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

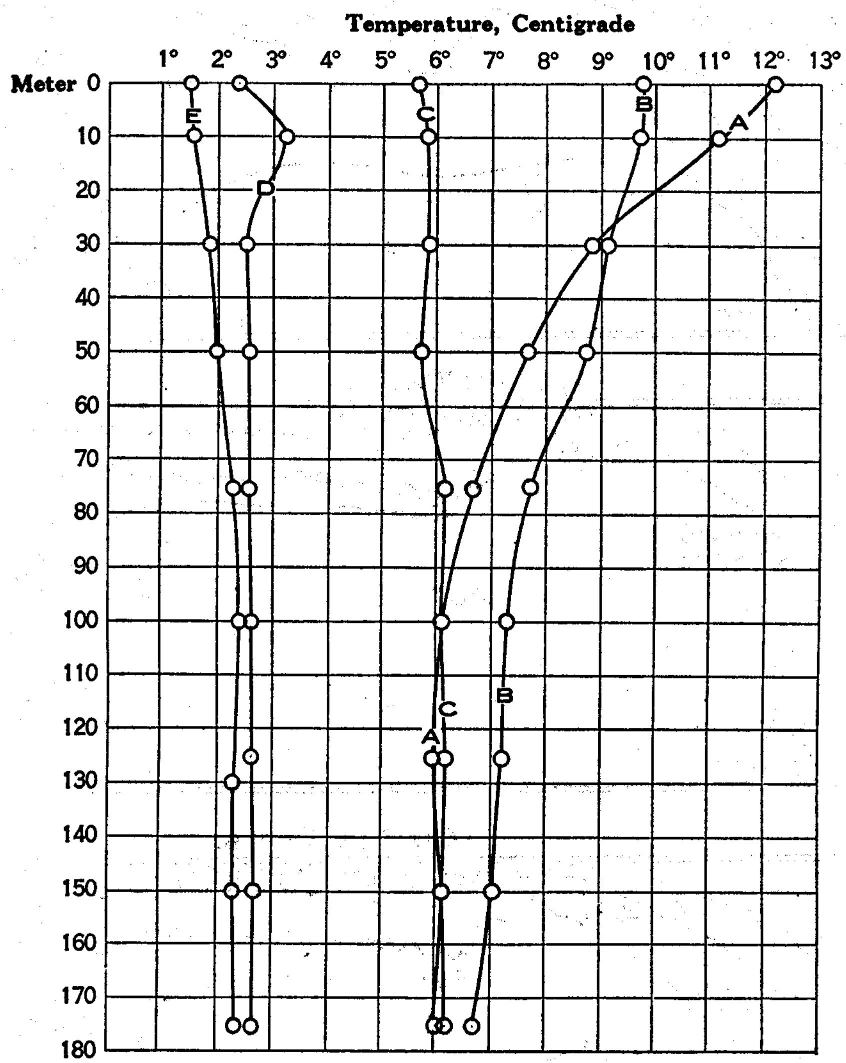

FIG. 79.—Vertical distributions of temperature at *Prince* station 3, in the Bay of Fundy, in autumn and winter, from Mavor's (1923) data. A, September 4, 1917; B, October 2, 1917; C, December 5, 1917; D, January 19, 1918; E, February 28, 1917.

MIDWINTER

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

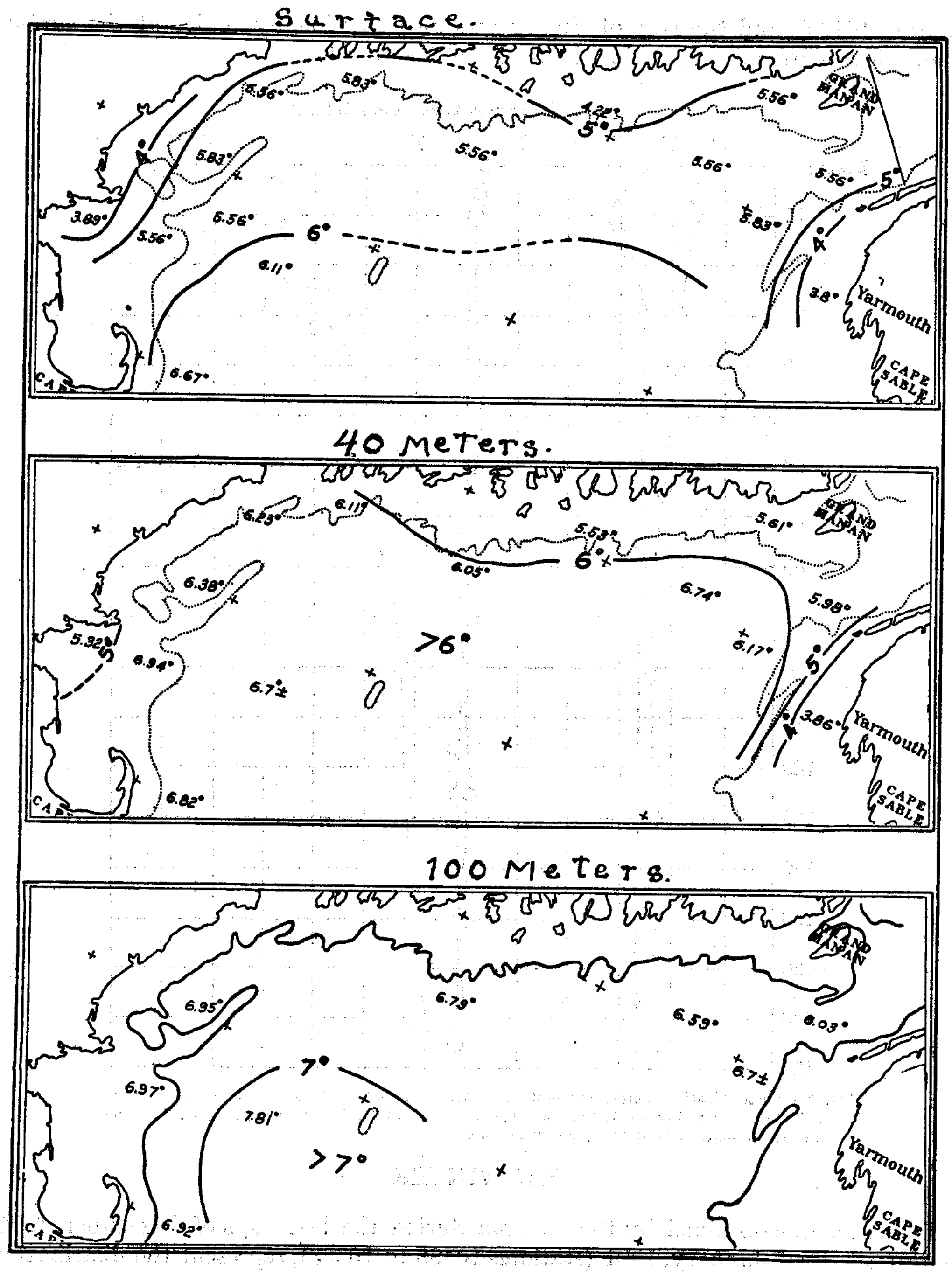

FIG. 80.—Temperature of the northern part of the gulf on the surface (upper chart), at 40 meters (middle chart), and at 100 meters (lower chart), December 29, 1920, to January 9, 1921

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

[46] The mean temperature of the air had been below normal at Boston on every day save three since Dec. 19.
[47] Gloucester Harbor, 42° 35′ N; Lubec Narrows, 44° 49′ N.

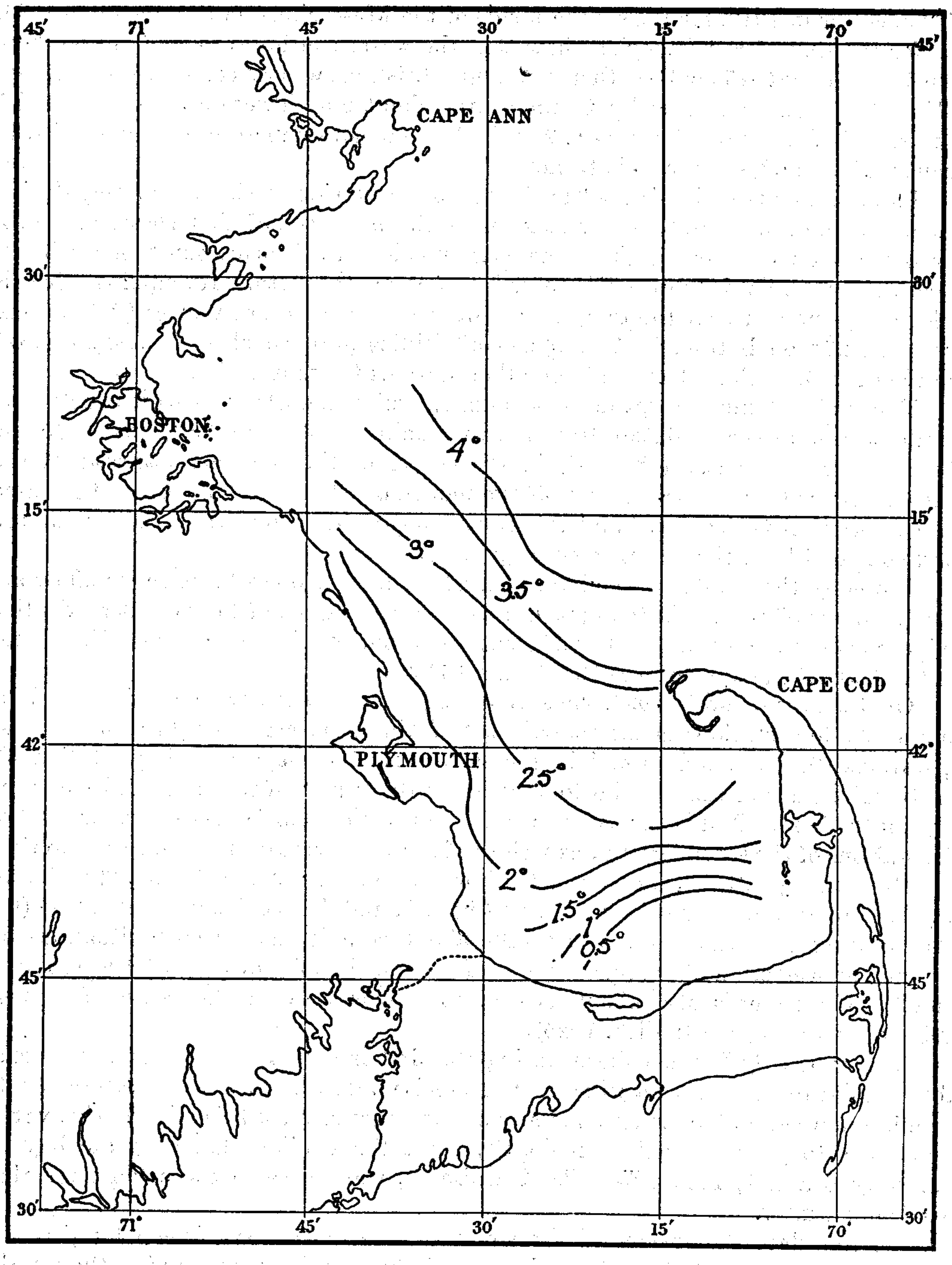

FIG. 81.—Surface temperature of the southern side of Massachusetts Bay, January 6 and 7, 1925

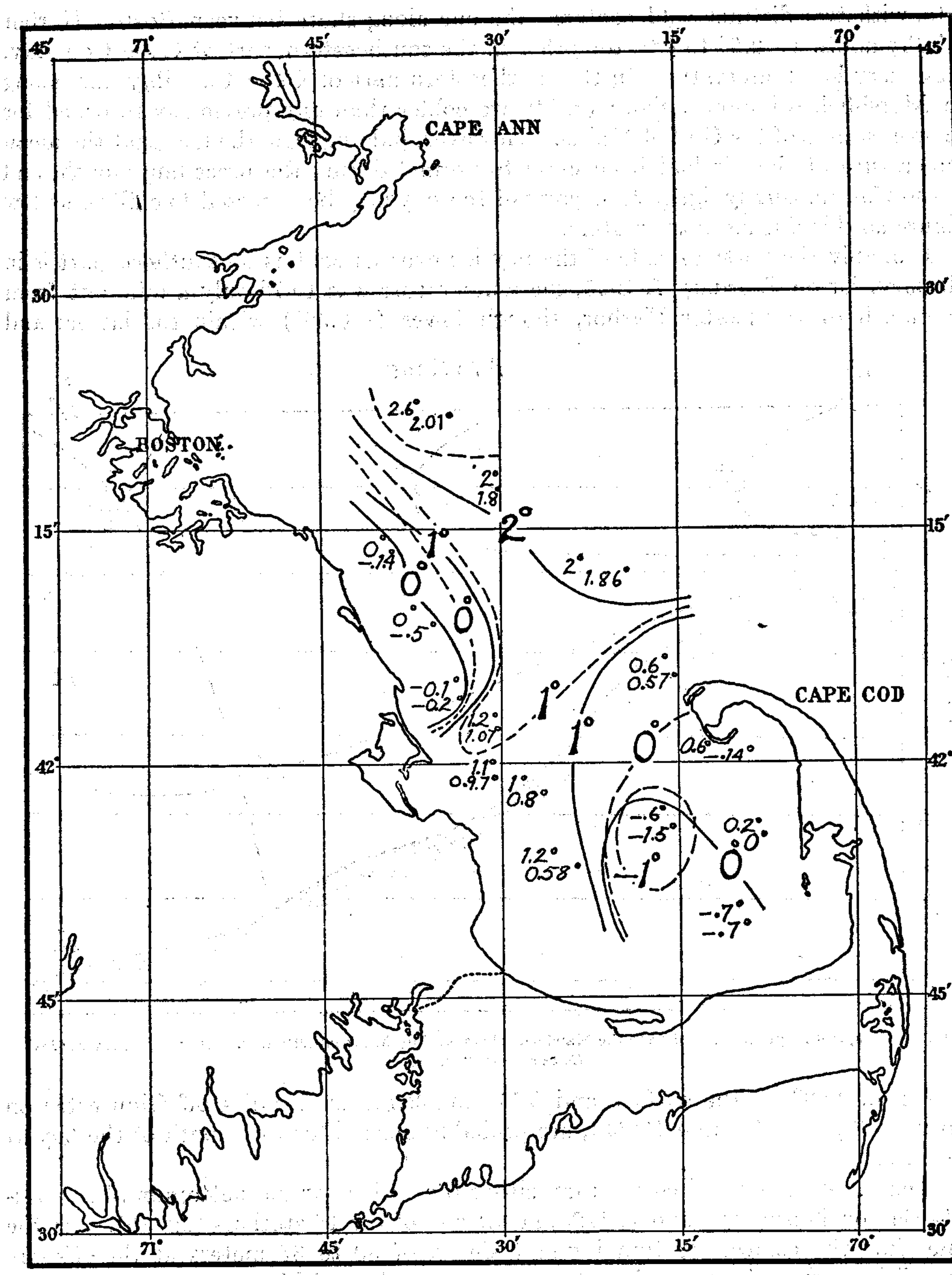

FIG. 82.—Surface temperature (solid curves) and minimum temperature (broken curves) of the southern side of Massachusetts Bay, February 6 and 7, 1925

