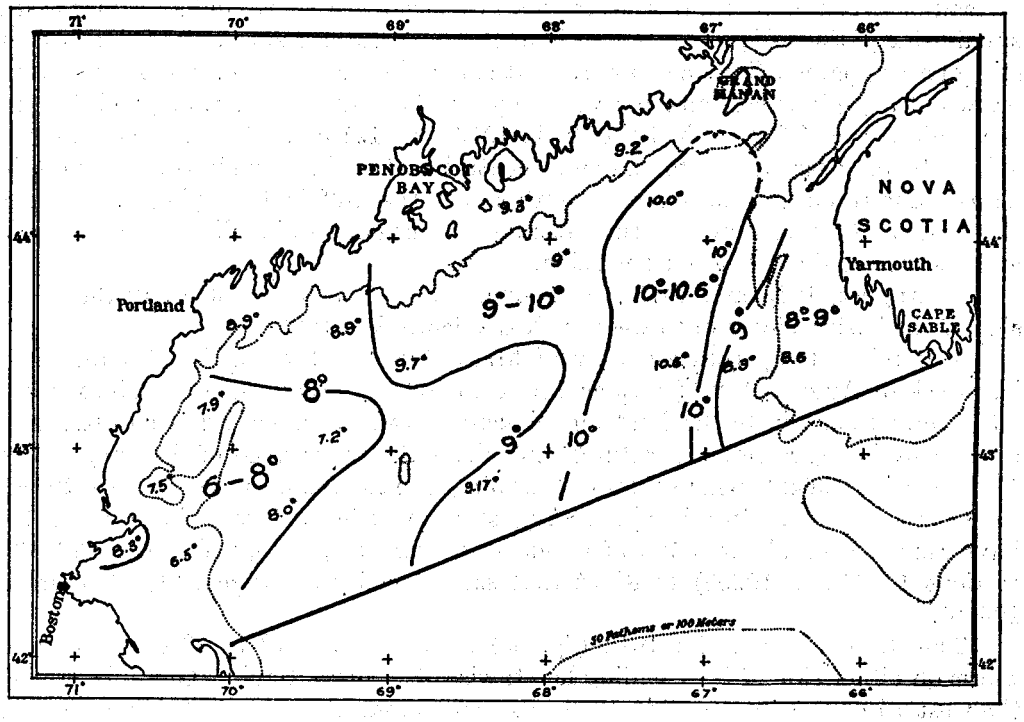

FIG. 52.—Temperature at a depth of 40 meters, August 5 to 20, 1913

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

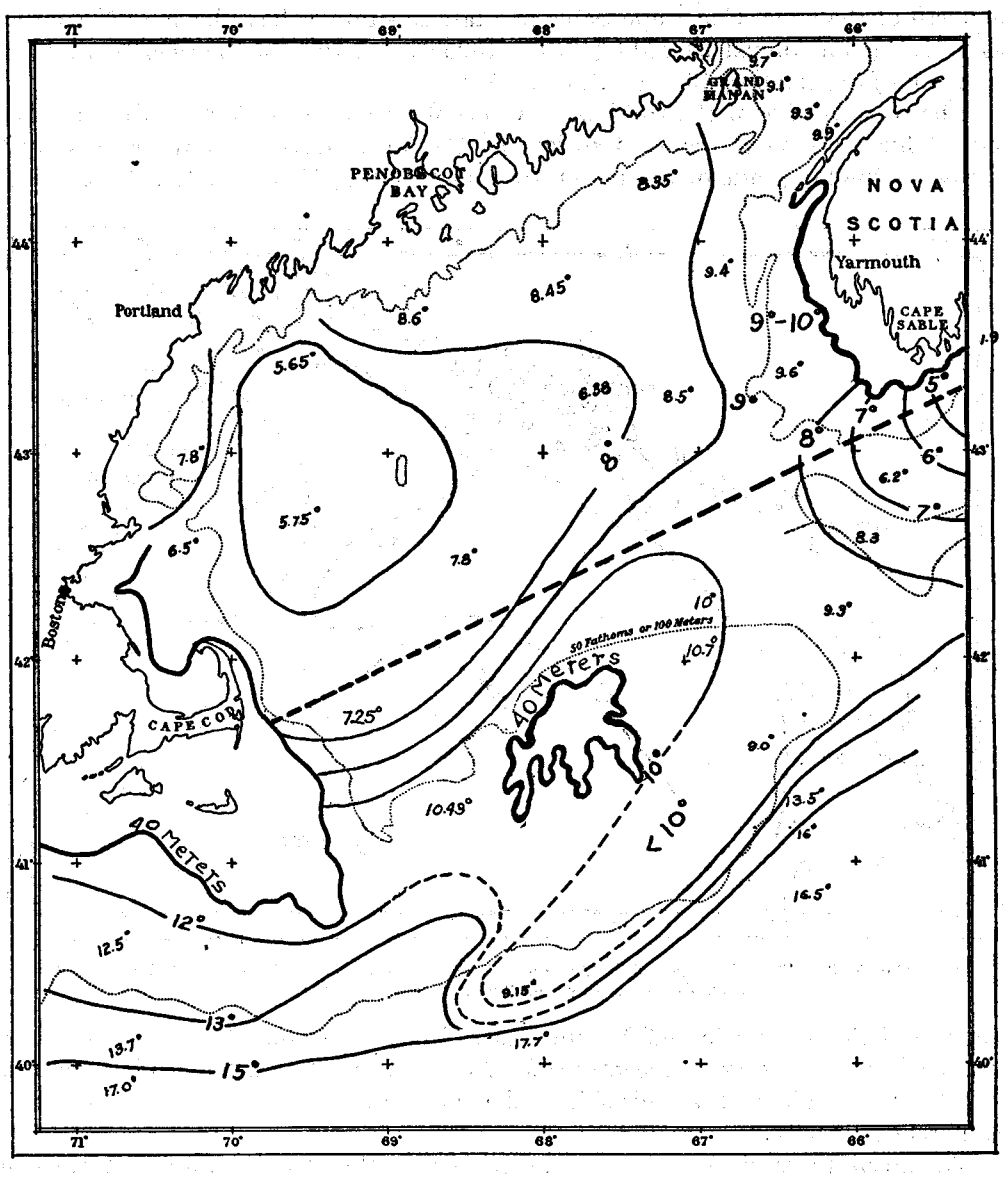

FIG. 53.—Temperature at a depth of 40 meters for July–August, 1914. North of the heavy broken line (Cape Cod to Cape Sable) the chart represents the state of the gulf from August 11 to 24; south of it, for July, combined with August. The Bay of Fundy temperatures are from Craigie (1916b)

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

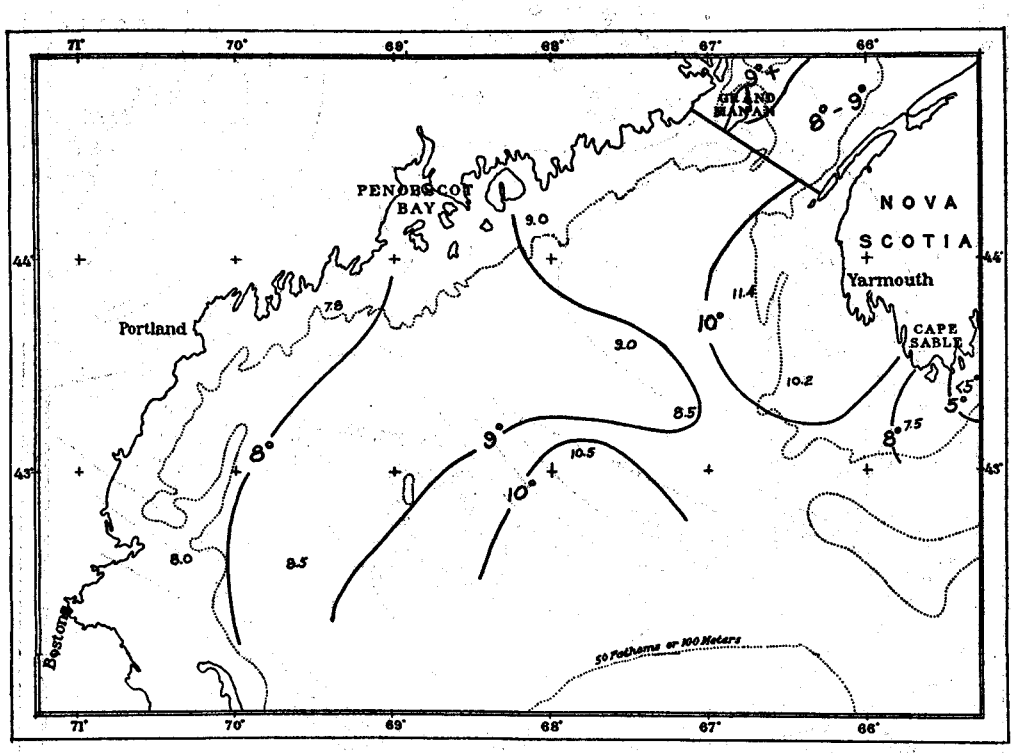

FIG. 54.—Temperature of the northern part of the gulf at a depth of 40 meters, August 31 to September 11, 1915. The Bay of Fundy temperature is for 1919, according to Mavor (1923)

