At most times there is no dominant drift into the gulf across Georges Bank, but on rare occasions overflows of tropic water take place at the surface, probably via that route.

The discharges of various rivers, added to rainfall, contribute annually to the gulf sufficient fresh water to form a layer half a fathom thick over its inner parts out to Georges Bank. The gulf also receives annually a blanket of rain water about a foot in thickness, in excess of the amount withdrawn by evaporation.

The gulf discharges water as a surface current around Nantucket Shoals to the westward; to some extent around the eastern end of Georges Bank,[50] and so out through the Eastern Channel.

It is not likely that the gulf ever receives water from the oceanic abyss, by upwelling, or directly from the Labrador current.

CIRCULATION IN THE GULF OF MAINE

Study of the circulation that dominates any part of the sea can be attacked in two different ways: (1) Directly, by observation with current meters or drift bottles, by ships' log books, and by interpreting the distribution of salinity and temperature, or (2) indirectly, by calculation of the hydrostatic forces tending to set the water in motion. The second method has greatly concerned oceanographers of late, and its value can hardly be overestimated in the study of ocean currents in the open sea; but its application to the Gulf of Maine is complicated by the disturbing factors introduced by the irregular contour of the bottom, the limiting coast line, and the strong tides, which not only produce currents of considerable velocity, but are constantly altering the slope of the surface. It is fortunate, therefore, that the following account can be based on the more direct methods of observation, supported by consideration of hydrodynamic forces as causative agents (p. 930).

TIDAL CURRENTS

No one can sail the Gulf of Maine without soon learning that its tidal currents run so strong that they must always be taken into account in coastwise navigation. Their velocities are so great, in fact, in most parts of the gulf, at the strength of ebb and flood, that for the ordinary observer they entirely obscure any dominant or nontidal drift that may be in progress.

No attempt has been made to add to the knowledge of the tides during our survey; but the following brief statement, condensed from the Coast Pilot, the tide tables and current tables of the Atlantic coast published by the United States Coast and Geodetic Survey (1923 and 1926), from the investigations of the Tidal Survey of Canada (Dawson, 1905 and 1908), and from other scattered sources, may be of interest.[51]

The flood, at its strength, runs northerly, the ebb southerly, along the whole line between Nantucket Shoals and the Northern Channel and likewise in the basin to

---

[50] For discussion of the discharge from the gulf see p. 974.

[51] In 1912 the *Grampus* recorded the velocity of the current near the mid-period of flood or ebb, hoping to learn the approximation of the direction and velocity at its strength. The value of these measurements is discussed in an earlier report (Bigelow, 1914, p. 83).

the north (Mitchell, 1881; Harris, 1907, pl. 7). This is also the case along the west coast of Nova Scotia on the one side of the gulf and along Cape Cod on the other; but the flood runs westward into Massachusetts Bay, as might be expected from the trend of the coast line, drawing southward around the tip of Cape Cod into Cape Cod Bay. There is also a flood current from the westward into the latter, resulting from a division of the tidal wave as it strikes the shore line at Manomet Head just east of Plymouth.

The promontory of Cape Ann also marks a division in the tidal streams; for to the northward of it the flood, setting westward in toward the land, veers to the north, paralleling the coast as far as Cape Elizabeth; to the eastward of Casco Bay the general direction of the flood at its strength is NNE. toward and through the Grand Manan Channel, complicated, however, by the flood currents setting into the bays and rivers. At the mouth of Casco Bay, for example, the tides flood to the north. In the Bay of Fundy the flood sets generally toward the northeast (i.e., inward).

In a general way the ebb, at its strength, is the reverse of the flood, setting out of the Bay of Fundy in a generally SW. to SSW. direction and around the coast of Nova Scotia to the south and southeast. Along the coast of Maine, from the Grand Manan Channel to Penobscot Bay, the tide ebbs southwesterly; southerly off Casco Bay. In Massachusetts Bay the ebb is generally eastward; southerly along Cape Cod.

Generally speaking, the velocity of the tidal currents is least along the sector of coast bounded by Cape Cod on the south and Casco Bay on the north, where velocities lower than 1 knot have been recorded at most of the observing stations for the flood at its strength. But the tide flows much more strongly (up to 1.8 knot) around the tip of Cape Cod and at the entrance to Boston Harbor. The Bay of Fundy stands at the other extreme, with velocities rising to 2.5 to 3 knots in the Grand Manan Channel; considerably higher even than this near the head of Minas Basin and elsewhere near the head of the bay. The velocity of the tides at strength is about 1 to 1.6 knots along the southern rim of the gulf; 1.5 to 2 knots along the west coast of Nova Scotia and out to the neighboring side of the basin.