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

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

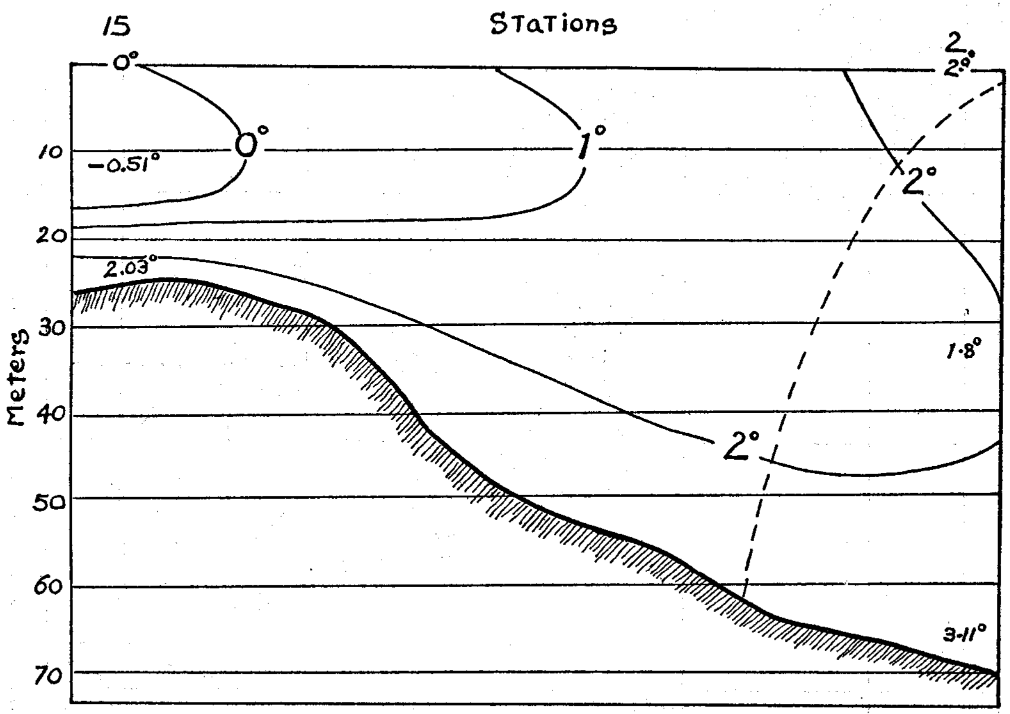

FIG. 83.—Temperature profile running from the Marshfield shore out into Massachusetts Bay, January 6 and 7, 2925 (*Fish Hawk* stations 2 and 15)

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

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

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

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

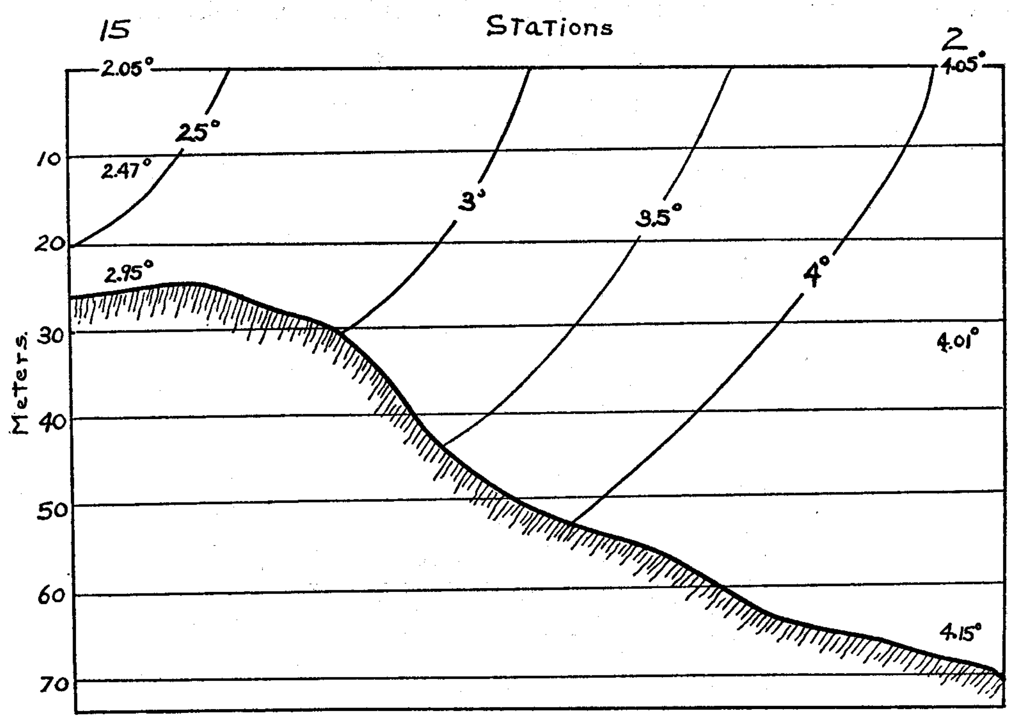

FIG. 84.—Temperature profile running from the Marshfield shore out into Massachusetts Bay, February 6, 7, and 27, 1925. The broken curve is the isotherm for 2° on February 24

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

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

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

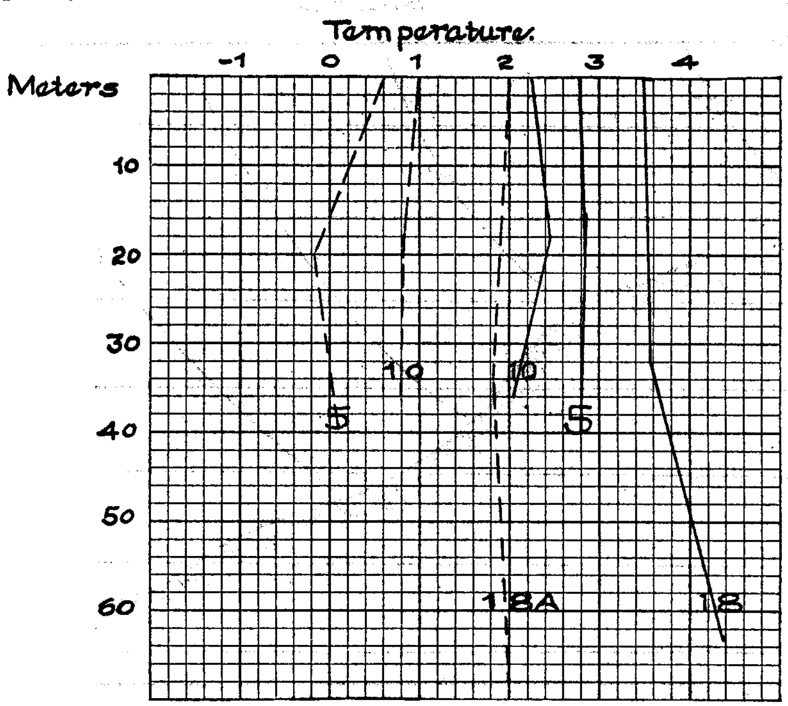

FIG. 85.—Temperature at three representative stations (5, 10, and 18 to 18A) in the southern side of Massachusetts Bay on January 6 and 7, 1925 (solid curves), and on February 6 and 7 (broken curves), to show change in one month

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

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

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

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

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

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

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

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

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

THERMAL SUMMARIES

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

1. MOUTH OF MASSACHUSETTS BAY, OFF GLOUCESTER

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

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

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

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

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

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

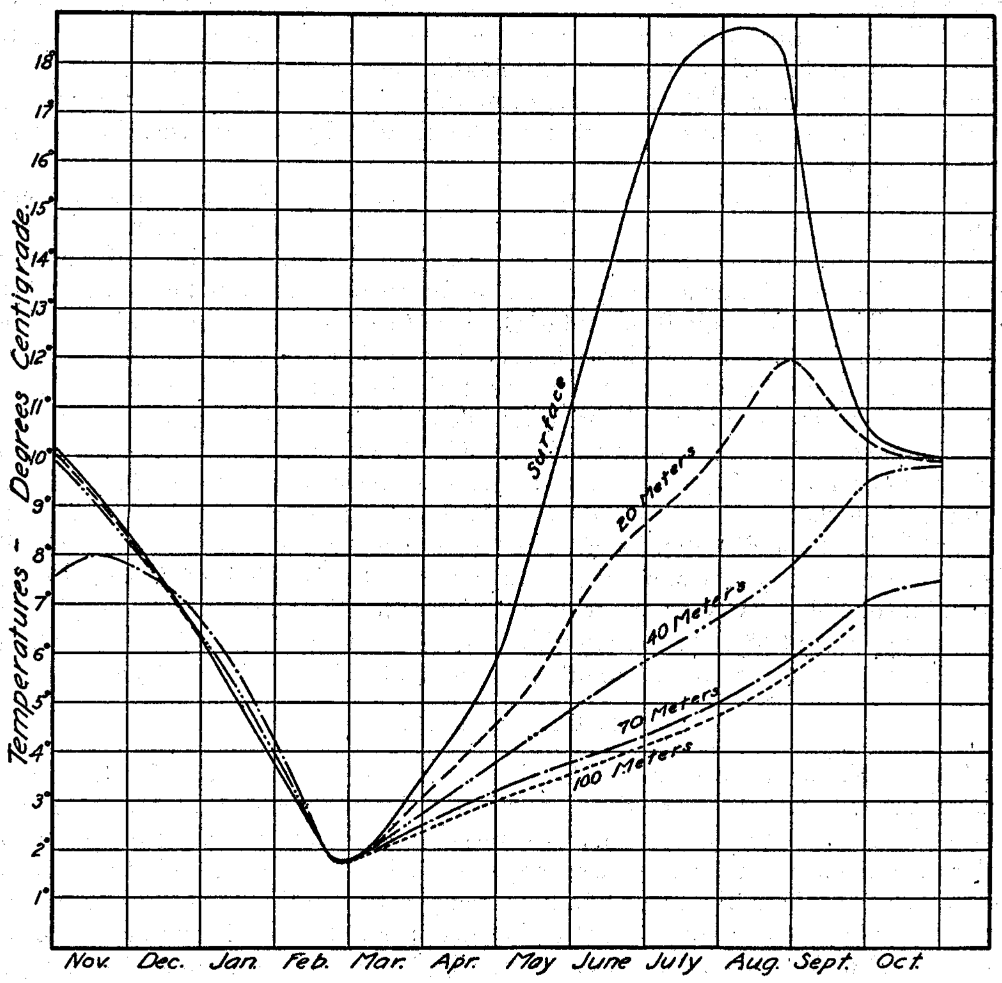

FIG. 86.—Composite diagram of the normal seasonal variation of temperature at the mouth of Massachusetts Bay, off Gloucester, at the surface, 20 meters, 40 meters, 70 meters, and 100 meters. The curves are smoothed. The station for August 9, 1923, is omitted because the water between the 20 and 150 meter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

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

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

2. BAY OF FUNDY

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

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

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

3. NEAR MOUNT DESERT ISLAND

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

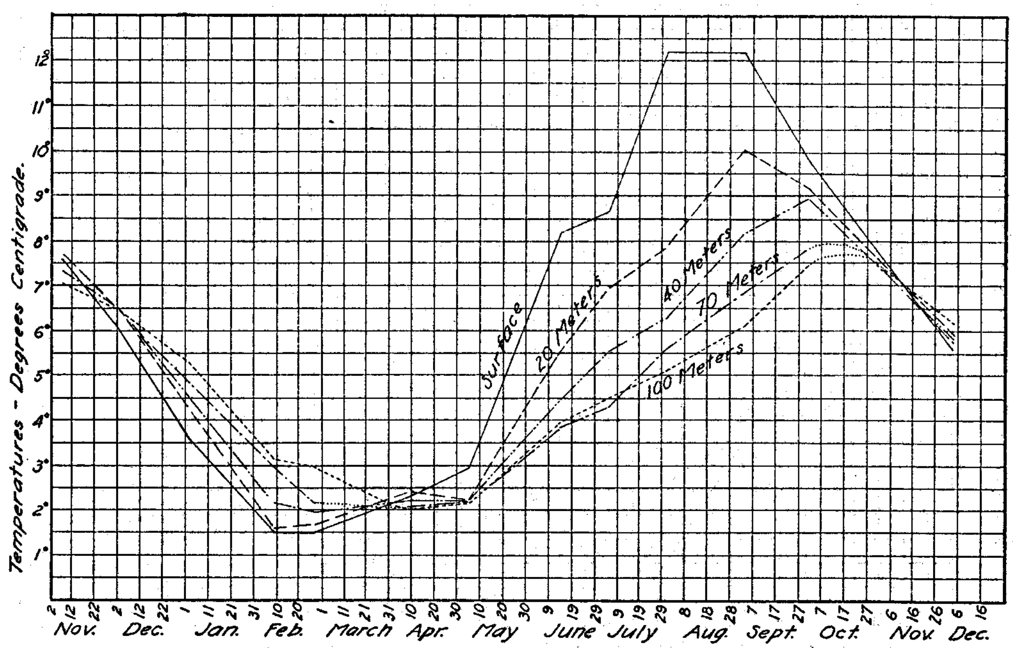

FIG. 87.—Composite diagram of the seasonal variations of temperature at *Prince* station 3, in the Bay of Fundy, between Grand Manan and Petite Passage, from November, 1916, to November, 1917, from Mavor's (1923) data