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

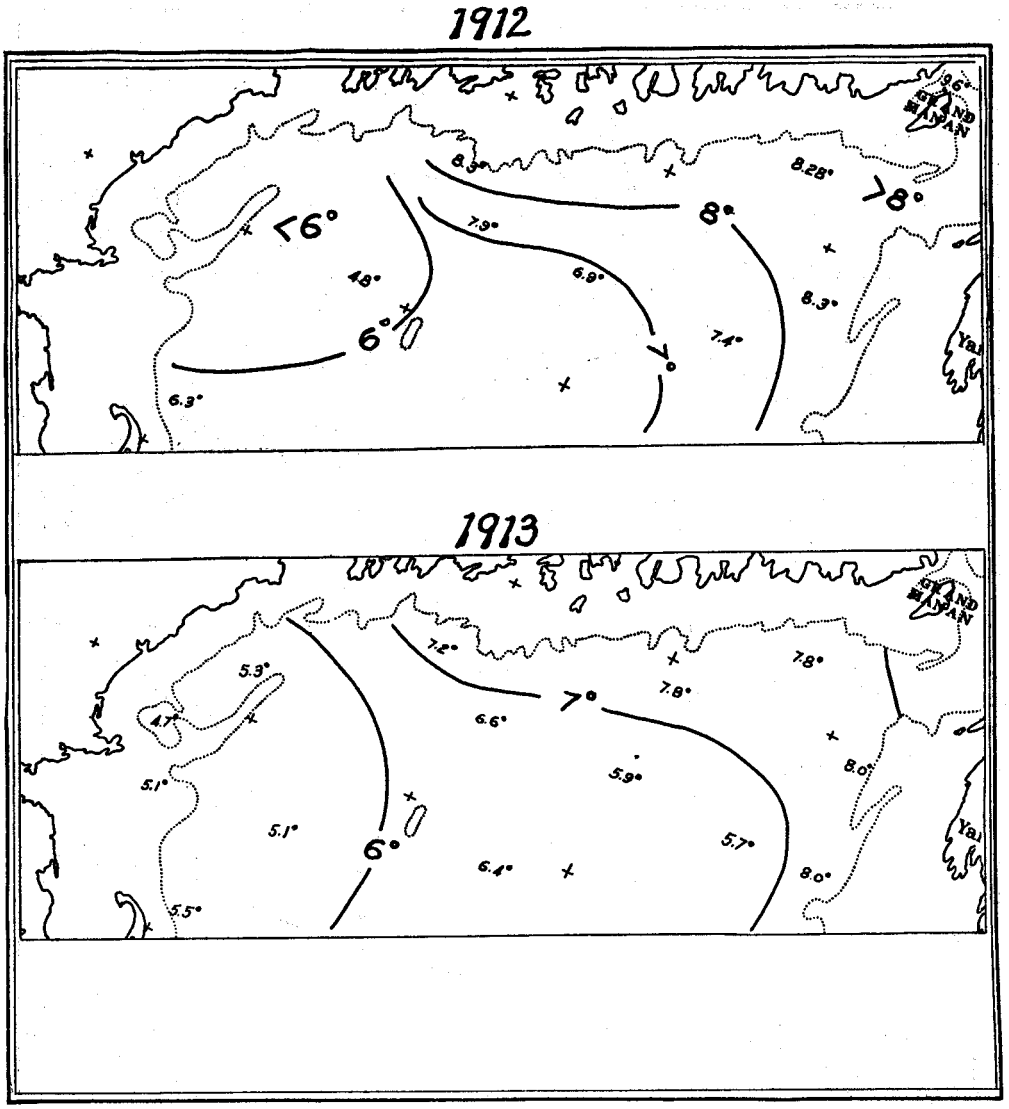

FIG. 55.—Temperature at a depth of 100 meters, August, 1912 (above), and August, 1913 (below)

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

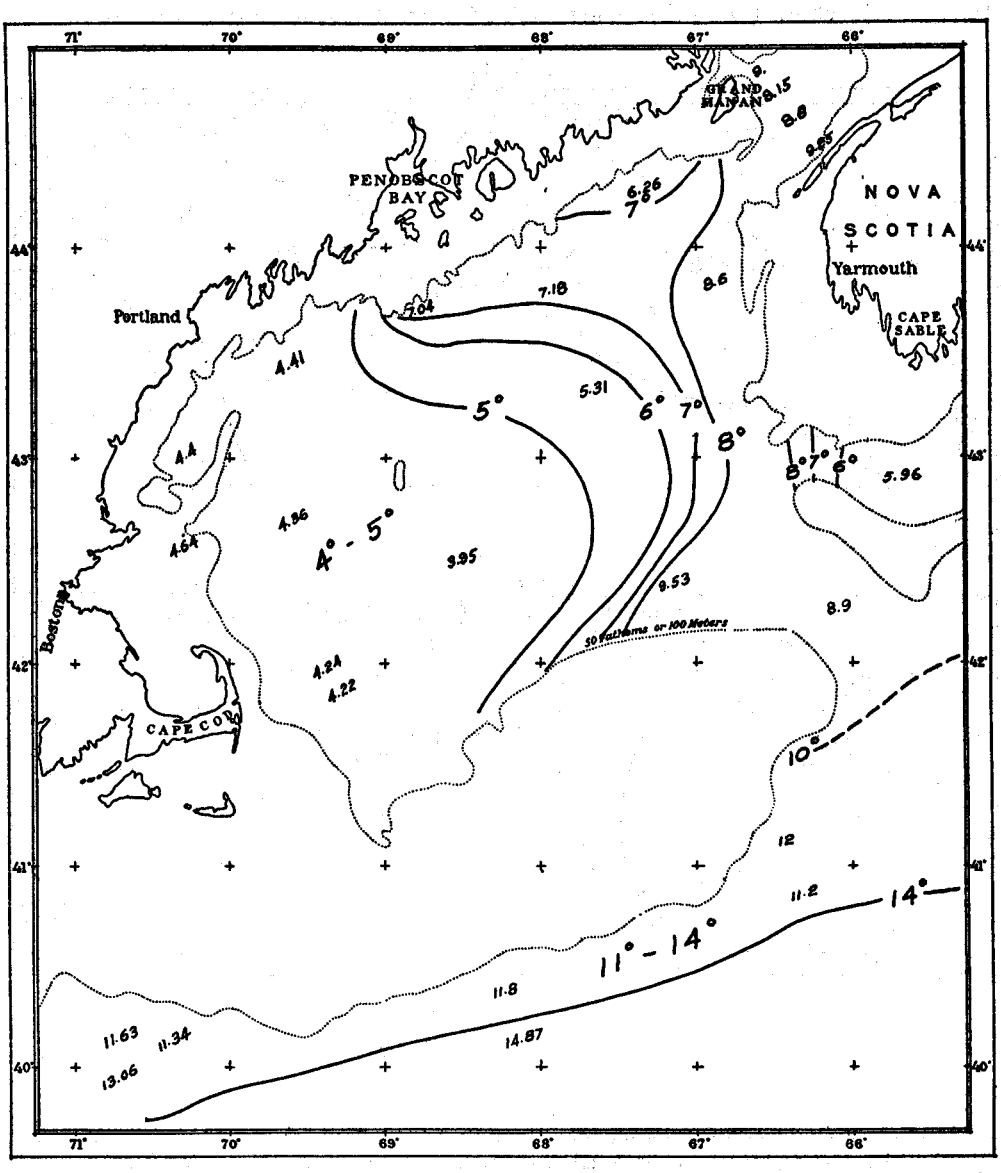

FIG. 56.—Temperature at a depth of 100 meters, July to August, 1914. North of Georges Bank the chart represents the state of the gulf during the last half of August; south of the bank the data are for July and August combined

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.

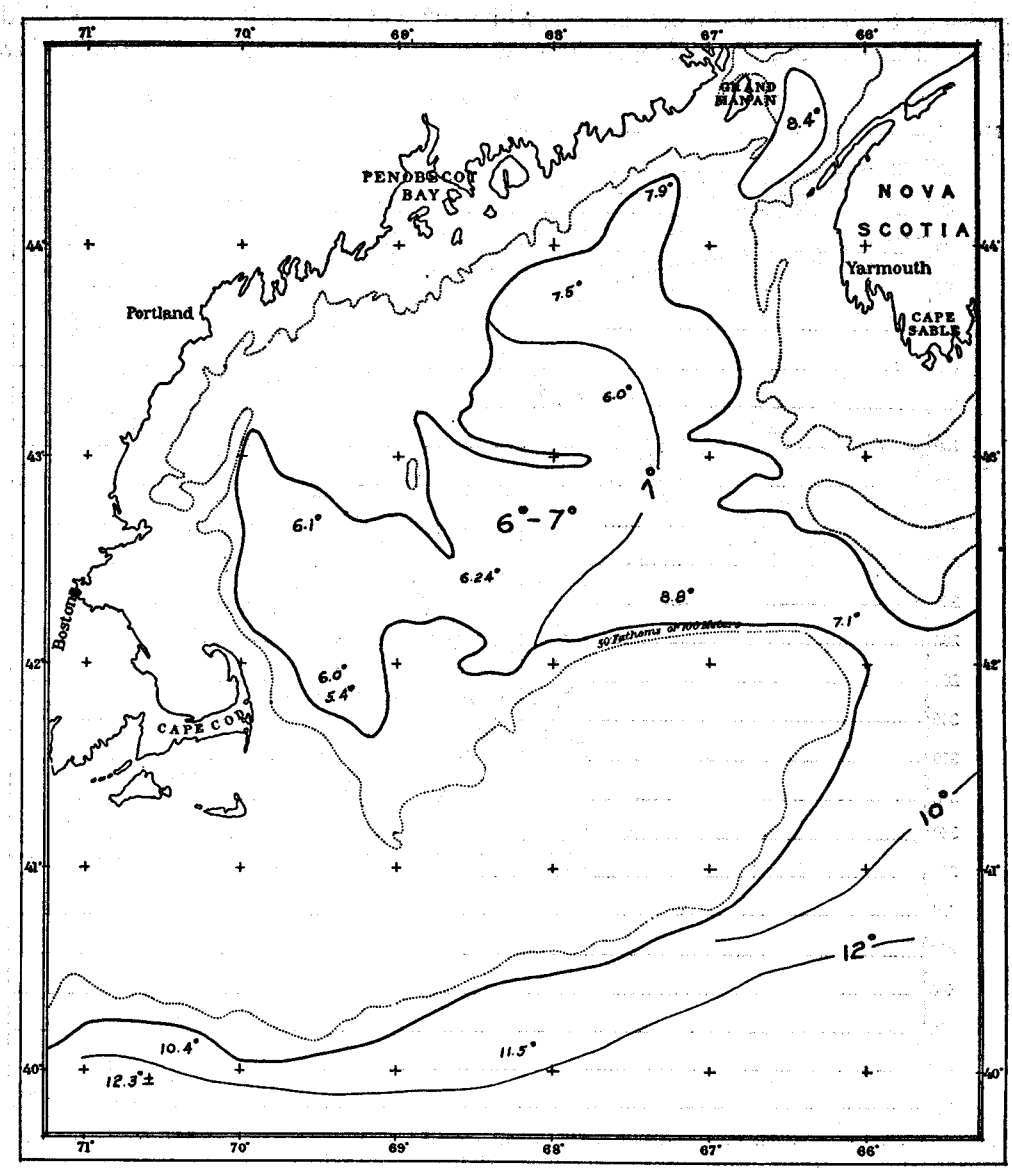

FIG. 57.—Temperature at a depth of 175 meters within the gulf for August, 1914. The temperatures along the continental slope are for July and August of that year, combined