The rise and fall of the tide is greater in the Bay of Fundy than anywhere else in the world; on the other hand, the tidal amplitude is certainly small over the offshore banks, though the rise and fall has not been measured there as yet.

The following summary of the rise and fall at representative stations, taken from the tide tables of the Atlantic coast (United States Coast and Geodetic Survey, 1926), will illustrate the transition from the mouth of the gulf inward along its two sides for ordinary tides:

Locality	Rise and fall of tide, in feet	Locality	Rise and fall of tide, in feet
WESTERN SIDE		EASTERN SIDE	
Outer shores of Cape Cod	4.3- 7.1	Shelburne, Nova Scotia	6.5- 7.9
Provincetown	7.5-11.1	Yarmouth, Nova Scotia	16.3-17.7
Gloucester	7.2-10.8	BAY OF FUNDY	
Portland	7.9-11.3	St. John	23.7-25.1
Bar Harbor, Mount Desert	9.2-12.6	Digby	27.2-28.6
Cutler (at western end of Grand Manan Channel)	12.9-16.3	Head of Minas Basin	48.7-50.1

DOMINANT OR NONTIDAL DRIFT

In the preceding summary of the tidal currents, directions and velocities are given for the flood and ebb at their strength. In some localities the direction continues virtually constant throughout ebb or flood, as the case may be. In most parts of the gulf, however, the current is to a greater or less extent a veering one, and there is some difference in velocity between flood and ebb. The resultant of movement by which any particle of water would fail to return at the end of any given tidal period (averaging 12 hours and 25 minutes) to the position from which it started its journey, is the dominant drift. The name "nontidal" is commonly used for this; the other appellation just given is preferable, however, there being some evidence that the dominant drift which we have been able to demonstrate for the Gulf of Maine has its source in the tidal currents.

On the high seas, where tidal currents are weak and the dominant drifts are often stronger, the ocean currents, as we now know them, have been charted chiefly by digestion of the drifts reported in the log books of passing ships. This source of information has failed to demonstrate any dominant set (as distinguished from tidal currents) in the Gulf of Maine, as might be expected where the tides are so strong and the resultant movement, if any, comparatively so weak.

MEASUREMENTS OF CURRENTS

A considerable number of measurements of the tidal currents have been made in the Gulf of Maine by the United States Coast and Geodetic Survey at the following localities: Portland lightship off Cape Elizabeth, near Cashes Ledge, three stations between Cape Ann and Cape Cod at the mouth of Massachusetts Bay, Boston lightship off Cape Cod, many stations at the mouth of Nantucket Sound and in the region of Nantucket Shoals, Nantucket lightship, and at a series of stations situated along the southern rim of the gulf from the South Channel to the offing of Cape Sable.

The Tidal Survey of Canada, under Doctor Dawson's direction, carried out an extended survey of the tidal currents at 19 stations distributed around the Nova Scotian coast from the offing of Shelburne to the Bay of Fundy, and within the latter, in the years 1904 and 1907 (Dawson, 1905 and 1908).

One current station also was occupied off Gloucester by the *Albatross* in March, 1920 (station 20051); and measurements of the velocity and direction of flood or ebb were made by the *Grampus* in the summer of 1912 at several localities in the western side of the gulf.

Thus, the western, southern, and eastern sides of the gulf are so well covered that these measurements could hardly fail to reveal the dominant set (if there be any) for that part of its periphery; but no systematic study has yet been made of the tidal currents along the eastern coast of Maine between Portland and the entrance to the Bay of Fundy.

Before proceeding to analyze these data we may first consider briefly what sort of information they may be expected to yield.

Readings of the current meter (or the simpler method of employing a float) give the rate of the current over a known interval of time and its direction.[52] These, then, are reduced to average velocities and directions for each tidal hour after the time of high water at some neighboring station of reference, and it is in this form that they appear in the current tables published in the United States Coast Pilot (United States Coast and Geodetic Survey, 1911, p. 151) and in the current tables for the Bay of Fundy (Dawson, 1908). In all such tables the direction stated is that toward which the current flows, referred to the true meridian. In other words, a "northeast" current is just the opposite of a "northeast" wind.

To plot the course which an imaginary body, floating in the water, would travel during the period from one high tide to the next, is perhaps the most graphic way to bring out the existence or absence of a dominant drift at any given locality. If the flood and ebb currents are exactly opposite in rate, duration, and direction, such a float would return precisely to its starting point, for there would be no resultant drift. In all probability, however, this would never happen in any part of the Gulf of Maine. If, with ebb and flood opposite in direction throughout their respective duration, one were stronger than the other, a dominant set would result parallel to the direction of the stronger. This condition is to be expected in narrow channels, such as the Grand Manan Channel, and close in along some parts of the coast line; but in most parts of the gulf the direction of the tidal current changes from hour to hour, running in a comparatively constant direction for only a few hours when ebb or flood is at its strength. In some localities the tidal current is perfectly rotary, with its direction veering uniformly throughout the half-tidal day. Such a state, for example, is to be expected about 16 miles to the eastward of Nantucket Shoals light vessel (United States Coast and Geodetic Survey, 1912, p. 10).