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

4. WESTERN SIDE OF THE BASIN

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

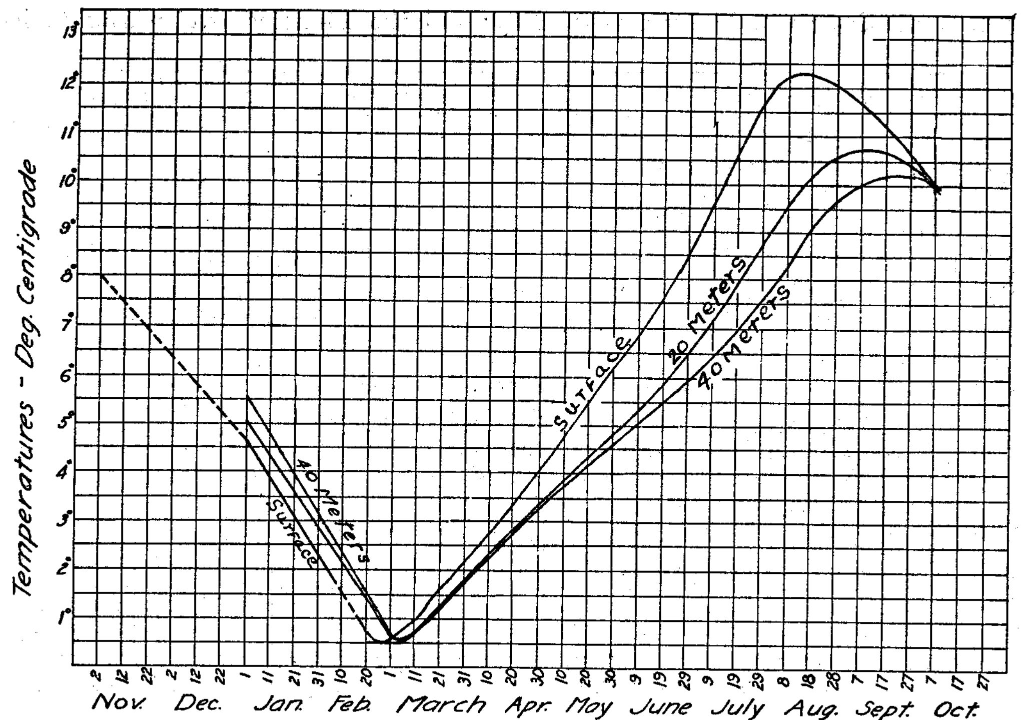

FIG. 88.—Composite diagram of the normal seasonal variations of temperature near Mount Desert Island, at the surface, 20 meters, and 40 meters, from data for the years 1915, 1920, 1921, and 1923. The curves are smoothed

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

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

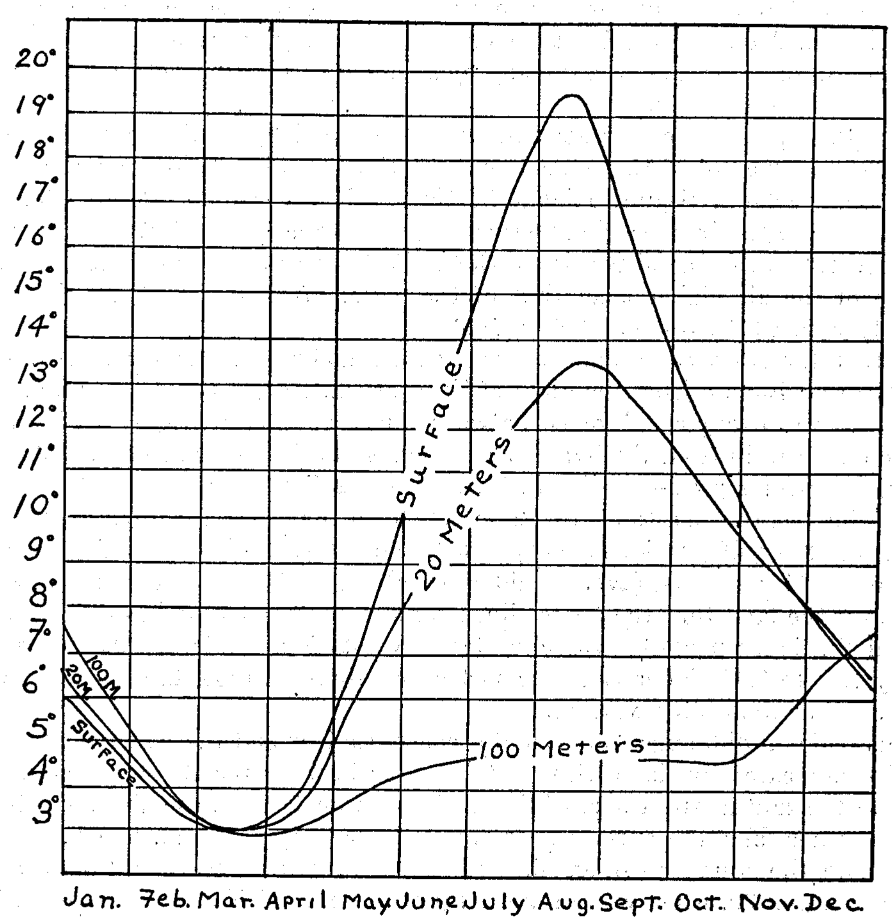

FIG. 89.—Normal seasonal variations in temperature at the surface, 20 meters, and 100 meters in the western side of the basin of the gulf, in the offing of Cape Ann, combined from the data for the several years and months. The curves are smoothed

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

RELATIONSHIP BETWEEN THE TEMPERATURE OF THE SURFACE AND OF THE AIR

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

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

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

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

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

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

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

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

General locality	Station	Date	Time	Amount by which air was warmer than water, °C.
Off Boston Harbor	20089	Apr. 6	3 p. m.	5.5
Off Gloucester	20090	Apr. 9	10.15 a. m.	1.0
Off Cape Ann	20091	...do	1.50 p. m.	5.7
Off Ipswich Bay	20092	...do	5 p. m.	2.5
Off Isles of Shoals	20093	...do	10.30 p. m.	.8
Platts Bank	20094	Apr. 10	3 a. m.	1.1
Near Cape Elizabeth	20095	...do	8 a. m.	1.9
Off Seguin Island	20096	...do	12.30 p. m.	9.4
Off Penobscot Bay	20097	...do	11 p. m.	1.0
Near Mount Desert Rock	20098	Apr. 11	4 p. m.	3.6
Near Mount Desert Island	20099	Apr. 12	1 p. m.	6.3
Northeast part of basin	20100	...do	4.30 p. m.	3.9
Do	20101	...do	9.30 p. m.	3.5
Off Yarmouth, Nova Scotia	20102	Apr. 13	2.15 a. m.	3.9
German Bank	20103	Apr. 15	1 p. m.	6.7
Off Seal Island, Nova Scotia	20104	...do	6 p. m.	4.7
North Channel	20105	...do	9.15 p. m.	4.1
Browns Bank	20106	Apr. 16	12.20 a. m.	3.5
Eastern Channel	20107	...do	4.35 a. m.	5.5
East edge of Georges Bank	20108	...do	8.50 a. m.	6.4
Southeast slope of Georges Bank	20109	...do	5 p. m.	5.8
East part of Georges Bank	20110	...do	8.30 p. m.	6.1
Do	20111	Apr. 17	1.15 a. m.	3.6
Southeast part of basin	20112	...do	5.35 a. m.	.7
Center of basin	20113	...do	1 p. m.	3.8
Near Cashes Ledge	20114	...do	8 p. m.	3.3
Basin off Cape Ann	20115	Apr. 18	3.40 p. m.	2.0
Off Cape Cod	20116	...do	9.55 a. m.	3.0
Do	20117	...do	1 p. m.	4.6
Cape Cod Bay	20118	Apr. 20	10.50 a. m.	8.3
Mouth of Massachusetts Bay	20119	...do	8.20 p. m.	6.9

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

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

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

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

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

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

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

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

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

Difference between surface and air temperatures (° C.)

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

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

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

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

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

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

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

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

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

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

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

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

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

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

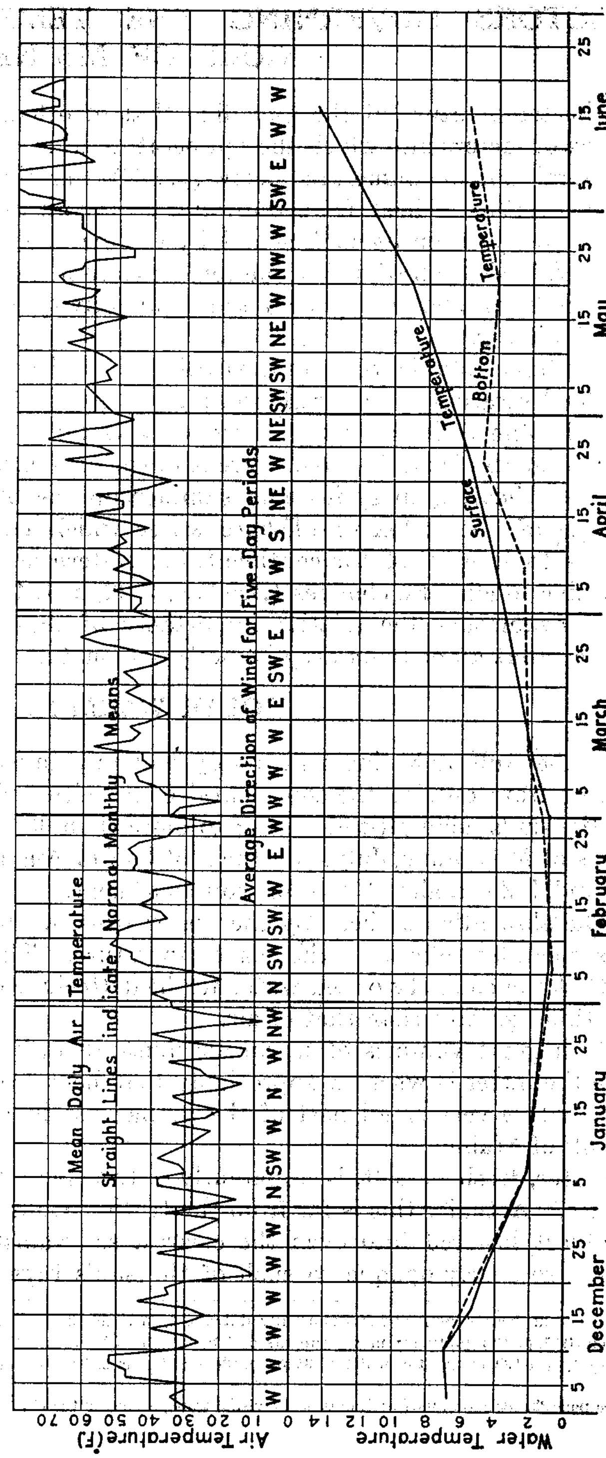

FIG. 90.—Surface and bottom temperatures off Plymouth, Mass. (*Fish Hawk* station 10, p. 1006); daily temperature of the air at Boston and direction of the prevailing wind from December 3, 1924, to June 17, 1925. Compiled by R. Parmenter

FACTORS GOVERNING THE TEMPERATURE OF THE GULF OF MAINE

The temperature of the gulf, like that of other boreal seas, is governed by a complex of factors into which the temperature of the water that enters the gulf from the several sources enumerated below (p. 854), warming by the sun's rays, and cooling by the radiation of heat from the water to the air in autumn and winter, as well as by evaporation from its surface and by the melting of snow (and locally of ice), all enter. Added to all of which the temperature at any given depth, date, and locality depends to a large degree on the local activity of vertical circulation, especially of tidal stirring.

Continued studies confirm the earlier generalization that the temperature of the superficial stratum of the gulf down to a depth of about 100 meters is governed chiefly by the chilling caused by rigorous winter climate and by the influx of cold water from the Nova Scotian current in spring, on the one hand, balanced against local solar heating in spring and summer, on the other, and against the warming influence of the influx of offshore water which enters its eastern side. As the gulf lies to leeward of the continent, its western and northern sides are the most responsive to climatic changes (Bigelow, 1922, p. 164).

In evaluating the relative importance of these several processes it is to be observed that all of them are distinctly seasonal in their effects.

SOLAR WARMING

In the Gulf of Maine, which very seldom is invaded by warm water from the south or from outside the continental edge—situated, too, at a temperate latitude, with the sun's noon altitude rising to more than 63° above the horizon during the months of May, June, July, and the first half of August—solar heating *in situ* is the chief and, indeed, almost the sole source of heat.

The absorption of heat by the water from warm air blowing over its surface exerts much less effect on the sea temperature. This last statement rests on the fact that the capacity of sea water for heat (technically its specific heat [50]) is about 3,000 times greater than that of air.

Such great volumes of warm air must, then, blow over the surface of the sea before the latter is warmed appreciably that heat from this source can be responsible for only a very small part of the vernal rise in temperature that characterizes the Gulf of Maine.

Water, fresh or salt, is apparently a transparent fluid when viewed in small volumes. Actually this is far from the truth. Consider, for example, how rapidly any object lowered into even the clearest sea vanishes from sight.[51] In fact, sea water is so nearly opaque to such of the sun's rays as convey most of its energy

[50] The specific heat of distilled water is usually stated as 3,257 times that of air. Sea water has slightly less capacity for heat, Krümmel (1907, p. 279) quoting from experiments by Thoulet and Chevalier (1898), giving the specific heat of water of 30 per mille salinity as 0.939 and that of water of 35 per mille salinity as 0.932, both at 17.5° temperature, taking distilled water as unity.

[51] See page 822 for actual measurements of the visual transparency of the Gulf of Maine at various times and places.

that only a very thin surface stratum of the sea is warmed by direct solar radiation. Further transference of the heat so gained, downward to the deeper strata, depends on other processes, discussed below (p. 678).

Oceanographers, therefore, long have realized that the thickness of the stratum that receives the heat of the sun directly depends on the distribution of this energy along the solar spectrum and on the transparency or opacity of the water toward rays of different wave lengths, which, in turn, depends largely on the clarity or turbidity of the water.

The altitude of the sun—i. e., the angle at which its rays strike the surface of the water—and the roughness of the water determine what percentage of the total radiation is reflected and what percentage penetrates. No attempt has yet been made to measure this for the Gulf of Maine; but there is no reason to suppose that the latter differs much in this respect from Puget Sound, where Shelford and Gail (1922) found about 25 per cent of the light reflected or shut out by the surface mirror between 10 a. m. and 2 p. m. in calm weather, with the loss increasing to 60 to 70 per cent, or even more, when the sea was rough. On the average, then, about 50 per cent of the solar radiation falling upon the gulf may be expected to warm the latter; the remainder is lost, so far as any direct effect on the temperature of the water is concerned.[52]

When we attempt to estimate the warming effect which the 50 per cent or so that does penetrate actually exerts at any given level, we must keep clearly in mind the distinction between the intensity of radiation and the extreme penetration of light. The latter has been the subject of repeated experiments, and, as might be expected, successive tests with more and more delicate photographic apparatus have revealed faint light at greater and greater depths. The mere fact, however, that light penetrates to depths as great as 1,000 to 1,700 meters [53] in amount sufficient to affect photographic plates does not imply an equal penetration of radiant heat in measurable amount, witness the fact that stars—even nebulæ—can be photographed though their heat is not appreciable on the earth. On the contrary, theoretic calculation and practical experiments unite to prove that the intensity of solar radiation falls off very rapidly as the depth increases, especially for the longer wave lengths.[54]

Hulburt (1926) has found that sea water is slightly more opaque than fresh water for the shorter wave lengths but shows about the same coefficient of absorption as fresh water for the longer.