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

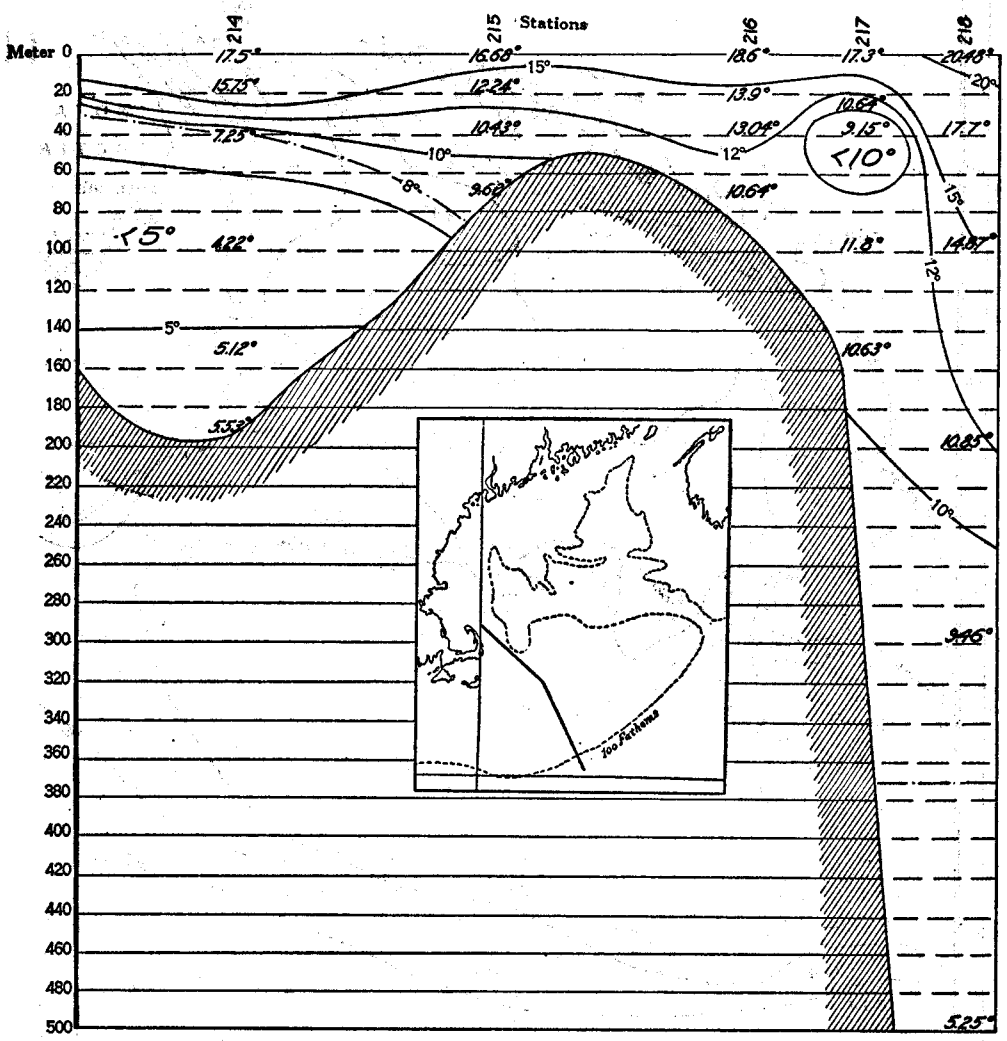

FIG. 58.—Temperature profile running from a point off northern Cape Cod, southeastward across Georges Bank to the continental slope, for July 19 to 21, 1914 (stations 10213 to 10218)

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.

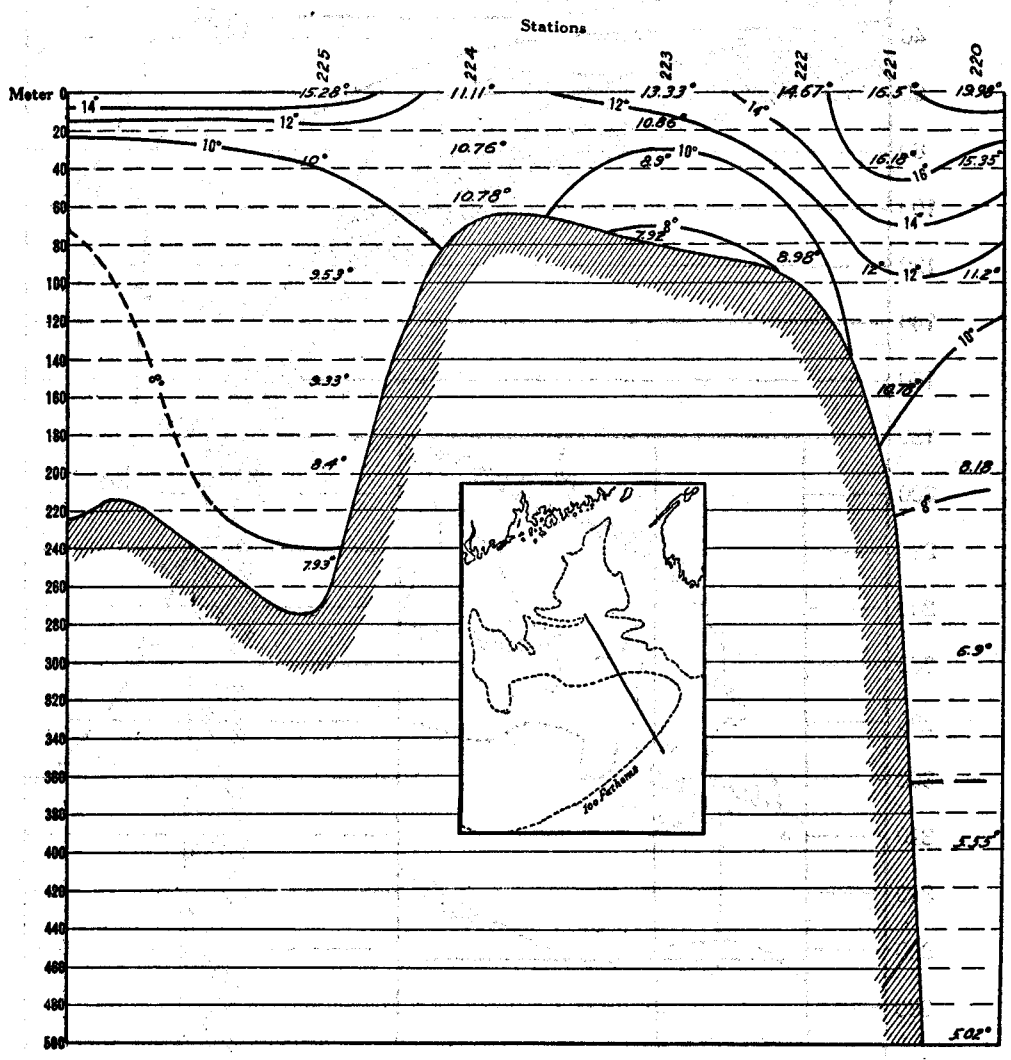

FIG. 59.—Temperature profile running from the eastern side of the basin, southeastward across the eastern end of Georges Bank to the continental slope, July 22 to 23, 1914 (stations 10220 to 10225)

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.

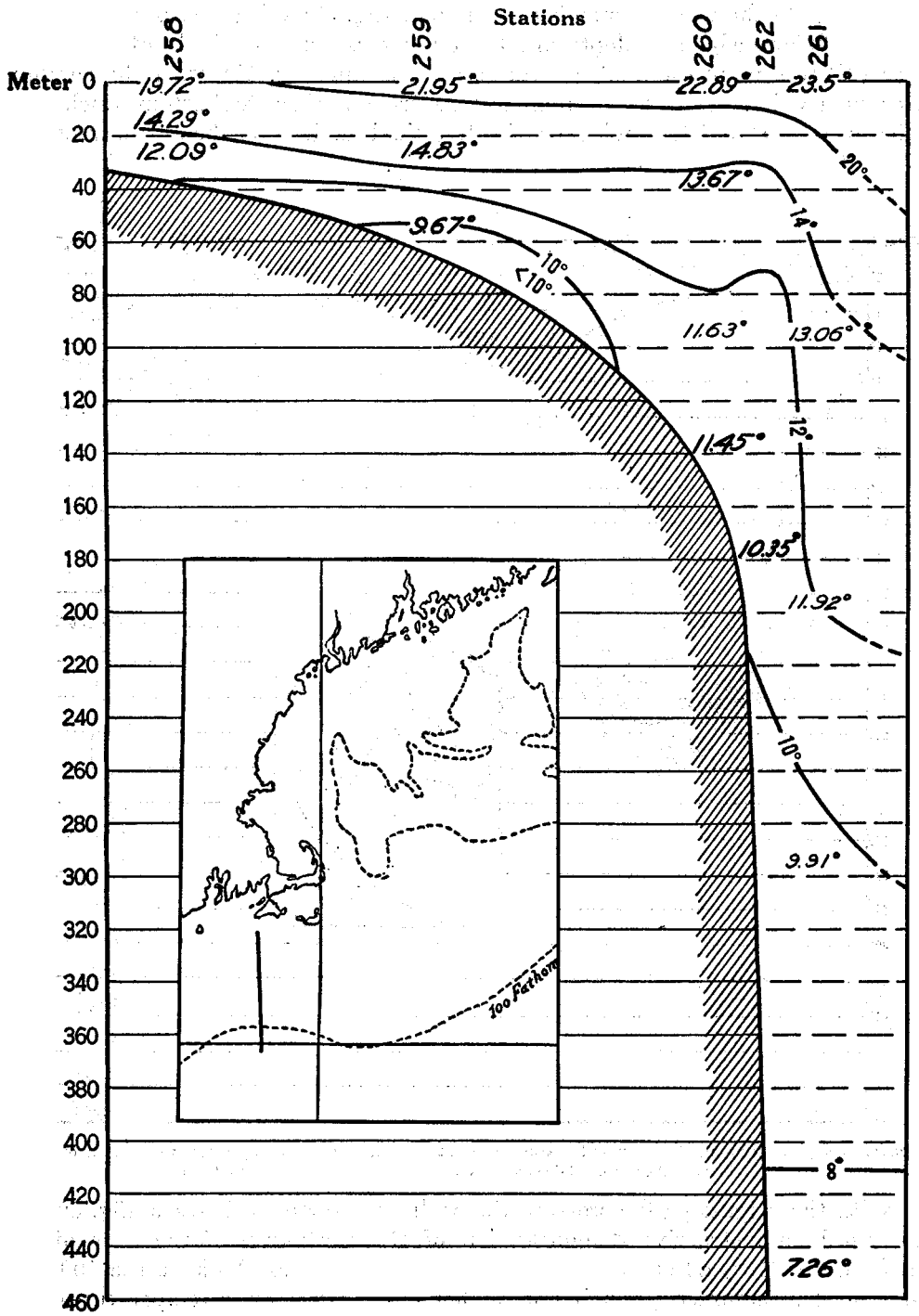

FIG. 60.—Temperature profile running southward from the offing of Marthas Vineyard to the continental slope, August 25 to 26, 1914 (stations 10258 to 10262)

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

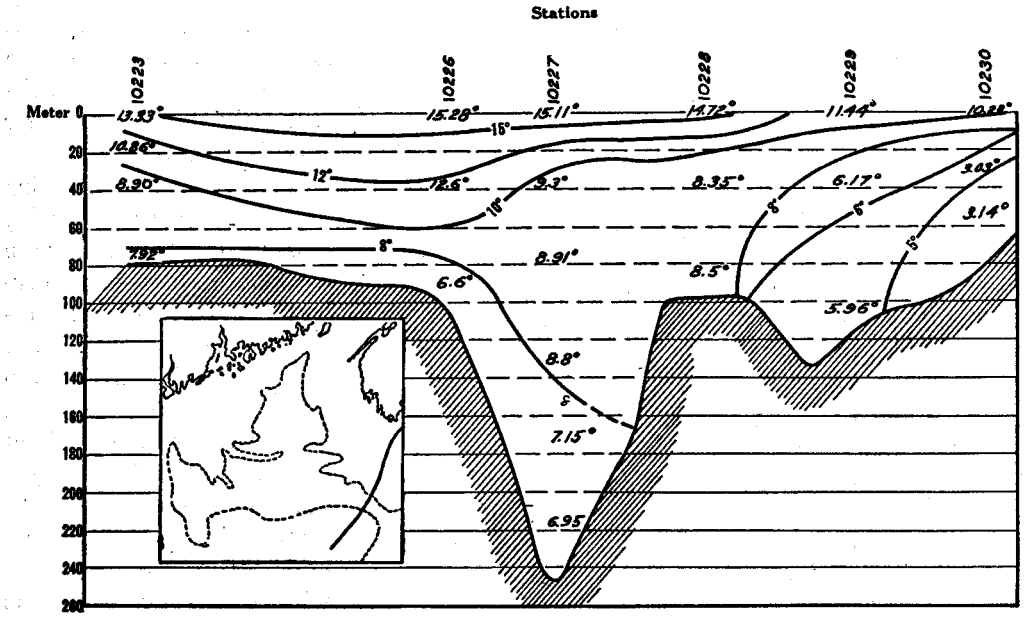

FIG. 61.—Temperature profile running from the eastern end of Georges Bank, across the Eastern Channel, Browns Bank, and the Northern Channel, to the offing of Cape Sable, July 23 to 25, 1914

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

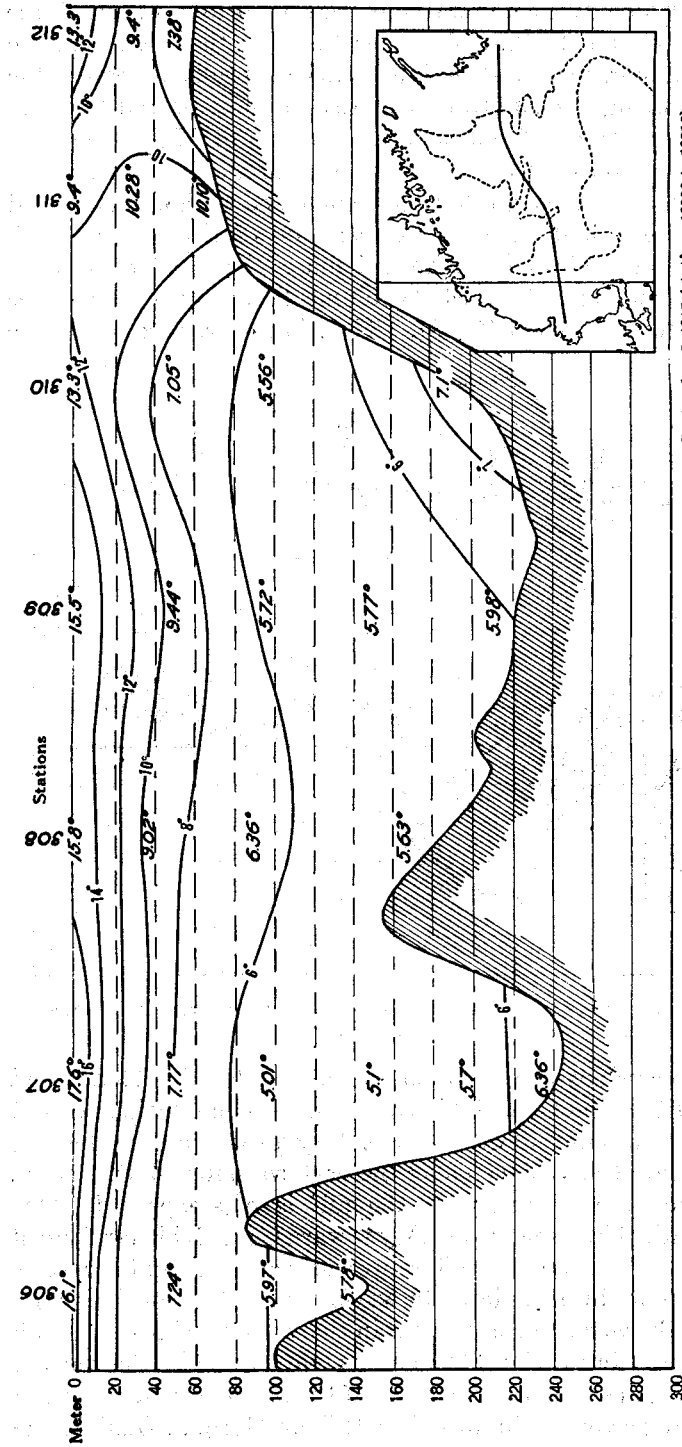

FIG. 62.—Temperature profile from the mouth of Massachusetts Bay to the offing of Cape Sable, August 31 to September 2, 1915 (stations 10306 to 10312)

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 10098).

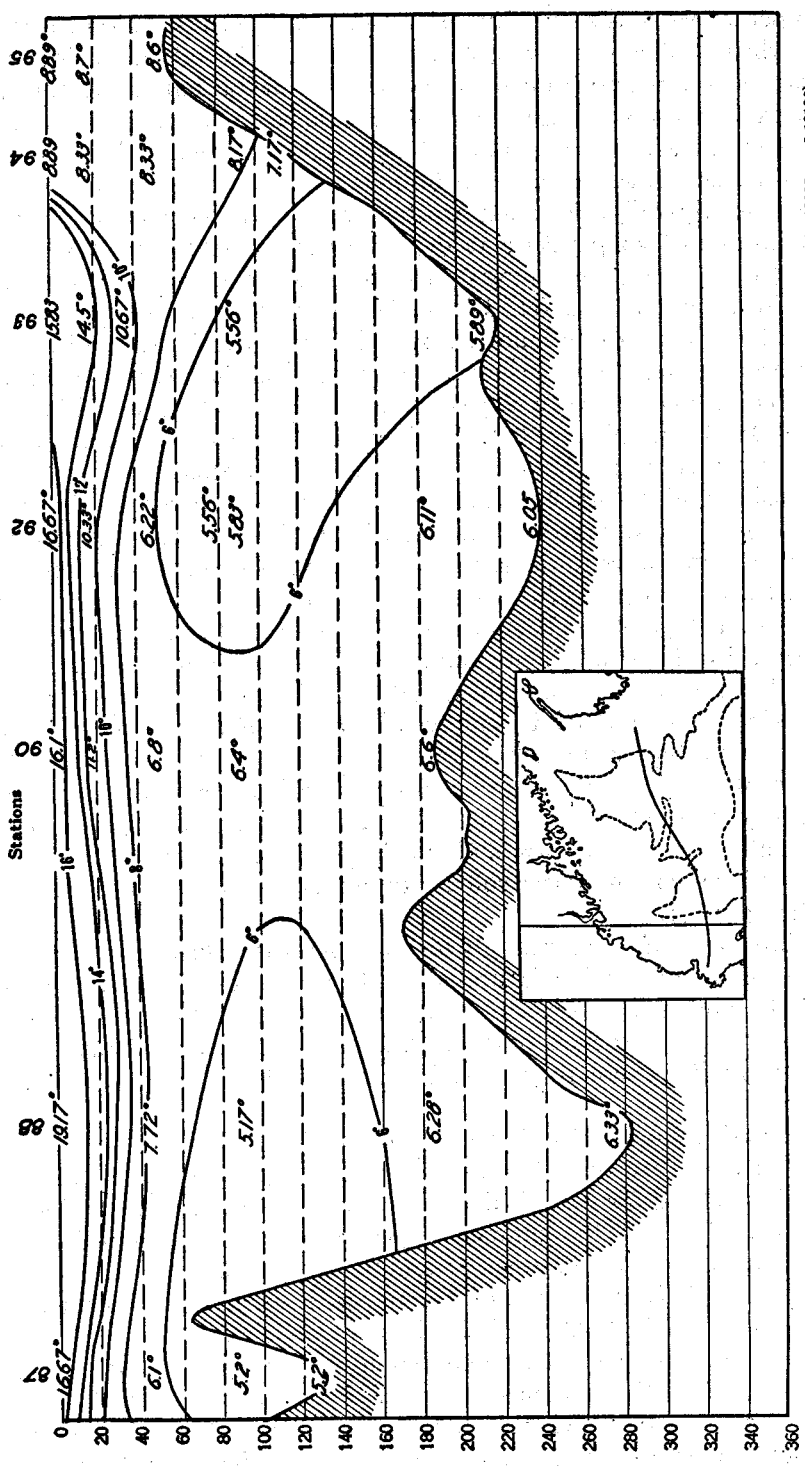

FIG. 63.—Temperature profile from the mouth of Massachusetts Bay to German Bank, August 9 to 20, 1913 (stations 10087, 10088, 10090, 10092 to 10095, and 10106)