The long waves below the visible end of the spectrum (the so-called "infra red" or "heat" rays) convey more energy than all the rest of the spectrum combined, bringing from 51 to 67 per cent of that part of the total energy of the sun that penetrates to the earth's surface near sea level through air of the same general order of humidity as prevails over the Gulf of Maine (Abbott, 1911, p. 289). The precise percentage conveyed by these infra red rays varies with the altitude of the sun.

[52] This is a much greater loss by reflection than Schmidt (1915) found for fresh-water lakes, where he records only a 6 per cent loss with the sun 30° above the horizon. Probably the state of the surface accounts for the difference

[53] See Helland-Hansen (1912); Grein (1913).

[54] For the coefficient of absorption of the visible part of the spectrum in pure water, see Krümmel (1907), Fowle (1920), and Kayser (1905).

I know of no direct measurements of the depth to which the infra red rays do actually carry heat into the sea water in measurable amount under the conditions of turbidity actually existing at sea, but even distilled water is so nearly opaque to them that they are almost entirely absorbed (for practical purposes, entirely so) in one meter, and their penetration into the sea is certainly less. That is to say, nearly half of the sun's direct radiant heat is expended, theoretically, upon this thin surface film.

According to a calculation carried out in the physical laboratory of Harvard University through the kindness of Prof. Theodore Lyman, 58 per cent of the energy conveyed by the visible part of the solar spectrum would be absorbed by passage through 9 meters more (i. e., a total of 10 meters) of perfectly clear distilled water, so that only about 20 per cent of the total solar energy entering the water would penetrate as deep as 10 meters, this small residual lying chiefly in the blue-green part of the spectrum. Certainly less than 1 per cent could penetrate as deep as 200 meters—chiefly in the ultra violet. Probably this calculation would apply equally to pure salt water. The sea, however, is never clear; and in boreal coastwise waters such as the Gulf of Maine, which are always comparatively turbid, the fine particles in suspension—silt or plankton—absorb so much of the sun's rays that the penetration of heat is much reduced.

It is, of course, with the depth to which the water of the gulf is measurably warmed by the direct penetration of solar radiation under conditions actually prevailing there that we are now concerned. This may be approximated by experiments that have been made in other seas. In the comparatively clear water of the Mediterranean, off Monaco, Grein's (1913) measurements[55] of the penetration of different parts of the solar spectrum showed that the wave lengths as long as the blue-green, and longer, were virtually all absorbed in the upper 50 meters, red-yellow in the upper 10 meters, as appears in the following table condensed from his account.

Intensity of light penetrating to different depths, taking the amount at 1 meter as 100

Depth, meters	Color and wave length					
	Red, 680–610	Orange-yellow, 620–585	Green, 570–486	Blue-green, 515–486	Blue, 475–420	Blue-violet, 435–400
1	100.00000	100.0000	100.0000	100.0000	100.000	100.0
10	.27000	.2000	16.6000	16.6000	43.700	80.0
50	.00021	.0032	.2200	.2500	20.100	20.0
100		.0001	.0030	.0033	.550	1.0
200			.0004	.0010	.004	.1

Translated into terms of solar energy, this means that at least 70 per cent of all the radiant solar heat that penetrated as deep as 1 meter was absorbed at a depth of 10 meters; and as nearly all of the energy of the infra red certainly was absorbed in that upper meter of water, it is not likely that more than 13 per cent of the solar heat that entered the water at all reached as deep as 10 meters by direct radiation,

[55] These experiments were made with a "revolving photometer," for description of which, and of the method by which the degree of blackening of the photographic plates was measured, see Grein (1913).

and virtually all of this residue was absorbed shoaler than 50 meters. Grein's exacting measurements, therefore, confirm Knott's (1904) conclusion that a. m. and p. m. temperatures taken by the "Pola" at 16 pairs of stations, with thermometers graduated to 0.1° C., showed no evidence of the penetration of direct solar radiation deeper than about 20 meters.

In more turbid northern seas we may expect the solar radiation to be absorbed in a still shoaler surface stratum, depending largely on the character and abundance of the plankton at the time. In Puget Sound, for example, Shelford and Gail (1922) found the first meter of water absorbing about 20 per cent of the visible light that actually penetrates below the surface, with only 8 to 10 per cent of even the shorter wave lengths reaching a depth of 10 meters under average illumination.

In the English Channel, Poole and Atkins (1926) found the illumination at 20 meters to be about 5.5 per cent as strong as just below the surface; while in the Bay of Fundy, according to Klugh (1925), only about 1.5 per cent of the illumination recorded just below the surface penetrates to 10 meters in August in bright sunlight.

In Lake Seneca, New York (probably still more turbid), Birge and Juday (1921) found that only 15 per cent of the solar energy that entered the water penetrated to a depth of 2 meters, 5.4 per cent to 5 meters, and only 1 per cent to 10 meters. Perhaps as striking an example as any in nature of the absorption of the sun's heat by the uppermost stratum of water is afforded by certain oft-quoted salt-water basins along the west coast of Norway, in which the salinity is very low at the surface but so high from the depth of 1 meter downward that the water is in extremely stable equilibrium. Here solar radiation in summer induces temperatures as high as 20° to 30° in the upper 2 meters of water but hardly affects the temperature deeper than about 5 meters. (See Helland-Hansen, 1912a, p. 65, for a discussion of these "Polls," as they are named locally.)

Judging from the similarity in latitude and in general hydrographic conditions, the penetration of solar radiation is probably of about the same order of magnitude in the open Gulf of Maine as in Puget Sound. If, then, the water of the gulf were entirely without motion, and if heat were conveyed downward by no other means than direct solar radiation, more than 90 per cent of such of the sun's radiant energy as penetrated the water at all would be expended within 10 meters of the surface, something like 98 per cent within 25 meters of the surface, and all but a fraction of 1 per cent at a depth of 100 meters. At times of year when the water was particularly turbid—spring, for example, during the active flowerings of diatoms—the solar radiation would be absorbed still more rapidly.

We must also bear in mind that that part of the sun's insulation which is intercepted by the superficial stratum of water does not act solely to warm the latter, but that a part of its energy is expended directly in evaporating water vapor from the surface (p. 680).

Under the conditions existing in the gulf it seems that if direct solar radiation warms the surface by 20° at any given locality in the gulf, the 10-meter level would certainly warm by only about 2°, very probably the 50-meter level would warm by no more than 0.2°, and the 100-meter level would not suffer change sufficient for our most delicate deep-sea thermometers to record during the part of the year when the water is gaining heat, unless this heat were carried downward into the deeps by some other process. The warming by direct solar radiation would therefore be virtually negligible during a single summer at depths greater than about 50 meters if there were no vertical circulation, this limit varying with varying states of turbidity and with the roughness or smoothness of the surface of the water as well as with the cloudiness of the sky, the haziness of the atmosphere, the percentage of foggy days, etc.

DISPERSAL OF HEAT DOWNWARD INTO THE WATER

With at least nine-tenths of the solar energy that enters the water of the gulf at all absorbed within 10 meters of the surface, and virtually all of it shoaler than 30 to 50 meters, the importance of vertical circulation in carrying down into the deeps water that has been warmed at the surface, and by bringing cold water up within the influence of the sun from below, becomes at once apparent.[56]

The vertical circulation of the gulf is discussed in another chapter (p. 924). It concerns us here, however, as the factor that chiefly governs the temperature of the mid-stratum between the depths of, say, 25 and 100 meters. In different parts of the gulf and at different seasons we find all gradations from water so stable, vertically, and with currents so weak that virtually no interchange takes place between the different strata, to the opposite extreme where the whole column is kept so thoroughly churned by tidal currents that the heat absorbed by the surface is uniformly dispersed downward. This last state characterizes nearly the entire area of the gulf during the first days of spring and is responsible for the fact that the whole upper stratum, down to 100 meters, at first warms at so nearly uniform a rate.

The vertical uniformity of temperature that characterizes Nantucket Shoals, locally, too, Georges Bank, parts of the Bay of Fundy, and the coastal belt along the west coast of Nova Scotia, results similarly from tidal stirring so active that it overcomes the tendency of the water to become stable as the spring progresses. Off the western shores of the gulf, however, where tidal stirring is not active enough to counteract the increasing stability of the column induced by the warming of the surface, the development of a light stratum at the surface tends more and more to insulate the deeper strata of water from the effects of solar warming as the season advances. The more stable the water becomes, the more effectively are the deeper strata protected in this way from thermal influences from above.

It is this obstacle, which the stable state of the water opposes to vertical circulation during the warm half of the year, which is responsible for the fact that the temperature rises so much more rapidly and to so much higher a value at the surface than only a few meters down, and which allows the persistence of much lower temperatures at depths of only 50 to 100 meters all summer. However, there is always enough vertical movement of the water everywhere in the Gulf of Maine to prevent this insulation of the deeper strata from becoming as effective as it is along the coast from New York, southward, during some springs (Bigelow, 1922).

Observations taken during our first cruises in 1912 (Bigelow, 1914) pointed to local differences in the strength of the tidal currents as chiefly responsible for the fact that the surface is so much colder, but the bottom, depth for depth, so much warmer along the coast of Maine east of Penobscot Bay and in the Bay of Fundy

[56] Conduction and the radiation of heat from one particle of heat to the next are negligible in this respect. (Wegemann, 1905; Krümmel, 1907.)

than it is off the western shores of the gulf in summer. The following exposition may more graphically explain this general phase of the gulf temperatures:

Let us assume two localities, both with an initial temperature of 2°, surface to bottom, but with vernal heating in the first (*a*) uniformally propagated downward through the whole column to a depth of 50 meters by active tidal stirring, but absorbed in regularly increasing ratio, with increasing depth, at the second (*b*), to *nil* at the bottom. If enough heat were received at the surface to warm the whole column at *a* to a temperature of 10°, the same amount of heat entering the water at *b* would warm the surface to 20° there, but not affect the temperature at all 50 meters down. The ideal condition represented by *a* is most closely paralled in the Gulf of Maine area by the most tide-swept parts of the Bay of Fundy region. An approximation to the vertical distribution of temperature at *b* is to be found in the western side of the basin off Cape Ann, where the surface warms from a winter minimum of about 3° in February to a summer maximum of about 19° to 20° in August, but where the temperature of the 50-meter level rises by only about 1° during the same interval. The relative rates at which heat is dispersed downward in these two parts of the Gulf of Maine correspond directly to the relative activity of the tidal currents, which are weaker in the deep water in the offing of Cape Ann than anywhere else in the Gulf of Maine.

THERMAL EFFECTS OF UPWELLINGS

Upwellings of water from below have little effect on the temperature of the surface stratum of the gulf in winter, because the whole column of water is then so nearly homogeneous that the rising currents have about the same temperature as the water which they replace. From April on, however, the upwellings that follow offshore winds in the western side of the gulf are reflected in a chilling of the surface, as described above (p. 550). This is not the case in the eastern side, however, or on the banks, where tidal stirring keeps the water more nearly homogeneous, vertically, throughout the warm season as well as the cold. The relationship between these upwellings from small depths and the temperature of the surface water is sufficiently described in connection with the midsummer state of the gulf (p. 588). I need only add that the thermal effect of vertical circulation of this sort along our New England coast has long been appreciated and has recently been discussed by Brooks (1920).

THERMAL EFFECTS OF HORIZONTAL CIRCULATION WITHIN THE GULF

The effects of the transference of cold water by the Nova Scotian current is discussed below (p. 680). A word is also in order as to the opposite process. The transference of heat, from the tropics to high latitudes, by the great ocean currents, is reflected on a very small scale in the Gulf of Maine in summer by the drift of surface water, warmed in the western side, across to Nova Scotia by the dominant anticlockwise drift. The outflow from the eastern end of Nantucket Sound, now reasonably established (p. 886), must similarly tend to raise the temperature of the water over Nantucket Shoals. On the other hand, the westerly drift from the Bay of Fundy combines with the active tidal stirring to maintain the low surface temperatures characteristic along the eastern sector of the coast of Maine.

In winter, when the coastal belt is the coldest part of the gulf, the dominant circulation tends to carry low temperatures from the western shores out over the central part of the basin, an effect illustrated by the distribution of temperature in Massachusetts Bay in February, 1925 (p. 658).

THERMAL EFFECTS OF EVAPORATION

The warming of the surface stratum of the gulf by solar radiation is constantly opposed by the draft of heat from the water as the latter evaporates. Quantitative statement of the cooling of the water which this process actually effects over the gulf is not yet possible, but such observations as have been made on the comparitive rapidity of evaporation of salt and fresh waters, and the actual measurements of the latter at land stations around the coast of the gulf, afford a rough picture of the order of magnitudes involved.

The latent heat of vaporization of fresh water depends to some small extent on the temperature at which evaporation takes place; the average for the range prevailing in the surface waters of the gulf of Maine (0° to 20°) is about 585 to 595 calories.[57]

I know of no determinations of the latent heat of evaporation for salt water, but probably it does not differ greatly from the above. The annual evaporation of a blanket of water about 0.7 meters thick from the surface of the Gulf of Maine, which is probably close to the truth (p. 842), would thus take enough heat from the upper 50 meters to cool the latter by about 8° if all the necessary energy were drawn from the water. Actually, however, a large part is supplied by direct solar radiation as it strikes the surface (p. 677), proportionately reducing the draft of heat made from the underlying water by the process of evaporation. No measurements of what percentage of the heat requisite for evaporation is thus supplied direct by the sun seem to have been made at sea, but it is certain that this can happen only while the sun is shining; and evaporation is much more rapid in sunlight than at night or under a cloudy sky—on the average about two and one-half times more rapid, according to Krümmel's (1907, p. 248) summation of the available evidence. The actual hours of sunshine average only about 50 per cent of the possible number at land stations around the gulf, with the sun above the horizon only about half of the time for the year as a whole at our latitude. Thus, a rough approximation of the yearly evaporation from the gulf would be about 0.3 meter (out of the total of 0.7 meter, as stated on p. 842) for the one-fourth of the time when the sun shines on the water, 0.4 meter during the remainder of the year. Without going deeper into this question this implies that the chilling effect of evaporation is certainly sufficient to reduce the mean temperature of the upper 50 meters in the gulf by at least 5° during the course of the year, and probably by at least 6°.