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

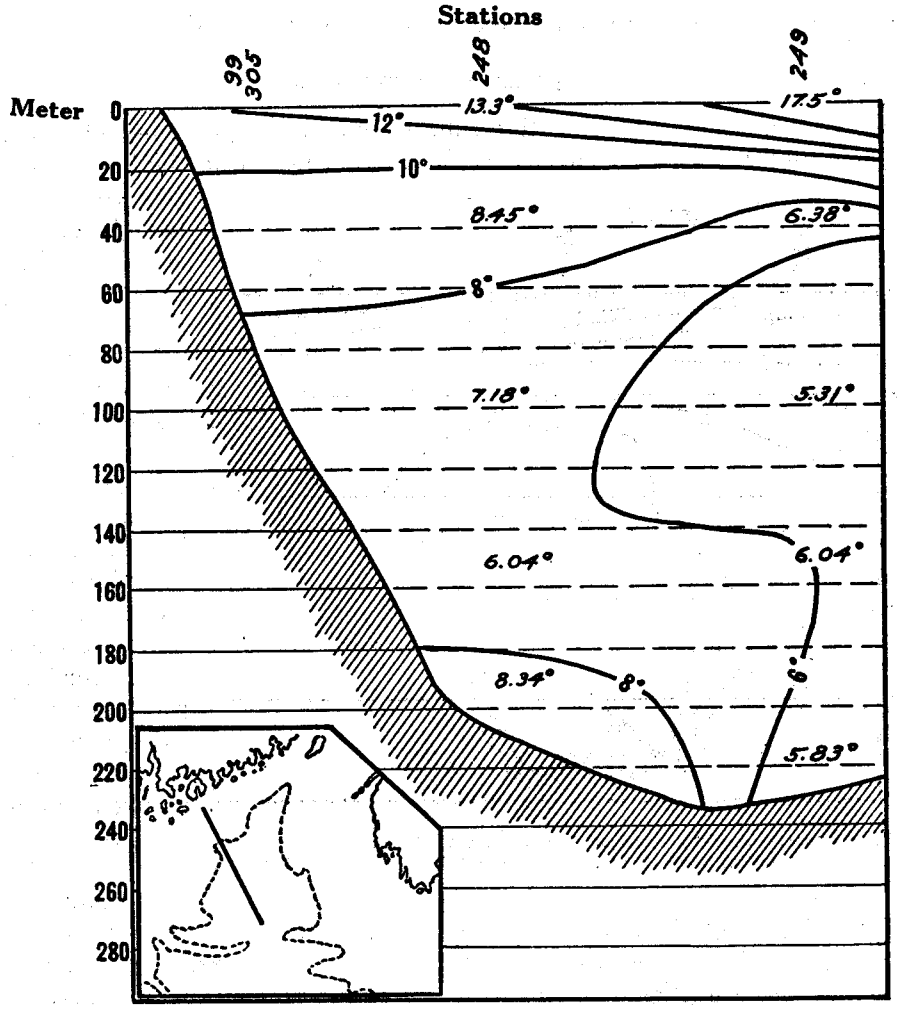

FIG. 64.—Temperature profile running southward from Mount Desert to the basin for August, from the data for the years 1913, 1914, and 1915, combined (stations 10099, 10248, 10249, and 10305)

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.

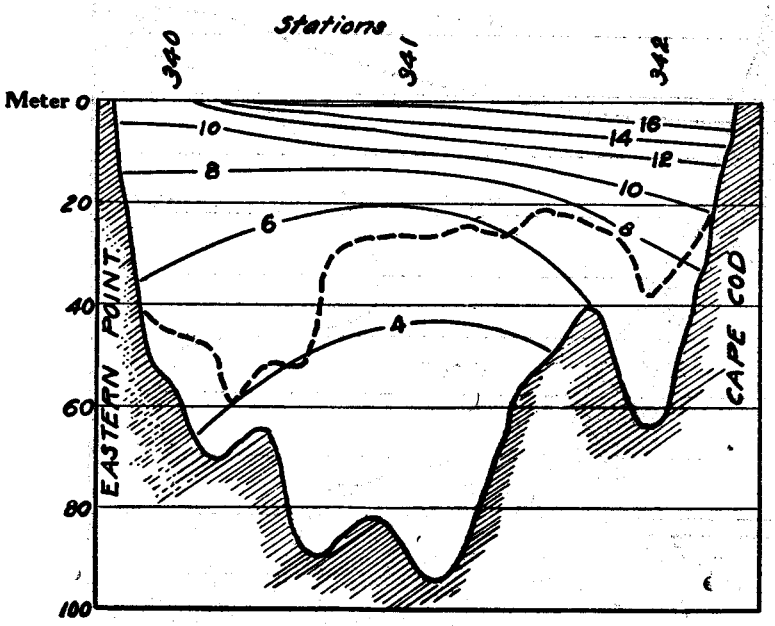

FIG. 65.—Temperature profile crossing the mouth of Massachusetts Bay just west of Stellwagen Bank, July 19, 1916 (stations 10340 to 10342). The contour of the bank is represented by the broken curve

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

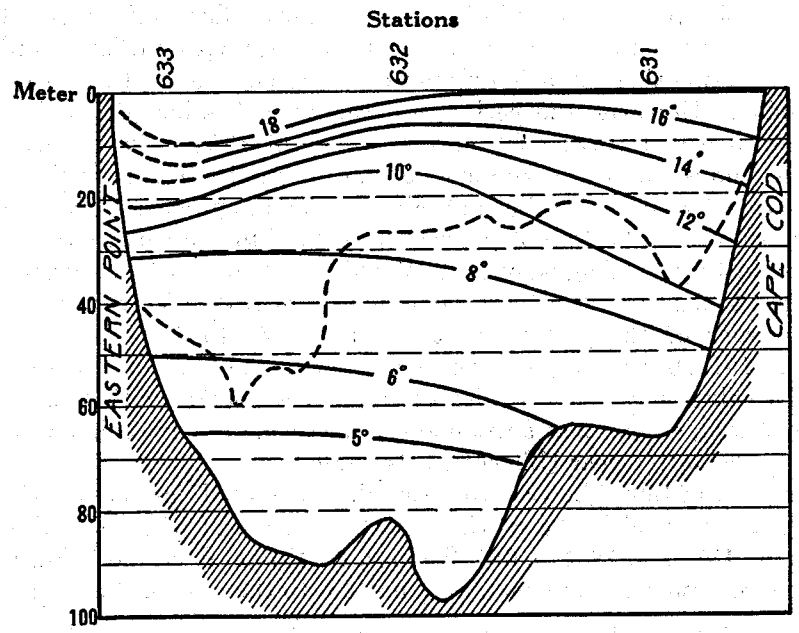

FIG. 66.—Temperature profile crossing the mouth of Massachusetts Bay from Gloucester to Cape Cod, August 22, 1922 (stations 10631 to 10633). The broken curve represents the shoalest contour of the bottom along the rim formed by Stellwagen Bank

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 aboüt 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	Temperature	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