THERMAL EFFECT OF THE NOVA SCOTIAN CURRENT

The distribution of temperature around and in the offing of Cape Sable makes it certain that the cold Nova Scotian drift exerts its chief thermal effect to the eastward of the cape. Nevertheless, it is now fully established that this cold current

[57] Determinations of the latent heat of evaporation of water vary somewhat. The value stated above is calculated from Herring's formula, L=94.21 (365−T) 0.31249. (Quoted from Smithsonian tables, Fowle, 1920.)

floods westward into the Gulf of Maine every spring, in some years into the summer. It is obvious that if this reached the gulf close to zero in temperature, as it is farther east, as well as in large volume, it would effectively cool the eastern side of the gulf just as it cools the coastal zone along outer Nova Scotia, for it is considerably colder than the central part of the gulf even at the season when the latter is at its coldest. This difference in temperature widens during the spring as the vernal warming of the gulf proceeds. Only once (March 29, 1919) have we found this icy Scotian water, 0° in temperature (p. 553) and low in salinity (p. 727), flooding the surface as far west in the gulf as the eastern side of the basin; and, as pointed out (p. 558), the duration of this intrusion of zero water seems to have been brief, because the temperature of this side of the gulf had risen to 2° to 4° by the 28th of April and to 4° to 6° by the end of May (p. 560).

I can not state whether the cold stream from Banquereau brings water as cold as this to the Gulf of Maine every spring. In 1920 it certainly did not do so until after mid April[58] (if at all), when the temperature was still no lower from German Bank and Cape Sable out across the Northern Channel to Browns Bank in the eastern side of the gulf than in the northern and western parts; in fact, slightly higher than in Massachusetts Bay, though the latter is so much farther removed from any possible effect of cold water from the east and north. In 1915 the band of zero water had extended westward past Halifax by the end of May, probably as far west as Shelburne. However, it is unlikely that the Gulf of Maine received any water so cold during that spring; surface readings as high as 3° to 3.5° in the region of German Bank on May 6 to 7 (stations 10270 and 10271) certainly do not suggest this. So sudden a dislocation in temperature had developed by June of that year between the eastern side of the gulf (5° to 8°, surface to bottom) and the coldest band on the Shelburne profile (0.7 to 0.9°, p. 582) that the latter no longer exerted any cooling effect on the temperature to the westward of Cape Sable.

This evidence suggests that while icy water from the Banquereau region (p. 832) reaches the Gulf of Maine as cold as zero for a brief period during some springs, in most years it is so warmed en route by mixture with water of higher temperatures in the neighborhood of Cape Sable that it enters the eastern side of the gulf only a degree or two colder than the water it meets there.

The thermal effect which the Nova Scotian current exerts on the Gulf of Maine is also limited by the fact that it passes Cape Sable as a surface and not a bottom drift (p. 712), its deeper strata being deflected past the Northern Channel and into the so-called "Scotian Eddy" by the obstruction offered to its westward movement by the rising slope of Roseway Bank (p. 836). With the advance of spring the surface of the Nova Scotian current warms, by the sun's rays, as the source of low temperature (ice melting to the eastward) is gradually exhausted, until by July the surface attains a higher temperature all along Nova Scotia (12° to 13°)[59] than around Cape Sable or in the eastern side of the Gulf of Maine, although the bottom water only 20 to 30 meters down continues icy cold. In consequence of this solar warming of the superficial stratum the surface drift that persists from the eastward past Cape

[58] On the 17th to 19th of that March the coldest water (+0.3° to 0.5°) was then apparently flowing westward between La Have and Roseway Banks at the 20 to 40 meter level.

[59] For summer temperatures over the Scotian shelf see Bjerkan (1919) and Bigelow (1917).

Sable in some summers enters the gulf about as warm as is the contribution from the Cape Sable dead water (p. 835); actually warmer than the water with which it mixes in the offing of Cape Sable or close by to the westward. Although icy cold water persists on bottom right through the summer only a few miles east of the cape, we have no evidence that anything from this source actually penetrates the gulf after May.

In short, the Nova Scotian current acts as a chilling agent in the Gulf of Maine for only a few weeks during the spring, and then more to retard vernal warming (p. 558) than actually to lower the temperature of the part of the gulf into which it debouches below the readings prevailing there before the current commences to flood past Cape Sable. During the short period of its westward flood, however, and for some weeks thereafter, its chilling influence on the eastern side of the gulf is obvious enough, as is described in the account of the distribution of temperature in the spring (p. 553).

We have next to consider how far the difference in temperature between the side of the gulf most directly exposed to the effects of the Nova Scotian current and the opposite side most remote from it is recognizable at other seasons of the year. This problem is complicated by regional differences in the activity of vertical stirring by the tides, reflected in lower and lower surface temperatures at successive stations around the shore line of the gulf from Massachusetts Bay to Nova Scotia, but higher and higher temperatures at the 50 to 100 meter stratum. In order to be instructive for the water mass as a whole, regional comparison must therefore be based on a calculation of the mean temperature of the entire column. To name one part of the gulf as potentially colder than another, or vice versa, on the evidence of temperature of any one given level can only prove misleading.

In calculating the mean temperature the gulf is best divided into two subdivisions—(1) the basin outside the 100-meter contour and (2) the shoaler water of the coastwise zone.

An earlier report (Bigelow, 1915) gives calculations of the mean temperature of the stratum inclosed between the surface and the 50-fathom level for the basin, which would apply closely enough to the upper 100 meters.

Approximate mean temperature (°C.) for the upper 50 fathoms, or 100 meters, of the basin, August, 1913

Locality	Station	Mean temperature	Locality	Station	Mean temperature
Off Gloucester	10087	7.9	Off Penobscot Bay	10091	10.0
Western basin	10086	9.7	Near Cashes Ledge	10090	8.6
North of Cape Ann	10105	8.3	Near central part of basin	10092	8.0
Near Isles of Shoals	10104	8.4	Off Mount Desert	10100	9.1
Off Cape Elizabeth	10103	9.1	Off Bay of Fundy	10097	10.2
Near Platts Bank	10089	8.3	Near Lurcher Shoal	10096	10.1
Off Monhegan Island	10102	9.2	East side of basin	10093	10.0
Off Penobscot Bay	10101	9.4	Do	10094	8.4

According to this table the eastern side of the basin, with the waters along the Nova Scotian slope and off the mouth of the Bay of Fundy, was potentially the warmest part of the gulf (10°), not the coldest, as the popular belief that an

"Arctic current" chills the surface there would demand. This upper stratum was as cold in Massachusetts Bay (farthest removed from the effect of the Nova Scotian current of spring) as it was off Penobscot Bay.

In August, 1914, we again found the mean temperature of the inner part of the basin of the gulf highest in the eastern side near Lurcher Shoal, lowest in the western side off Cape Elizabeth, and slightly higher (7.7° to 9.9°) in the northeastern part in general than in the western (6.8° to 8°), as follows:

Approximate mean temperature (° C.) upper 100 meters, August, 1914

Locality	Station	Mean temperature	Locality	Station	Mean temperature
Off Gloucester	10253	7.7	Off Penobscot Bay	10250	8.8
Off Cape Cod	10256	8.0	South of Mount Desert	10248	8.7
Western basin	10254	7.6	Do	10249	7.7
South of Cashes Ledge	10255	8.6	Off the Bay of Fundy	10246	8.6
Near Isles of Shoals	10252	8.0	Off Lurcher Shoal	10245	9.9
Off Cape Elizabeth	10251	6.8			

Similarly, the mean temperature of the upper 80 meters (the whole column) was as high on German Bank (9.9°), off Machias, Me. (9.7°), and at the western end of the Grand Manan Channel (9.8°) in August, 1912, as it had been off Penobscot Bay or on Platts Bank a week previous (9° to 9.7°), or as it was in Massachusetts Bay two weeks later (about 9.6°). The 80-meter mean was slightly higher off Cape Cod, however (about 11°), on August 29 of that year.

Our data do not afford so satisfactory a regional survey of the mean temperature of the coastwise zone shoaler than 50 to 60 meters because we have taken few observations so close to the land, and it is obvious that regional comparisons for any given stratum within this belt will be misleading unless the observations are made at approximately the same date and at localities where the depth of water is about equal. The few readings that have been taken on Nantucket Shoals show the whole column of water 1° to 2° warmer (mean about 10° to 12°) than in equal depths in the Bay of Fundy (mean 9° to 10°), an instructive comparison because the temperature is kept nearly uniform, vertically, in both these areas by the swirling tides. The mean was also slightly higher over the 50-meter contour in Massachusetts Bay in August, 1922 (11.7° and 13°, stations 10633 and 10640), than we have found it at about this depth off Mount Desert and farther east along the coast of Maine at the same season (usually 9° to 10°); higher, too, than the mean at 35 meters depth in Passamaquoddy Bay in August (10° to 11°), [60] though the difference in depth would suggest a relationship of the opposite sort.

Our summer cruise of 1913 afforded evidence to the same effect, the mean temperature being considerably lower on German Bank (8.7°, station 10095) at the end of the second week of that August than off Cape Elizabeth (about 11° at station 10103). In August, 1914, also, the mean for the upper 50 meters was about 9.7° on German Bank and between 10° and 11° near the Isles of Shoals across the gulf. However, in the cold summer of 1916 (p. 628) the mean for 40 to 45 meters was almost exactly the same at two stations in Passamaquoddy Bay in mid-August (8.5° and 9.4°), in

[60] Calculated from Craigie's (1916) temperatures.

St. Marys Bay on September 2 (9.8° in 48 meters), and in 40 and 45 meters off Yarmouth Harbor, Nova Scotia, on September 7 and 9[61] (9.2° and 9.8° in 40 and 45 meters) as off Cape Cod on August 29 (9° at station 10398). Much lower summer temperatures prevail to the eastward of Cape Sable, a dislocation illustrated for 1914 by mean values of 10.9° on the northeastern part of Georges Bank and of about 9° on Browns Bank, contrasting with only about 5° at the 50-meter contour off Cape Sable (station 10230) during the last week of July.

These data may be summarized as follows: No definite tendency is shown toward lower mean values for the upper stratum in the one side of the basin of the gulf than in the other, outside the 100-meter contour, in years neither unusually warm nor unusually cold. When we take into account the sharp temperature gradient that characterizes most parts of the Gulf of Maine in summer, as a result of which even slight upwellings from the mid-depths (at, say, 75 to 100 meters) would considerably lower the mean temperature of the shoaler stratum, the most striking result of the calculation is the uniformity of the gulf made evident.

In the coastal belt the mean temperature is usually, though not invariably, a degree or so lower in the northeastern corner of the gulf in summer than in the southwestern side; and it is possible that in years when the movement of water westward along Nova Scotia persists late into the season (1924, for example, p. 834) this regional difference in temperature is wider than has actually been recorded in the summers when our general surveys of the gulf have been carried out. In evaluating it, not only must the possible effect of this cold current be taken into account, but also the difference in latitude between the different stations of observation, which, *per se*, corresponds to some difference in temperature. The most interesting regional comparison which the available records afford from this point of view is between the waters on Nantucket Shoals, on the one hand, and Passamaquoddy Bay, on the other, both being subject to tidal stirring so active that the water remains comparatively homogeneous from surface to bottom throughout the year, and both experiencing about the same amount of fog during the spring and summer.[62] The difference in latitude between these two localities is about 3½°. The mean temperature of the upper 30 to 40 meters of Passamaquoddy Bay is usually between 8.5° and 10.5° in August, when it is at or close to its maximum for the year, differing 1° or 2° in either direction at different stages of the tide and from year to year. On Nantucket Shoals mean temperatures of 10° to 13° have been recorded in summer, so that a difference of about 2° is to be expected between these two regions. According to Krümmel's (1907, pp. 400 and 401) tabulation and diagram this about equals the average difference in surface temperature between the latitudes of the shoals (41°) and of Passamaquoddy Bay (44° 30′), whether for the oceans as a whole or for the North Atlantic alone.

The differences in latitude between Massachusetts Bay (lat. about 42°) and the northeastern shores of the gulf generally (lat. 44° to 44° 30′) corresponds to a difference of between 1° and 2° in mean annual surface temperature for the North Atlantic as a whole.

[61] Calculated from Vachon's (1918) tables.

[62] According to the pilot chart (United States Hydrographic Office), Nantucket Shoals is somewhat the foggier region of the two in June (40 to 45 per cent of foggy days; 30 to 40 per cent in the Bay of Fundy); but in July about half the days see some fog in the eastern side of the gulf, only 30 to 40 per cent on the shoals.

As every coastwise navigator knows, there is much less fog along the western shore of the gulf from Cape Cod to Cape Elizabeth than there is at the mouth of the Bay of Fundy. Consequently, the former is exposed to more hours of direct sunlight, tending to accentuate the difference in temperature resulting from differences in latidude, *per se.* On the other hand, winds from the quadrant between west and south, such as prevail over the Gulf of Maine during July and August (p. 965), tend to drive the warmed surface water eastward toward Nova Scotia, thus transferring heat from southwest to northeast (with more or less colder water welling up along the western shore), and so in part to counteract the difference in the rate of solar warming which would otherwise accompany the difference of latitude. With a "run" of easterly winds the direction of surface drift will be reversed. Thus, it is by no means a simple task to account for variations in the mean temperature as narrow as those prevailing between different parts of the Gulf of Maine in the summer months. The much wider regional variations in surface temperature or in the temperature of the water at any given level below the surface follow much more obvious causes.

I think it sufficiently established, however, that the difference between the mean temperature of the column of water (in other words, its potential temperature) in the northeastern part of the gulf and in the southwestern part is not greater in most summers than can be accounted for by the difference of latitude and by such other local causes as fog, the direction of the wind, and the regional difference in the activity of the vetical tidal mixing, on which too much stress can hardly be laid.

This is still more certainly the case in winter, when the temperature of the gulf is so nearly uniform, vertically, that station for station comparison of the actual readings at once reveals any regional differences in the mean temperature.

In winter it is only close along shore that any unmistakable difference between the northeastern and southwestern parts of the gulf can be demonstrated, and this is not wider than can be accounted for by the difference in latitude.

Winter temperatures at representative stations during the cold months, ° C.

Locality, date, and station	Surface	40 meters	100 meters
Western side:			
Off Boston Harbor, Dec. 29, 1920, station 10488	3.90	5.34	----------
Off Gloucester, Dec. 29, 1920, station 10489	5.56	6.94	6.97
Off Gloucester, Mar. 1, 1920, station 20050	2.50	1.89	1.52
Eastern side:			
Yarmouth (Nova Scotia) sea buoy, Jan. 4, 1921, station 10501	3.80	3.86	----------
Off Lurcher Shoal, Jan. 4, 1921, station 10500	5.83	6.17	6.70
Off Mount Desert Island, Mar. 3, 1920, station 20056	1.15	.49	1.95

The foregoing discussion leads to the conclusion that the cold water from the Nova Scotian current is soon so thoroughly incorporated with the water of the gulf, after the flow past Cape Sable slackens, that in most years the regional disturbance of temperature which it causes at first is entirely dissipated by June. Even in years when the longshore drift continues to pass Cape Sable until late in the summer (p. 834), it may, at the most, hold the mean temperature a degree or two lower along western Nova Scotia until July than it is out in the neighboring basin of the gulf. After that (earlier still in "early" seasons) the surface water contributed by this source and by the Cape Sable "dead water" (p. 834) reaches the eastern side of the gulf as a warming, not as a chilling, agency, actually 1° to 3° higher in temperature than the water with which it mixes to the westward of Cape Sable.

One more thermal aspect of the Nova Scotian current (this the most important of all) demands brief examination—namely, its more general influence on the temperature of the gulf as distinct from any regional differences which it may cause within the latter. In other words, to what extent is the Nova Scotian current responsible for the boreal character of the gulf? Would the latter be considerably warmer without it?

Until systematic exploration of the gulf was undertaken in 1912 it was generally assumed that the considerable contrast in temperature between the Gulf of Maine, on the one hand, and the tropic water outside the edge of the continent abreast of its mouth, on the other, resulted directly from the chilling effect of some such cold stream from the north and east, though the Labrador and not the Nova Scotian current was usually given this credit. There is no escape from the conclusion that with water at least 3° lower in temperature than that of the gulf flooding into the latter for several weeks every spring, the gulf must be somewhat cooler than it would be if this source of cold should be dammed off.

The older view, that some Arctic current or other controlled the temperature all along the seaboard of the gulf, was largely based on the supposition that the latter is a very cold body of water. It is a truism that the gulf, with a mean annual surface temperature of about 8° to 9°, is considerably colder than the average for its latitude over the oceans as a whole, which is given by Krümmel (1907) as about 14°; so, in fact, is the whole coastal belt along the North American seaboard from Nova Scotia to Florida. However, "cold for its latitude" is by no means synonymous with "cold for its geographic position", and it is more because of its contrast with the tropic waters of the so-called "Gulf Stream" than because of its absolute temperature that the coolness of the Gulf of Maine has impressed students and laity alike. In attempting to estimate whether the gulf is actually colder, and if so, how much colder, than it would be if its offshore banks were to rise above water and so dam it off from currents, warm or cold, the situation of the gulf to leeward of the continent, and the air climate over the land mass from which the chilling winds of winter blow out over the sea, are factors of primary importance. The actual effect which winter chilling by cold air exerts on the temperature of the gulf is discussed in some detail in a later section (p. 692). For clarity, however, I must repeat here that owing to the great difference in capacity for heat between air and water the gulf is but little warmed by warm air blowing over it in summer (drawing its vernal warming almost wholly from direct solar radiation), but is very effectively chilled by the cold air of winter.

If the Nova Scotian current did cool the surface of the gulf generally to a temperature more than a degree or two lower than would result from this winter chilling alone we might expect the mean temperature of the upper 40 meters to prove considerably lower in the eastern side of the gulf than in the western the year round; but by actual observation the difference is no wider in this respect between the parts of the gulf most and least open to the cold current than might be expected to accompany the difference in latitude between the stations in question.

The mean annual temperature of the surface of the gulf affords evidence to the same effect, this being about the same at the mouth of Massachusetts Bay (9 to 10°) as the annual mean for the air at neighboring localities around its shore, or slightly warmer. A similar relationship has been recorded between the mean annual temperature of the surface water of the Bay of Fundy[63] and of the air over the neighboring parts of New Brunswick and of Nova Scotia.

Most instructive clues to the temperatures that might be expected to prevail in the deep strata of the Gulf of Maine if its basin were so nearly inclosed that it could not be affected appreciably by currents from outside are to be found in the relationships between its deep temperatures and those of the Norwegian fjords (Nordgaard, 1903) and of the Black Sea.

In the southwestern Norwegian fjords, where a very heavy rainfall maintains so high a stability that convectional overturnings are confined to the superficial stratum, so that this alone is directly exposed to winter chilling, the bottom temperature is not only uniform throughout the year but is almost precisely the same as the mean annual temperature of the air.[64] So close, in fact, is the correspondence that, Nordgaard tells us, one need only take a reading of the bottom temperature in one of the deep southern fjords to know the mean annual temperature of the air. In the northern fjords, however, which receive so much less rain that the water is less stable, salinity and temperature become nearly equalized from surface to bottom by convectional circulation in winter, just as they do around the coastal belt of the Gulf of Maine, and as a result of this winter chilling causes wide seasonal variations and winter temperatures lower than the mean annual temperature of the air at 200 meters and deeper. In both these classes of fjords, as Nordgaard (1903, p. 46) points out, the bottom temperature is purely the result of local factors, the topography of the bottom being such that "no supply of heat by a submarine current is possible," nor any supply of cold of similiar origin.

More pertinent to the Gulf of Maine is the relationship between the air and water temperatures of the Black Sea, situated at about the same latitude (most of its area is included between the parallels of 41° and 45°), but in a somewhat warmer climatic zone.[65]

At depths greater than 150 to 200 meters the entire area of the Black Sea is 8.8° to 9° the year round (Spindler and Wrangell, 1899; Skvortzov and Nikitin, 1924), contrasting with mean air temperatures for the year of about 9.6° at Odessa, on the north shore, about 11° over the western (Bulgarian) watershed, and about 14.3° at Batum on the eastern coast. That the deeps of the Black Sea should be so much colder than the mean annual temperature of the overlying air, in spite of the warming effect of the bottom current flowing in from the Mediterranean, reflects the age-long effects of winter chilling from above. Obviously the differential can not be credited to any Arctic current in this case.

While no part of the Gulf of Maine is as thoroughly protected from thermal influences from the sea outside as are the Norwegian fjords and the Black Sea, such

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[63] Between 6° and 7° for the year 1916-17, according to Mavor's (1923) tables.

[64] Nordgaard (1903) quotes 7° as the mean annual temperature of the air at Bergen, 6.8° to 7° at 400 meters and deeper in the neighboring fjords.

[65] The Black Sea is usually represented on climatic charts as occupying the belt inclosed between the mean annual isotherms for 10° and 15.56°.

conditions are approximated in the deep bowl off Gloucester. By analogy, therefore, we might expect the mean annual temperature of the bottom water of the latter to be lower than the mean annual temperature of the air over the neighboring land, quite independent of any possible chilling by northern sources. And such, by our observations, is the case, the mean bottom temperature of 4° to 5° at 70 to 150 meters depth in this sink being 3° to 4° below the mean annual temperature of the air at Plymouth and Gloucester, on the two sides of the bay, or at Concord, Mass., some 20 miles inland.[66] We have not taken readings enough in the deep trough between Jeffreys Ledge and the Isle of Shoals to establish the mean annual temperature as closely there, but such data as are available point to a mean annual value of 4° to 5° at 100 to 150 meters for this locality, about 3° lower than the mean annual air temperature at Portland, Me. (7.3°).

Near Mount Desert Island, which may be taken as representative of the coastal waters of eastern Maine, the mean annual temperature of the bottom water (close to 5° to 6° at a depth of 40 to 50 meters) is about 1° cooler than the mean temperature of the air at Bar Harbor near by, but nearly the same as the air at St. Johns, New Brunswick, and at Eastport, Me. Mean temperatures of 4° to 5° at depths of 100 to 175 meters in the Bay of Fundy for the year November, 1916, to November, 1917,[67] again prove 1° or 2° lower than the mean annual temperature of the air at St. Johns, New Brunswick, on the one side of the Bay, or at Yarmouth, Nova Scotia, on the other (5° to 6°).

The foregoing comparison warrants the tentative generalization that in those parts where regional interchange of water is most hindered by submarine barriers the mean temperature of the bottom water averages about 1° to 3° lower than the mean annual temperature of the air over the neighboring lands, a rule applying whether vertical circulation be active, as in the Bay of Fundy, or weak, as off Gloucester. The mean annual bottom temperature at equal depths also proves decidedly uniform in such situations in the two sides of the gulf. In the open basin of the gulf the deepest water averages warmer, a fact discussed in a subsequent section (p. 691). In short, it is not necessary to invoke more than a slight influence on the part of the Nova Scotian current, if any, to account for thermal differences between bottom water and air no wider than those just quoted.

Brief analysis will, I think, convince the reader that this conclusion applies equally to the cold mid layer that usually persists through the summer in the basin of the gulf. The presence of a cold layer of water of this sort in the mid depths, with higher temperatures below as well as above it, has sometimes been classed as a sure criterion for Arctic water. This, however, is not necessarily the case. True, such a state characterizes the polar seas in summer (Nansen, 1902; Helland-Hansen and Nansen, 1909; Knudsen, 1899; Matthews, 1914); and wherever such a layer is colder than −1° in summer, as it is in the Labrador current and in the extensions of the latter around the slopes of the Grand Banks (Matthews, 1914; Fries, 1922 and 1923; E. H. Smith 1922 to 1924a; Le Danois, 1924 and 1924a) we have positive evidence of Arctic water, for nowhere else does winter cooling alone cause temperatures as low as this in the open sea on either side of the North Atlantic south of latitude 60°.

[66] The mean annual temperature is higher (about 10°) at Boston than at most other stations around the bay.

[67] Calculated from data tabulated by Mavor (1923).

However, a cold layer of this same sort, though not so low in temperature, can equally be produced in any partially inclosed boreal sea. All that is requisite is that the surface layers be exposed to a rigorous winter climate, alternating with rapid solar warming in summer, over depths great enough to allow a more or less constant inflow of warmer ocean water below the level to which winter cooling penetrates (Bigelow, 1917, p. 237).

In the Baltic, for example, a cold layer reminiscent of the previous winter's chilling persists at a depth of 50 to 100 meters until well into the summer (Knudsen, 1909; Krümmel, 1907, p. 471; Witting, 1906); but increasingly active vertical circulation, which accompanies the cooling of the surface after August, entirely dissipates this stratum of low temperature there by late autumn, just as happens in the Gulf of Maine. The following serial temperatures for the Alland Deep (in the Baltic) in winter, spring, summer, and autumn, are introduced for comparison with the Gulf of Maine.[68]

Depth	February	May	August	November
	°C.	°C.	°C.	°C.
Surface	0.1	4.2	12.3	6.1
100 meters	2.4	1.8	2.5	5.3
250 meters	3.9	2.0	3.5	4.0

A cold mid layer of the same sort persists into the summer in the Black Sea, where it is self-evident that cold Arctic currents play no part in the temperature cycle and where, consequently, the low temperatures recorded at 60 to 100 meters in August must be purely the product of local influences, as Andrusoff (1893) has pointed out.

With melting ice no more important in the Black Sea than it is in the Gulf of Maine,[69] the cooling agent chiefly responsible must be the loss of heat from the surface by radiation during the cold months.

The general account of temperature, and especially the temperature sections for the western basin in successive months (fig. 5), makes it clear that the cold layer recorded in summer in the Gulf of Maine reflects the persistence of the low temperature to which the whole upper 100 to 150 meters is chilled in winter, but which is obliterated by autumn, just as happens in the Baltic. No connection appears on the profiles between the development of this cold layer in the western side of the gulf as the spring advances, and the inrush of Nova Scotian water into the eastern side.[70]

[68] From Krümmel (1907, p. 471), after Witting (1906).

[69] The northwestern bays and harbors of the Black Sea (e. g., Odessa Gulf and Kherson Bay) usually freeze over part of the time each winter; but ice very seldom extends more than 2 or 3 miles seaward, and even these shallow areas of low salinity are sometimes open all winter, while the open sea south of the Crimean peninsula never freezes (British Admiralty, 1897). Consequently the amount of ice that actually melts in the Black Sea proper each spring is so small that we can hardly suppose it has any appreciable effect on sea temperature there.

[70] In an earlier report (Bigelow, 1917) I referred to the Gulf of St. Lawrence as a thermal example of this same sort; but Huntsman's (1924 and 1925) more recent hydrographic studies indicate a greater inflow of icy water from the Labrador current through the Straits of Belle Isle than Dawson's (1907 and 1913) earlier observations of the strait had suggested. Consequently, the persistence into the summer of the minimum layer there, close to 0° in temperature at about 100 meters' depth, results at least in part from the cold water flowing in and from the melting of the Arctic ice which this brings with it in winter and early spring, as well as from winter chilling and the melting of ice frozen locally within the Gulf of St. Lawrence.

The evidence just outlined leads to the conclusion that the Nova Scotian water flowing into the Gulf of Maine from the eastward in spring does not lower the general temperature of even the coldest localities and levels in the gulf more than a degree or two below the values that would prevail were the gulf as nearly inclosed as are the Black Sea or the Norwegian fjords. Nevertheless, the Nova Scotian current does act as a decidedly effective cooling agent, for without the cold water from this source the comparatively high temperature of the slope water, of the surface inflows from the region off Browns Bank, and of occasional overflows of tropic water (p. 836), would hold the gulf several degrees warmer than it actually is. These warm sources the Nova Scotian current counteracts, and in counteracting them it has its chief thermal importance in the Gulf of Maine.

THERMAL EFFECT OF THE SLOPE WATER

Were the gulf an inclosed basin, with little or no inflow over its floor, we should expect to find its bottom temperature certainly no higher then 5° to 6° and probably as cold as the mean annual temperature actually is in the deep sinks in the western side of the gulf, namely 4° to 5° (p. 688). In reality, however, we have only once found the bottom water in the basin of the gulf colder than 4° in depths of 175 meters, or deeper, at any locality, season, or year.[71] Only 4 out of 64 deep stations in the basin have given bottom readings lower than 4.5°. On the other hand, 26 have been warmer than 6° on bottom; and the bottom temperature for all as deep as 175 meters has averaged about 6°, or 1½° warmer than the mean annual temperature at the 100-meter level around the shores of the gulf and 2° warmer than the mean bottom temperature in the trough of the Bay of Fundy. The high salinity, coupled with the precise temperature of this bottom water, identifies it beyond dispute as slope water flowing in along the trough of the Eastern Channel (see discussion p. 842). The slope water, then, brings warmth to the deeps of the gulf sufficient to raise the bottom temperature of the basin a degree or two higher than would be the case if no such current flowed in; consequently it must be named a warm current as it affects the gulf, not a cold one.