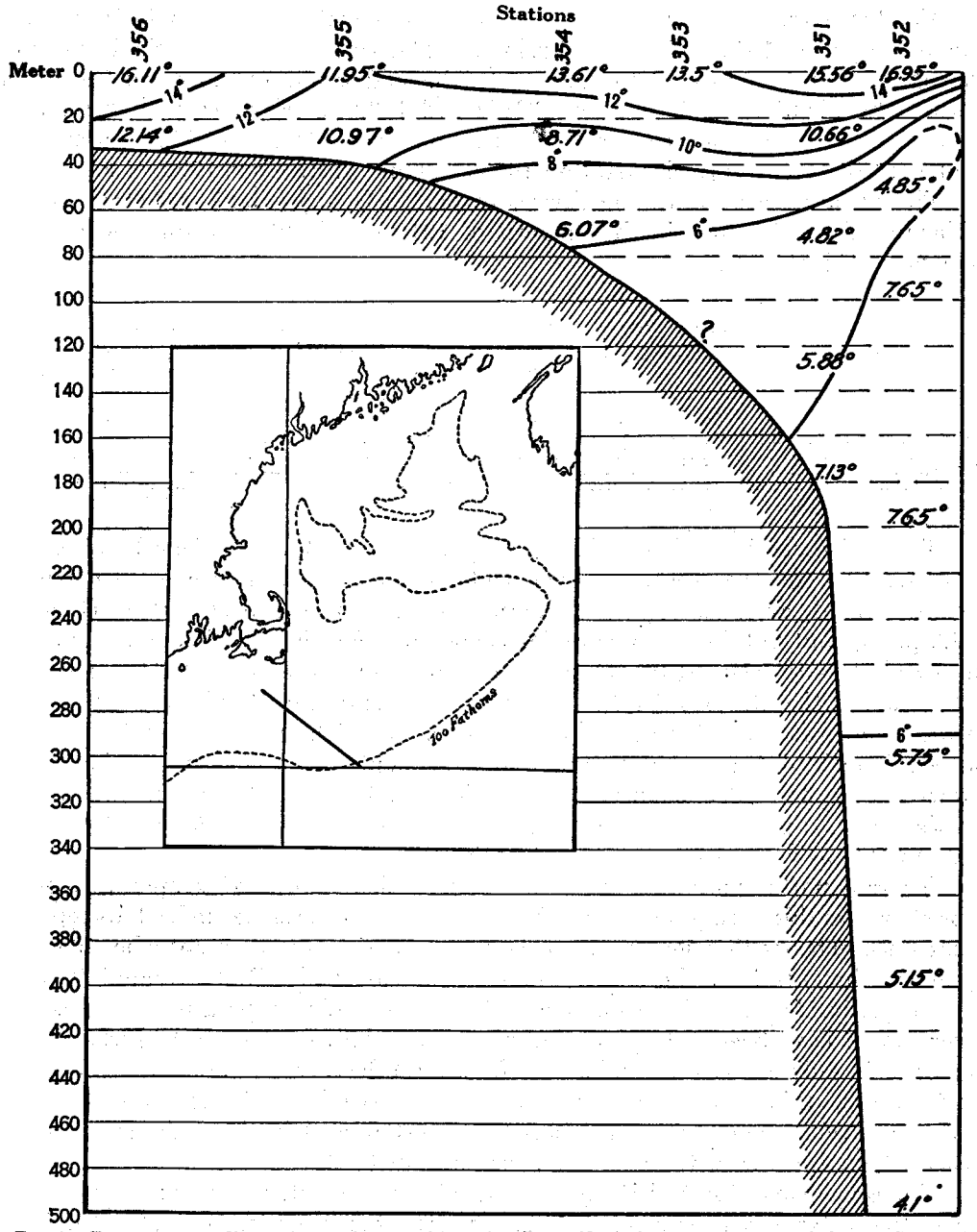

FIG. 67.—Temperature profile running southeastward from the offing of Nantucket to the continental slope of Georges Bank, July 24 to 26, 1916 (stations 10351 to 10356)

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 Eng-

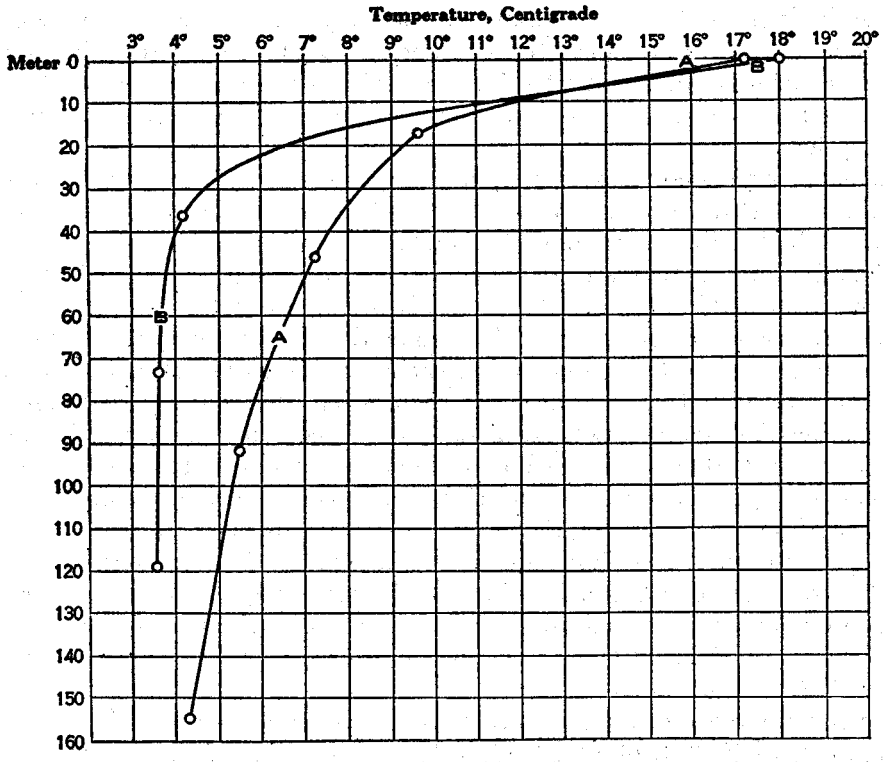

FIG. 68.—Vertical distribution of temperature off Cape Elizabeth on August 15, 1913 (A, station 10104), and on August 7, 1923 (B, latitude 43° 18′, longitude 69° 44′)

land 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).

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	18.9	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	6.8	
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	6.8	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	10.3
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	8.9	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).

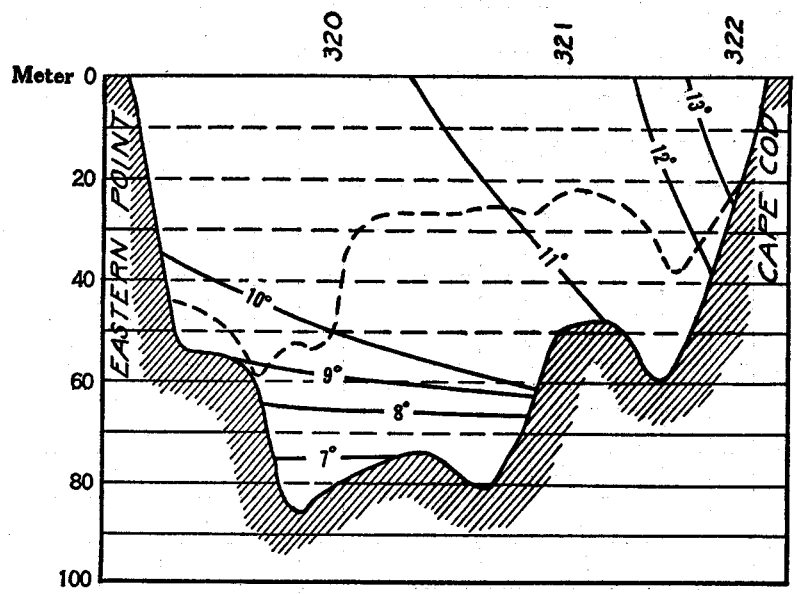

FIG. 69.—Temperature profile at the mouth of Massachusetts Bay, inside Stellwagen Bank, September 29 to October 1, 1915 (stations 10320 to 10322). The broken curve shows the contour of the bank

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

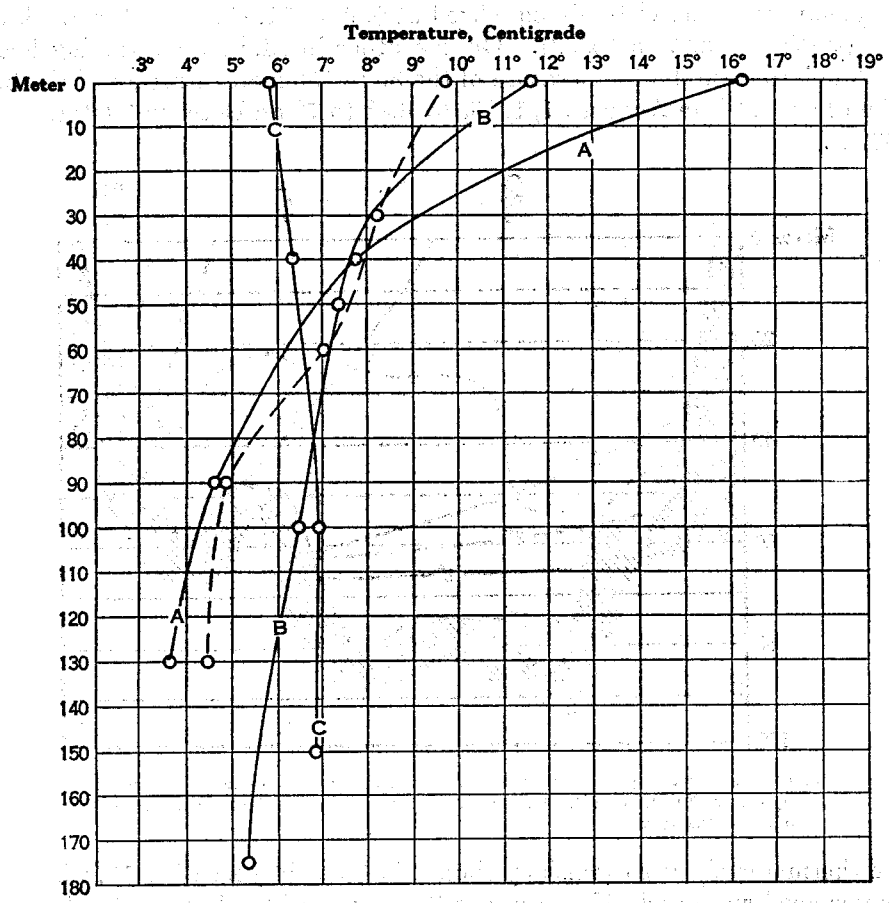

FIG. 70.—Vertical distribution of temperature in the trough between the Isles of Shoals and Jeffreys Ledge, to show the progress of autumnal cooling. A, August 15, 1914 (station 10252); B, October 4, 1915 (station 10325); C, December 30, 1920 (station 10493). The broken curve is for November 1 of the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

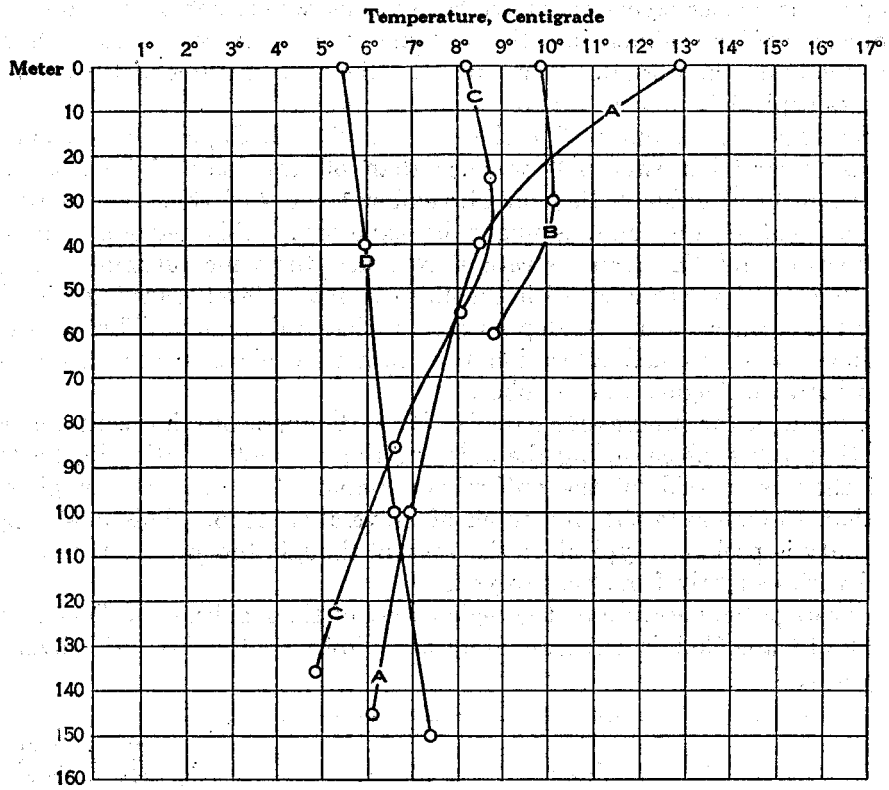

FIG 71.—Vertical distribution of temperature off Penobscot Bay at successive dates, to show the progress of autumnal cooling. A, August 14, 1914 (station 10250); B, October 9, 1915 (station 10329); C, November 2, 1916 (station 10402); D, January 1, 1921 (station 10496)

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.

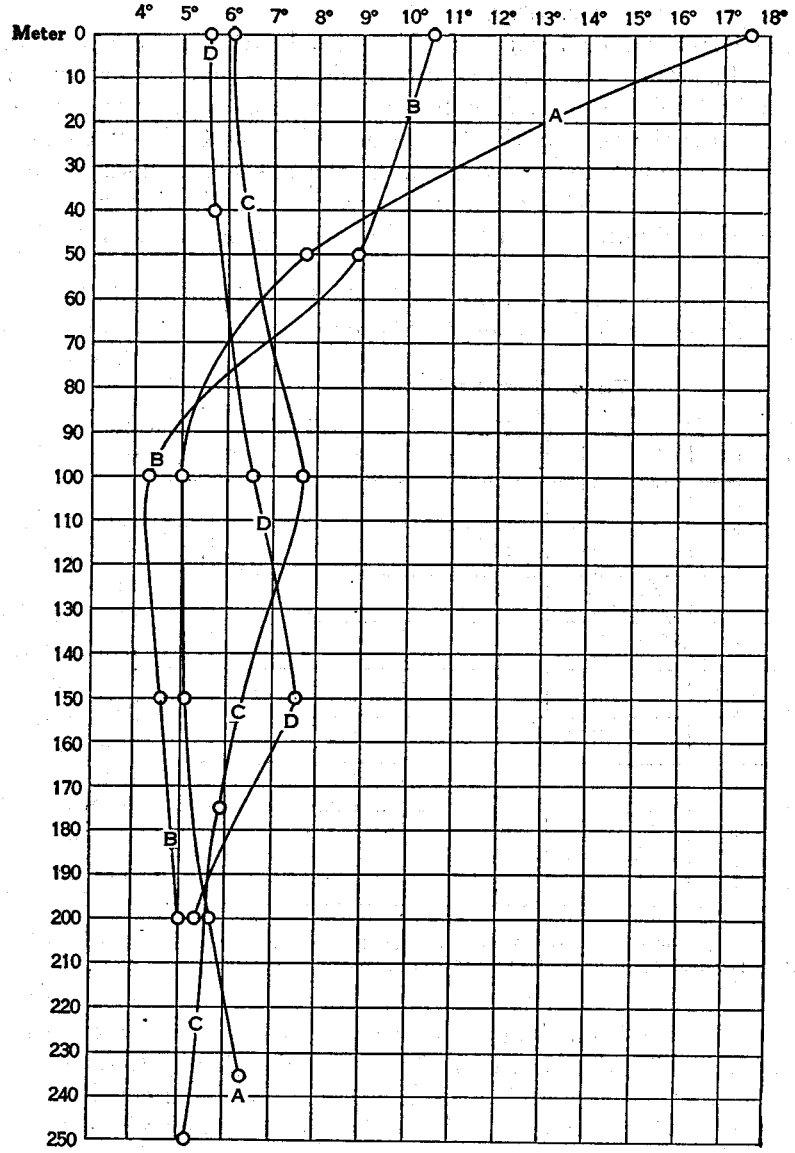

FIG. 72.—Vertical distribution of temperature in the western arm of the basin of the gulf in autumn and winter. A, August 31, 1915 (station 10307); B, November 1, 1916 (station 10401); C, December 29, 1920 (station 10490); D, January 9, 1921 (station 10503)

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 extralimital 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).

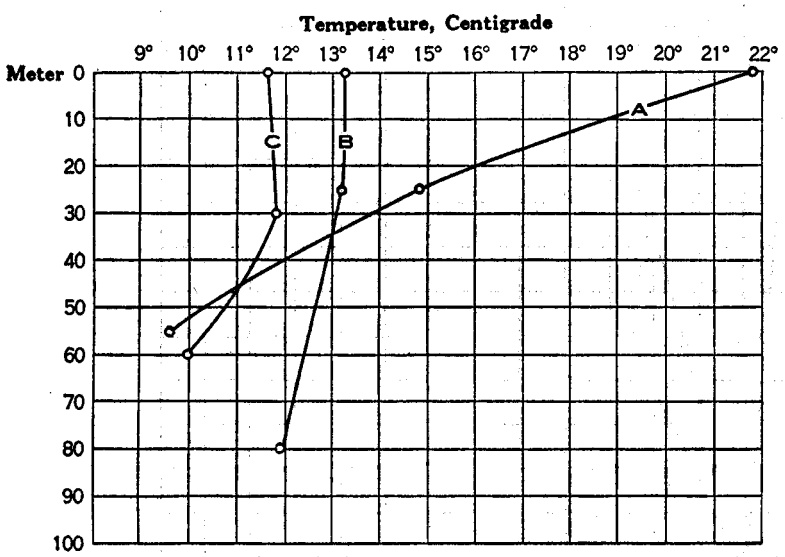

FIG. 73.—Vertical distribution of temperature off Marthas Vineyard to show autumnal cooling. A, August 25, 1914 (station 10259); B, October 22, 1915 (station 10333); C, November 1, 1916 (station 10406)

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

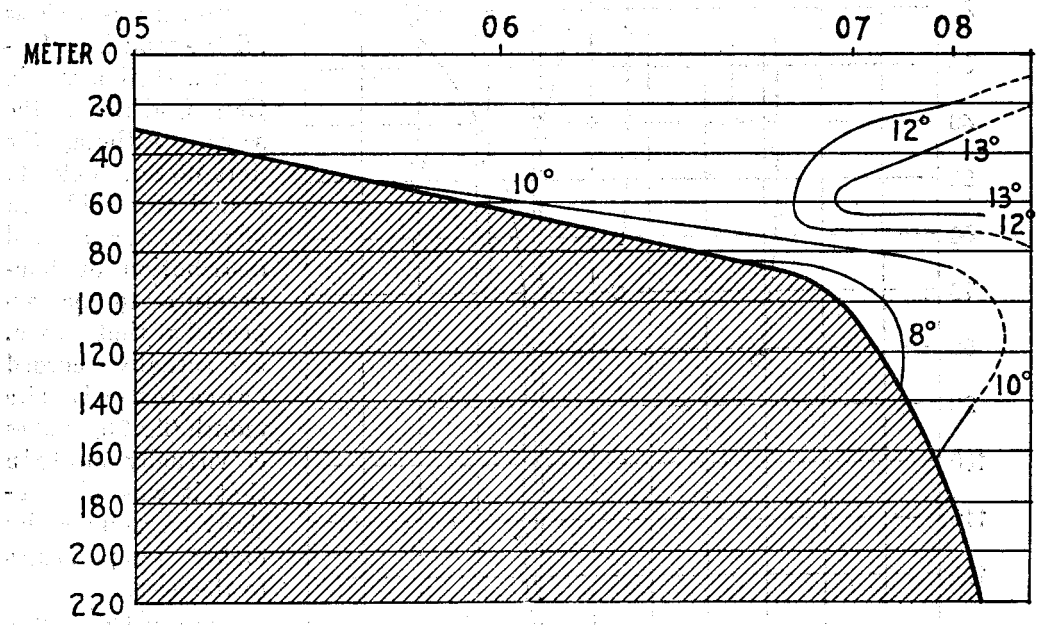

FIG. 74.—Temperature profile crossing the continental shelf off Narragansett Bay, November 10 and 11, 1916 (stations 10405 to 10508)

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.

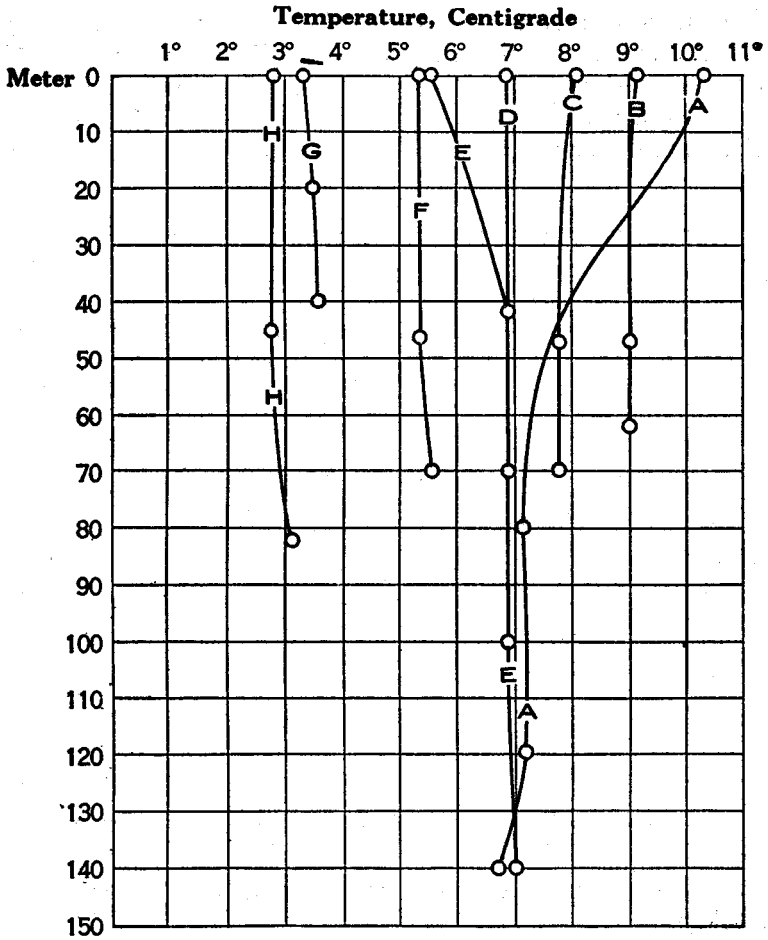

FIG. 75.—Vertical distribution of temperature in the offing of Gloucester on successive dates of the autumn and winter. A, October 1, 1915 (station 10324); B, November 20, 1912 (station 10047); C, December 4, 1912 (station 10048); D, December 23, 1912 (station 10049); E, December 29, 1921 (station 10489); 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 Glouces-

ter 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.