The physical characteristics of the slope water, as it drifts inward along the bottom of the Eastern Channel, have proved so uniform from season to season and from year to year (temperature about 6° to 7° and salinity about 34.6° to 35° per mille in spring and summer) that the causes for the variations recorded in the temperature and salinity of the deepest water within the gulf are to be sought in fluctuations in the volume and velocity of the inflowing bottom drift rather than in variations in the temperature or salinity of the latter. Such fluctuations, in turn, almost certainly have a two-fold cause. In part they result from corresponding variations in the amount of slope water being manufactured along the continental slope to the eastward shortly prior to the date of observation, and in the proportional amounts of the various waters, cold and warm, that enter into its composition. The seasonal or or other secular differences in the density gradient over the continental slope from Browns Bank to La Have Bank, however, probably play a more important rôle in

[71] Bottom temperature 3.54° at 180 meters at station 10283 off the Bay of Fundy, June 10, 1915.

this connection by governing the Archimedian force that tends to pump the slope water westward to the Eastern Channel and so into the Gulf of Maine. This works most effectively in spring and early summer, but fluctuates so narrowly from season to season that only very narrow variations are to be expected in the temperature or salinity of any part of the gulf deeper than about 150 meters, from season to season or from year to year, or have actually been recorded there.

This uniformity in the physical state of the bottom water on the floor of the deep trough of the gulf proves that the effects of the alternate seasonal warming and chilling of the surface do not penetrate deep enough to obscure the dominance of the slope water there; but the slight seasonal rise and fall of temperature that has been recorded at the bottom of the deep sink off Gloucester and between Jeffreys Ledge and the mainland (from which the slope water is barred by inclosing rims too shoal for it to overflow) is evidence that slight (but measureable) winter cooling and summer warming from above may be detected down to 200 meters, so far as the depth alone is concerned.

It is because the slope water is warm, by comparison with the water with which it mixes within the gulf, that the bottom of the latter is usually warmest in the eastern side of the basin, at depths greater than 150 meters, where the inflowing current is chiefly localized (p. 921), coldest in the "sinks" in the inner parts of the gulf, from which the slope water is more or less effectually barred by submarine rims.

The following differential table shows that the slope water has little effect on the deep temperature in such situations, as exemplified by the sink off Gloucester and by the trough between Jeffreys Ledge and the Isles of Shoals. This generalization applies also to the Bay of Fundy, from which most of the slope water is deflected by the topography of the bottom. In summer and autumn, it is true, the 175 to 200 meter level may be as warm within the bay (6° to 7°) as without; but low salinity proves that this high bottom temperature chiefly reflects the active convectional currents of the bay by which solar heat received at the surface is dispersed more evenly downward there than it is anywhere else in the gulf in water equally deep.

Depth, meters	Cape Ann bowl, deepest level taken			Basin outside, corresponding level [1]		
	Date	Station	Temperature	Date	Station	Temperature
			°C.			°C.
150	Mar. 1, 1920	20050	1.68	Feb. 23, 1920	20049	5.66
150	Apr. 9, 1920	20090	([2])	Apr. 18, 1920	20115	5.38
120	do	20090	2.25	do	20115	±3.80
130	May 4, 1915	10266	3.55	May 5, 1915	10267	4.69
110	July 10, 1912	10002	4.61	July 15, 1912	10007	±4.61
128	Aug. 9, 1913	10087	5.17	Aug. 9, 1913	10088	[3]±5.50
180				do	10088	6.28
140	Aug. 22, 1914	10253	4.49	Aug. 22, 1913	10254	±5.30
140	Aug. 31, 1915	10306	5.78	Aug. 31, 1915	10307	±5.10
120	Oct. 31, 1916	10399	5.23	Nov. 1, 1916	10400	±4.40
150	Dec. 29, 1920	10489	7.00	Dec. 29, 1920	10490	±6.00

[1] The table shows only the differential existing on the given dates between the deepest level, where a reading was taken within the bowl, and the corresponding level in the basin outside. It does not represent the seasonal cycle for the latter because of the difference in levels from station to station.

[2] 150-meter reading not taken.

[3] 130 meters.

Further evidence that slope water is of little importance in the thermal cycle of the Bay of Fundy results from the fact that we found the 200-meter level 1° colder (4.3°) within the latter than just outside (5.4°) in March, 1920 (stations 20079 and 20081), with a corresponding difference in salinity. A reading of 1.71° reported by Mavor (1923) at 175 meters in the bay on April 9, 1917, is colder than the coldest reading so far obtained anywhere in the open basin of the gulf at this depth.

The deep readings for different times of year warrant the following generalizations: At depths greater than 150 meters the temperature is most nearly uniform through the year in those parts of the gulf which the slope water reaches in greatest volume, and shows its widest seasonal fluctuation in the partially inclosed bowls that receive least water from this source. Were it not for this deep current flowing in, the floor of the gulf would be several degrees (perhaps 3° to 4°) cooler in winter than is actually the case, and its mean for the year slightly lower. The bowl off Gloucester and the trough west of Jeffreys Ledge show the nearest approach to the thermal state that would prevail in the gulf were it neither open to the inflowing bottom current nor stirred by such strong tides as those that disturb its eastern side.

The thickness of the bottom stratum where temperature is governed by the volume and precise physical characters of the slope water is of interest. Its upper boundary in the inner part of the basin of the gulf may be set tentatively at about the 150-meter level, rising to within 80 to 100 meters of the surface in the southeastern part at the entrance to the Eastern Channel. On the other hand, the deep temperature is most influenced from above where tidal or other convectional stirring is most active.

WINTER CHILLING

Abyssal upwelling, as I have shown (p. 853), is barred out as a possible source of autumnal cooling in the Gulf of Maine. It is equally certain that the Nova Scotian current usually serves as a cooling agent in the gulf only in the spring, because none of our observations for autumn or winter suggest that progression of cooling from east to west across the gulf, which would reflect any inflow of cold water past Cape Sable at that season. We must therefore credit the very rapid loss of heat which the Gulf of Maine suffers in autumn and winter entirely to local causes, chiefly to the radiation of heat out from the surface to and through the colder air above it; to evaporation; in less degree to the melting of the snow that falls on the sea; and, locally, to the melting of ice.

The warming effect of the sun's rays is combatted the year round by local influences tending to reduce the temperature of the water or as least to retard vernal warming. Evaporation from the surface, for one thing, uses up heat, thus cooling the water (p. 680). Furthermore, the heated surface radiates heat out into the air whenever the temperature of the latter drops below that of the water, even in spring and summer.

The solar energy absorbed by the water is more than enough to offset these forces up to mid or late August; consequently the temperature of the surface of all parts of the gulf continues to rise. However, the amount of solar heat daily absorbed by the water, at its maximum when the sun is at its highest declination, is constantly decreasing after June 22 to 23; and after a certain date toward the end of summer or early in autumn, a date that varies regionally, as described in an earlier chapter

(p. 636), the surface chills. At first this chilling chiefly reflects the convectional mixing of the upper stratum, by which the substratum is warmed, in proportion as the surface is cooled, combined with the effects of evaporation from the surface. Meantime the mean temperature of the whole column of water continues to rise slowly at first, then remains stationary for a time as the sun continues to lose strength. At the mouth of Massachusetts Bay, for example, the mean temperature of the upper 40 meters was slightly higher on August 31, 1912 (station 10045, about 12°), than it had been on July 10 (station 10002, about 11°), although the surface had cooled from 18.3° to 16.1° in the interval. In 1915, too, the mean temperature of the upper 100 meters remained virtually unaltered at the mouth of the bay from August 31 to October 1 (about 8° at stations 10306 and 10324), although the surface temperature fell from 16.1° on the first date to 10.3° on the second, and the mean temperature of the upper 40 meters from 11° to 9°. In fact, it is doubtful whether the column of water, as a whole, actually commenced to lose heat at the mouth of the bay before the end of that October (p. 638). In 1916, again, the mean for 80 meters was about 1° higher near Cape Cod on October 31 (station 10399, about 7°) than it had been at the mouth of the bay near by on July 19 (station 10341, about 6°), the 80-meter temperature having risen in the meantime from about 3.7° to about 5.8°, though the surface reading had fallen from 16.4° to 10°.

Thus, the heat received from the sun is sufficient to balance the loss of heat by evaporation and by radiation at night, when the temperature of the air is cooler than the water, until the date when the mean temperature of the air falls permanently below that of the water, so to continue through the autumn and winter. Thereafter the upper 100-meter stratum of water constantly loses heat, no longer merely simulating this loss by convectional equalization. As this loss of heat is chiefly the result of radiation, out from the water into the air, the efficacy of this process deserves a word.

Although warm winds, as we have seen, heat the water below them to only a small degree, and slowly, because of the very much higher capacity of the latter for heat, cold winds, on the contrary, chill the surface of any body of water, fresh or salt, very rapidly because dry air is extremely transparent to radiation, especially to the long wave lengths (Abbott, 1911; Hann, 1915). Because of this "diathermacy," and because water is a good radiator,[72] the surface radiates out very large amounts of heat from September on, whenever the air is cooler than the water, dry, and the sky clear of clouds, fog, or mist, very little of it being absorbed by the lower stratum of the air.

The greater the difference in temperature between the air and the water, and the drier the air, the more rapidly does the water lose heat in this way. When the air is damp, or the sky clouded, the radiation from the surface of the sea is intercepted by this water vapor, so that the water loses heat slowly under such circumstances even if the temperature of the air be considerably the lower. It happens, however, that the humidity rules low and the sky usually is clear during the coldest winter weather of New England and of the Maritime Provinces, especially at night. Consequently, other conditions most favor radiation just when the differential

[72] Schmidt (1915) found about 83 per cent as much radiation from a water surface as from a black surface.

between sea and air temperature is widest, as it is from November on through the winter over the Gulf of Maine (p. 671).

Water itself is so opaque to radiation that only the thin surface film that is actually in contact with the air loses heat rapidly when the air is the colder of the two, for it effectually insulates the deeper strata. Consequently, the rate of radiation from water to air depends on the activity of vertical circulation; the more actively the water is stirred by tides or waves, and the more constantly the surface layer is replaced by water from below, the more rapidly will the column give off its heat to the colder air and so cool off with the advance of autumn and winter.[73] For this reason it would be reasonable to expect the gulf to reflect the autumnal cooling of the air most closely where tidal stirring is most active, and temperatures taken by Vachon (1918) in the St. Andrews region in 1916 prove this to be the case.

The coldest winter winds of the region blow from the land out over the gulf, and these cold westerly winds predominate in the western side of the gulf during the three winter months (p. 965). Consequently, the water loses heat most rapidly in the coastwise belt around the western and northern shore of the gulf, over which a fresh supply of icy air from the land is constantly passing, as long as the cold winds blow from the quadrant between north and west. The wind, in turn, is warmed by the absorption of radiant heat from the surface of the water in its passage over the latter; for although the lower stratum of air absorbs but a trifling percentage of this total radiation, its capacity for heat is so low that but little heat need be intercepted by it to raise its temperature considerably. This interception is favored, furthermore, by the increasing humidity given the air by the evaporation that is constantly taking place from the surface of the water. The result is that by the time the air has traveled a certain distance out from the land, its temperature rises so close to that of the water, and the air is made so humid, that the sea loses heat by radiation but little faster than it gains heat from the sun, even in midwinter.

In any sea exposed to a rigorous air climate, winter chilling may be expected to proceed much more rapidly in inclosed harbors, among the islands, and close in to the land generally, than it does only a few miles out at sea. This general rule is exemplified in a typical way by the Gulf of Maine, where the stations closest to the land have proved considerably the coldest in late autumn, winter, and early spring. The thermal history of Massachusetts Bay during the winter of 1924–25 affords a good example of this.

Storm winds also hasten the winter chilling of the water by the stirring action exercised by the waves, which may reach down to very considerable depths at this season, when the water has little vertical stability. In severe winter storms the whole upper stratum, 100 meters thick, may be mixed in this way and a constant supply of new water thus brought up to the surface, there to give off its heat to the icy air.

Were vertical stirring not so active in autumn, the immediate surface would cool off even more rapidly than it actually does, and the whole coastwise belt of the gulf, if not the entire area, would freeze over in winter. At the same time, however, the surface film would interpose so effective a barrier to the radiation of heat upward

[73] See Nansen (1912) for an illuminating discussion of the loss of heat from the surface of the Northern Atlantic in winter, and on the extent to which this is governed by the freedom of vertical circulation.

from the deeper strata, by its opacity to this process (p. 694), that the water only a meter or two down would lose heat much less rapidly than happens in reality, so that the 20 to 30 meter level probably would not show enough cooling during the winter months for the change in temperature to be measurable on our ordinary deep-sea thermometers.

Actually, however, vertical circulation is most active during the cold half of the year; consequently, the mixing of the various strata of water is constantly bringing up fresh water from below, to radiate its heat out into the atmosphere. The fact that the upper 100 meters, or so, cools off so uniformly during the winter, instead of only a thin surface film, is therefore wholly the result of convectional movements of the water particles, induced either mechanically (by winds or tides) or dynamically, if the surface water so chills that it becomes heavier than the underlying layer, which, however, seems never to take place in the open gulf (p. 929).

The rigorous climate of northern New England and of the Canadian Province of New Brunswick so profoundly influences the sea temperature of the Gulf of Maine that the following tables of the air temperatures at stations bordering the gulf may be of interest.[74]

Normal air temperatures (Fahrenheit)

Locality	Month											
	January	February	March	April	May	June	July	August	September	October	November	December
Boston	27.0	28.0	34.5	45.3	56.6	65.8	71.3	68.9	62.7	52.3	41.2	31.6
Portland	22.0	23.8	32.0	43.0	53.5	62.6	68.0	66.2	54.2	49.1	37.6	27.1
Eastport	20.1	20.4	28.9	38.3	46.9	54.4	59.8	59.7	55.2	46.6	36.8	25.3

Mean winter temperatures °F, with departures from normal (J. W. Smith, 1913–1921)

Locality	December		January		February		March	
	Temperature	Departure	Temperature	Departure	Temperature	Departure	Temperature	Departure
1911–12								
Boston	----------	----------	21.4	−5.6	27.7	−0.3	36.0	+1.0
Portland	----------	----------	15.3	−6.7	28.2	− .6	30.2	−1.8
Eastport	----------	----------	14.3	−5.8	20.4	−1.0	28.8	− .1
1912–13								
Boston	38.5	+6.9	39.3	+12.3	27.7	−0.3	42.4	+7.4
Portland	32.3	+5.2	31.6	+ 9.6	21.0	−2.8	35.2	+3.2
Eastport	28.7	+3.4	27.8	+ 7.7	17.2	−4.2	32.0	+3.1
1914–15								
Boston	30.4	−1.2	33.0	+6.0	33.2	+5.2	35.8	+0.08
Portland	24.4	−2.7	26.4	+4.4	28.4	+4.6	32.2	+ .02
Eastport	23.6	−1.7	24.6	+5.5	27.6	+6.2	29.9	−1.00

[74] From the U. S. Weather Bureau.