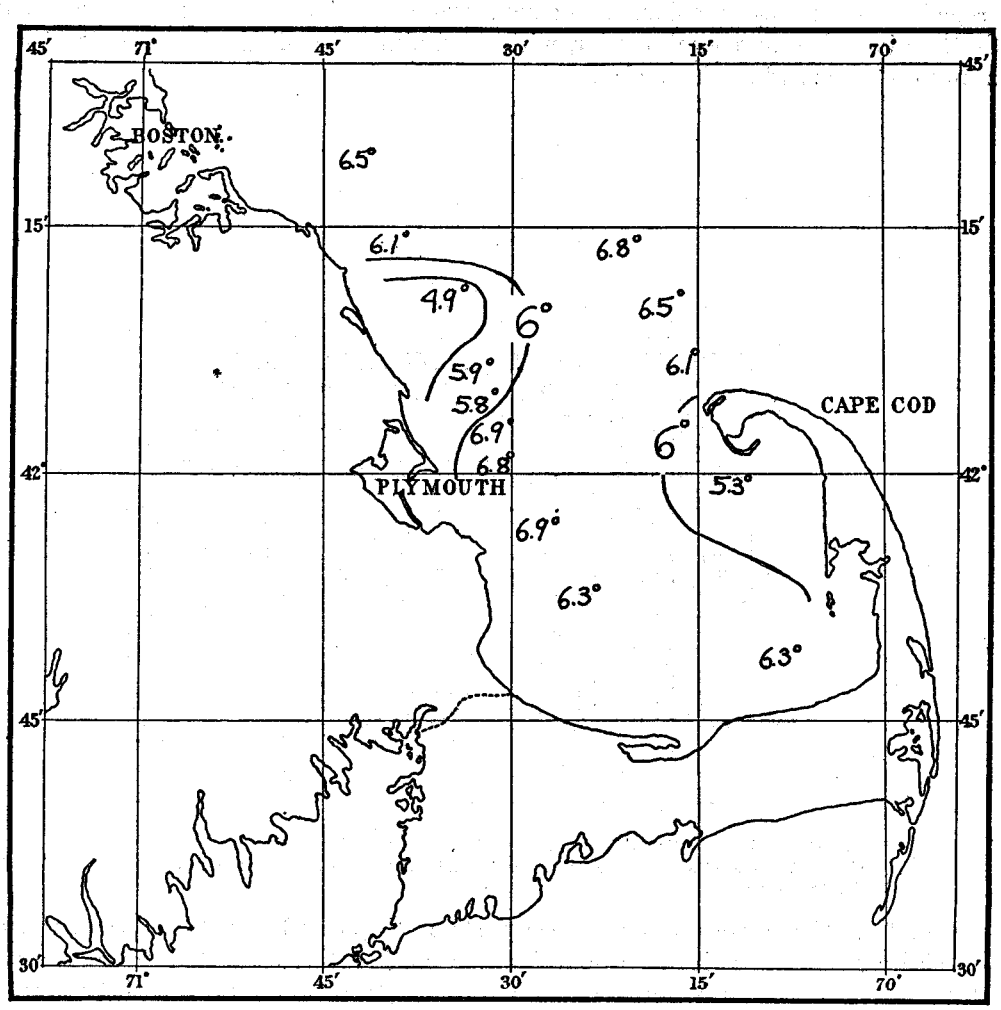

FIG. 76.—Surface temperature of Massachusetts Bay, December 9 to 11, 1924

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.

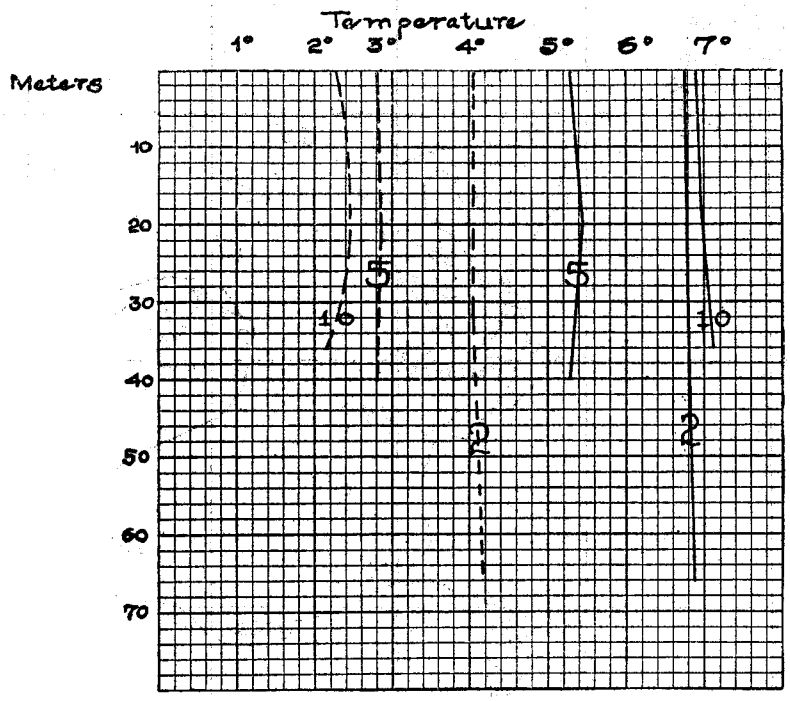

FIG. 77.—Vertical distribution of temperature at three representative stations in the southern side of Massachusetts Bay on December 9 to 11, 1924 (solid curves), and January 6 and 7, 1925 (broken curves).

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

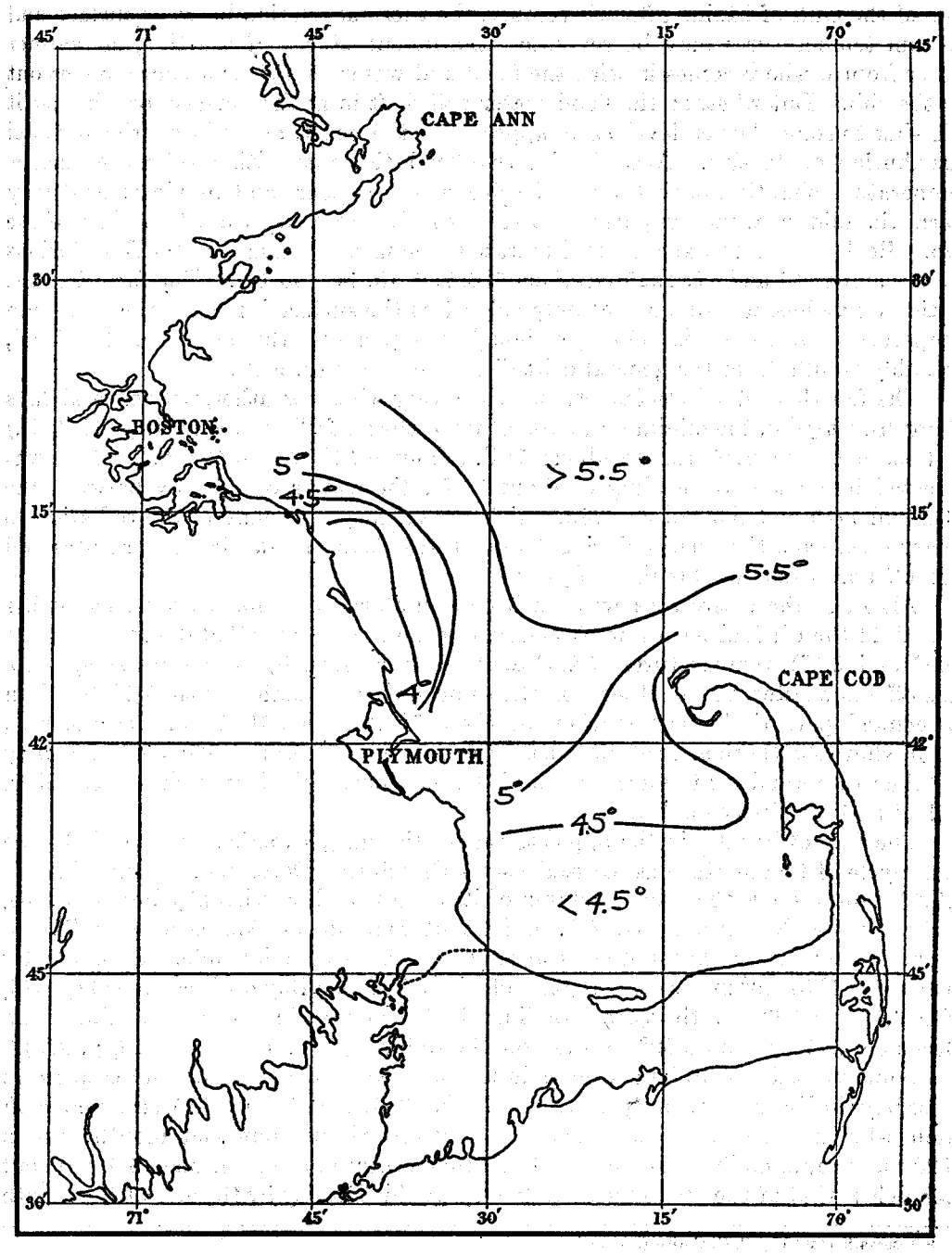

FIG. 78.—Minimum temperature of the southern side of Massachusetts Bay, irrespective of depth, December 16 and 17, 1924

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. (−18.3° 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.