Mean winter temperatures °F, with departures from normal (J. W. Smith, 1913–1921)—Continued

1915–16								
Boston	34.2	+2.6	33.0	+6.0	25.5	−2.5	30.6	−4.4
Portland	29.4	+2.3	26.6	+4.6	20.6	−3.2	26.8	−3.2
Eastport	29.6	+4.3	22.6	+2.5	19.3	−2.1	24.6	−4.3
1919–20								
Boston	28.8	−2.8	21.0	−0.6	27.6	−0.4	39.2	+4.2
Portland	22.8	−4.3	14.6	−7.4	22.2	−1.6	34.6	+2.6
Eastport	20.0	−5.3	11.5	−8.6	21.1	−0.3	30.4	+1.5
1920–21								
Boston	35.6	+4.0						
Portland	27.8	+0.7						
Eastport	27.5	+2.2						

The diagrams of air and surface temperature at Gloucester and at Boothbay for the winter of 1919–20 (figs. 29 and 30) show the temperature of the water closely following that of the air in its 10-day fluctuations, and reflecting a loss of heat by radiation more or less rapid as the difference between the temperature of air and water is greater or less.[75]

The loss of heat from the surface of the gulf increases proportionately from November on, as the average difference between air and water increases, a general rule illustrated by the temperature cycle of Massachusetts Bay for the winter of 1924–25 (p. 651). The water continues to suffer a net loss of heat in this way until the average temperature of the air once more rises above that of the water, an event to be expected about the tenth of March (p. 668).

CHILLING EFFECT OF MELTING SNOW

Another cooling agent becomes effective from December until spring—namely, the melting of the snow that falls on the surface of the gulf. The amount of heat taken from the water by melting snow is, of course, that required to melt an equivalent amount of ice; a fall of 1 foot of snow (a moderate snowstorm for northern New England and the Maritime Provinces) would represent approximately 1–1½ inches of ice, more or less according to the quality of the snow.

The normal snowfall, by months, for the lands bounding the gulf is tabulated below from data supplied by the United States Weather Bureau; also the actual snowfall for representative winters since the oceanographic investigation of the gulf was undertaken.

Normal snowfall and its equivalent in water, both given in inches

Locality	November		December		January		February		March		April	
	Snow	Equivalent water	Snow	Equivalent water	Snow	Equivalent water	Snow	Equivalent water	Snow	Equivalent water	Snow	Equivalent water
Boston	0.6	0.08	5.8	0.55	9.7	0.87	13.7	1.23	9.0	0.87	3.7	0.46
Portland	3.6	.64	10.8	1.70	16.0	2.32	20.0	3.02	11.7	1.82	4.2	.78
Eastport	3.4	.40	11.7	1.26	17.6	1.72	19.7	1.90	13.3	1.28	10.1	1.04
Yarmouth, Nova Scotia	4.0	.40	14.4	1.47	20.3	2.03	21.8	2.18	13.3	1.30	5.5	.50

[75] The air temperature of the coldest days was many degrees below the 10-day averages shown on the diagrams, often 10° colder than the surface of the water.

Snowfall, in inches

Locality	November	December	January	February	March	April
WINTER, 1912–13						
Boston	0.3	9.2	0.3	7.7	0.5	1.4
Portland	(1)	4.7	5.0	14.1	5.1	1.2
Eastport	2.0	6.9	7.9	14.6	9.3	3.7
Yarmouth, Nova Scotia	12.2	7.7	1.2	16.3	3.5	1.1
WINTER, 1914–15						
Boston	(1)	4.1	7.0	5.1	(1)	----
Portland	7.4	8.1	1.9	10.5	0.8	----
Eastport	4.5	9.0	12.2	10.3	4.8	----
Yarmouth, Nova Scotia	4.1	15.3	10.2	7.2	2.5	----
WINTER, 1915–16						
Boston	0.2	6.7	4.8	30.3	33.0	6.5
Portland	(1)	12.1	12.2	20.2	36.3	7.9
Eastport	(1)	4.4	14.0	21.8	14.7	4.2
Yarmouth, Nova Scotia	3.0	6.1	21.3	29.4	53.4	1.7
WINTER, 1919–20						
Boston	0.2	2.9	24.8	32.5	11.0	2.0
Portland	2.7	4.3	24.2	44.6	13.6	0.3
Eastport	1.9	16.9	20.2	37.2	14.2	13.7
Yarmouth, Nova Scotia	2.4	13.6	28.0	15.2	3.7	8.0

[1] Trace

On the average, the coastwise belt of the gulf annually receives a blanket of snow aggregating about 42 inches in thickness off Boston, 66 inches at Portland, 76 inches off Eastport, and 79 inches at Yarmouth, Nova Scotia. Translated roughly into terms of ice, this means 4.5, 11, 8.5, and 9 inches, respectively, or an equivalent of about 8 inches of ice as the mean for the coastwise belt from the land out about to the 25-meter contour. Farther out from the shore a larger proportion of the winter's precipitation comes down as rain, less as snow, but no measurements of the snowfall have been made at any offshore station in the gulf.

As to melt 1 kilogram of ordinary fresh-water ice requires heat enough to raise the temperature of 75 to 80 kilograms of water by 1°,[76] melting 8 inches of ice will take heat enough from the water to cool a stratum 12 to 14 meters thick by about 1°; and probably this is a fair measure of the average cooling effect of snow falling on the coastwise belt of the Gulf of Maine within 5 to 10 miles of the land.

CHILLING EFFECT OF MELTING ICE

The melting of floating ice in high northern and high southern latitudes exerts a potent effect upon the distribution of temperature[77] in the North Atlantic; and the melting of ice, whether frozen locally or of Arctic origin (p. 689), is the most potent

[76] Recent measurements place the latent heat of fresh-water ice between 75 and 80.3 calories. (Krümmel, 1907, p. 507.)

[77] Salt-water ice is less effective as a cooling agent than fresh-water ice (floe ice, that is, than berg ice), because its latent heat of melting is somewhat lower. Petterson (1883) gives this as approximately 52 to 53 calories for ice frozen from water of about the salinity of the Gulf Maine.

factor in producing the low temperature of the mid-layer of the Gulf of St. Lawrence.

The chilling effect of ice melting in the Gulf of St. Lawrence, and to a greater extent of the drift ice melting over the Banquereau–Sable Island Bank region is, in turn, brought indirectly to the Gulf of Maine by the cold water flowing westward past Cape Sable in spring and early summer (p. 832); but no ice, either of Arctic or of St. Lawrence origin, has ever been known actually to enter the Gulf of Maine though pans (almost certainly from the latter source) do rarely drift down past Cape Sable along the edge of the continent or outside it. Consequently, as the surface of the open Gulf of Maine never freezes, ice melting *in situ* plays only a very subordinate role in its temperature complex, except in its shallow and more or less inclosed bays and among the islands that skirt its northern shores.

Cape Cod Bay offers an instructive example, on a small scale, of the effect that melting ice exerts upon the sea temperature, for more or less ice freezes over the flats along its western side nearly every winter. The greatest amount forms during heavy blows from the northwest, when it may stretch out 2 or 3 miles from the shore and pack several feet high along the beach. When ice has so formed, easterly winds and high tides soon disperse it; and, according to the United States Coast Pilot (1912, Part III, p. 59), "instances are on record of this ice, and that forming in the shallower parts of Cape Cod Bay in severe winters, being driven by the winds out into the bay, where it masses into heavy fields or windrows, sometimes as much as 10 feet or more thick, making the navigation of parts of the bay unsafe or impracticable at times."

Unfortunately, no observations were taken in Cape Cod Bay during the ice season of the almost Arctic winter of 1919–20, or until April of the succeeding spring; but in 1924 a considerable amount of ice formed along the west shore of the bay between the 20th and 26th of December, during a spell of very severe weather (p. 655), and the temperatures taken by the *Fish Hawk* on January 6 and 7, 1925, showed the effect by a drop in temperature at the near-by station (No. 7) from about 4.3°, two weeks previous, to about 0.3°. Ice chilling was also reflected still more clearly in the fact that the water was colder just off Wellfleet Bay (station 7) than anywhere else in the southern part of the Massachusetts Bay region on that date, as is described above (p. 655).

The sea ice that freezes in greater or less amount among the islands along the coast of Maine in all but the warmest winters must also exert a local chilling effect on the water as it melts, but no measurements of this have yet been made.

In severe winters, when much ice forms in Vineyard Sound, most of it reported to drift out to the eastward past Nantucket, melting ice must lower the temperature of the Nantucket Shoals region indirectly or directly. Here, again, however, definite data are lacking.

Ice is also an effective chilling agent in shallow bays such as Barnstable and Plymouth, for the flats, laid bare at low tide, skim over with ice on cold winter days or nights, which melts when the tide floods again. This is one reason (active tidal circulation is another) why such situations serve as centers for chilling in winter, just as they do as centers for warming in summer.

THERMAL EFFECT OF THE RIVER WATER

The great volume of river water that pours into the gulf every spring, at a temperature only a few degrees above the freezing point, when the ice goes out of the lakes and the snow melts, must tend at first to delay the vernal warming of the gulf. However, no attempt has yet been made to estimate its actual effect.

SUMMARY OF THERMAL DETERMINANTS

The interaction of the several major factors that govern the temperature of the gulf is so complex that a summary of them may be useful.

It is definitely established that the gulf owes the particular temperatures proper to it, and especially the wide seasonal range of temperature, chiefly to its geographic location to leeward of the continent and to the rigorous land climate. Only in a much smaller degree is it influenced by warm or cold currents flowing into it.

Our successive cruises and the observations taken in the Bay of Fundy by the Biological Board of Canada, therefore, corroborate the view long ago advanced by Verrill (1874) that the waters of the Gulf of Maine are not abnormally cold, considering their geographic location and the rigorous climate of the neighboring land mass; that, in short, to describe its temperature as "Arctic," as has so often been done, is entirely a misnomer.

The chief source of warmth for the superficial stratum of the gulf is the solar heat absorbed by the water *in situ*. Vernal warming is therefore chiefly of local origin. The rapidity with which solar heat is dispersed downward in the water and the depth to which it penetrates depend on the activity of vertical circulation, whether by tides, winds, storm waves, or dynamic overturnings; and the regional differences in the temperature gradient, which develop in the gulf in summer (Massachusetts Bay at the one extreme, the Bay of Fundy and Nantucket Shoals at the other), result chiefly from differences in the thoroughness with which the tides churn the water.

The low surface temperature that prevails along the eastern coast of Maine and in the Bay of Fundy in summer, as contrasted with the Massachusetts Bay region, is chiefly due, therefore, to local causes and not to the "Arctic current" that has so commonly been invoked to account for it.

The surface stratum of the gulf likewise receives heat from warm winds blowing over its surface, from surface water drifting into its eastern side from the region of Browns Bank and the Cape Sable dead water, and also, at long intervals, from overflows from the tropic water outside the edge of the continent.

Vernal warming is opposed by the Nova Scotian current flowing from the eastward, past Cape Sable, into the gulf. During the brief period when at its maximum, this current may lower the surface temperature by a couple of degrees right across to the western side of the basin, thus temporarily producing a regional differentiation; and it considerably delays vernal warming in the eastern side probably every year. However, this cold drift is so thoroughly incorporated into the water of the gulf soon after the actual flow past the cape slackens that no regional differentiation from this source can be traced definitely in the gulf after midsummer. Neither is its general temperature made more than 2° to 3° lower than would be the case if the gulf were entirely barred to currents, cold or warm; but the chilling effect of the Nova Scotian current is more important than this bald statement suggests, for it counteracts, by several degrees, the effect of the warm sources just mentioned.

Autumnal and winter chilling, so conspicuous a feature of the gulf, results primarily from the loss of heat from the surface by radiation, after the date when the mean temperature of the air falls below that of the water; neither cold currents from the north nor upwelling from the oceanic abyss have any major part in it.

Snow falling and melting on the surface is also a cooling agency of some efficacy; so, locally, is melting ice in Cape Cod Bay and among the islands along the coast of Maine. River drainage, by its low temperature in early spring, also tends to retard vernal warming. Evaporation from the surface also tends to chill the water throughout the year, accounting for a probable cooling of the mean temperature of the upper 50 meters by 5° to 6°.

The temperature of the superficial 100 meters of water is governed chiefly by these climatic (including solar) influences from above, by the thermal effect of the inflows into the eastern side of the gulf, and by the chilling effect of evaporation from the surface.

The cold layer that persists in the basin throughout the summer at a depth of 100 to 150 meters in most years is simply reminiscent of the lowest temperature to which this level chilled during the preceeding winter—not of an Arctic current. This layer is colder than the deeper water in most summers because the temperature of the latter is determined chiefly, not by seasonal climatic influences, but by the volume of the warmer slope water flowing in through the eastern channel, and by the course that this current follows inward along the two branches of the trough of the gulf. If the inflow of slope water is smaller than usual, or cooler, the summer temperature of the inner part of the basin is virtually uniform, vertically, from about 100 to 150 meters down to the bottom, as was the case in 1912.

It is not yet possible to estimate, quantitatively, what thermal effect the slope water has on the upper layers of water as it is gradually incorporated into the Gulf of Maine complex. Any increment from this source will tend to cool the surface stratum in the summer but to warm it in winter and early spring.

The chilling effects of the rigorous winter climate of the land mass to the west and of the Nova Scotian current, balanced against solar warming plus the warming effect of the slope water and of the surface indrafts from the Browns Bank–Cape Sable deadwater region, maintain a comparatively constant state in the gulf from year to year; but it is easy to see how any one of them, if more or less effective than usual, might profoundly influence its waters. In attempting to determine the causes of such fluctuations as have been recorded, the evidence of salinity, as well as of temperature, must be weighed.

Unusually high summer temperatures, with normal salinity, might result either from a mild winter preceding, from unusually rapid solar warming during the spring, or from a smaller increment from the Nova Scotian current than normal. High temperature, with very high salinity, would point either to an unusual inflow of slope water during the preceding winter or to one of the rare overflows of tropic water (p. 836). Abnormally low summer temperatures, with normal salinity, would