In the Gulf of Maine and on its offshore banks tidal currents veer always to the right—i. e., with the hands of the clock—most rapidly, in most cases, at the times of high and low water. Thus, a particle of water or any floating object, such as a buoyant fish egg, drifting during a tidal period, would follow a course varying in different parts of the gulf from a closed circle (bringing it back close to its starting point), through various types of veering spirals, to courses nearly opposite in direction for the two tides but unequal in distance. In most parts of the gulf, therefore, any such floating object would not follow the dominant or nontidal set *directly*, but in a zigzag or spiral course, traveling a much greater distance in the daily tidal components than the distance made good along the azimuth of the nontidal set.

The dominant set that results from a veering current may be deduced in various ways. If calculation be preferred, an approximation is easy with the ordinary navigational traverse tables in precisely the same way the navigator calculates, from his dead reckoning, the distance and course made good for the day.

In most cases a graphic method of summation is to be preferred. The following (now in common use and recently described in detail by Mavor (1922)) is, perhaps,

---

[52] It should be borne in mind that in tabular statements of currents the words "velocity" and "distance" are not synonymous; for, obviously, if the current is flowing at a rate of 1 mile per hour at one hour, and at 2 miles per hour an hour later, the distance made good during the interval is neither 1 mile nor 2 miles, but the mean of the two. This caution is added because some of the published tables of currents have been ambiguous in this respect.

the most convenient and yields approximations close enough for most purposes: Lay down a meridian, marking it N. and S. Then simply plot, to scale, the average distance and direction of the current for each successive hour, as successive lines, giving to each the correct compass bearing, commencing with high water as the starting point. Then the distance by which the location reached at one high water fails to coincide with the preceding high water, measured by the same scale, gives an approximation to the distance covered by the dominant set in one tidal day. The angle between the line connecting the two and the meridian first laid down gives the approximate direction.[53]

It is obvious that the smaller and more frequent the time intervals for which the mean velocity and direction are determined by the current meter, the closer will be the approximation yielded by this method of graphic summation, or by any other.

The work of the two governmental surveys just mentioned (of Canada and of the United States) has been directed primarily to the study of the tides as these affect navigation. Mitchell (1881), however, showed that resolution of the periodic observations at stations in the South Channel, on Georges Bank, and in the Eastern and Northern Channels demonstrated a dominant or nontidal drift at every station, in some cases of considerable velocity. A nontidal drift has also been published for many stations off Cape Cod and in the region of Nantucket Shoals (United States Coast and Geodetic Survey, 1912, chart to face p. 9), as well as for the vicinity of Cashes Ledge (Harris, 1907), long before the general importance of these drifts in the general circulation of the gulf was appreciated.

Dawson (1905, p. 16), on the other hand, believed that the currents in the eastern side of the gulf were strictly tidal, showing no "general movement of the water in any one direction in this region which is at all well marked." Mavor (1922), however, on submitting Dawson's current tables to the method of graphic summation described above, found that a dominant drift was demonstrable at every station, varying in "distance made good" for a single tidal period from about 1 mile to about 6½ miles. Dominant drifts of greater or less magnitude also result from tidal measurements taken at Portland and Boston lightships by the United States Coast and Geodetic Survey and at our *Albatross* station off Gloucester. The number of current stations is now so considerable that the presence of some such set is certainly characteristic of the parts of the gulf which they cover.

Some resultant drift in one direction or another is, in fact, to be expected anywhere in the open sea, set in motion by the temporary effects of the winds alone, if from no other cause. Whether or not such drifts as are revealed by measurements of the tidal currents can be interpreted as evidence of a dominant movement of the water as a whole depends, therefore, on their relative constancy at given stations and on whether they are consistent in direction, one with another, over considerable areas.

This last criterion can be tested most readily by plotting on a general chart of the area the dominant drifts calculated for the various stations.

The current arrows on such a chart for the Gulf of Maine (fig. 173) show this requirement met to a degree somewhat surprising when we remember that the observations were scattered through a long series of years and that the "sets" at the

---

[53] It is convenient to use a position plotting sheet, such as can be had from any dealer in navigational supplies.

individual stations varied widely in their duration, some being continued through several successive months and others only for a few days. Even if nothing else whatever were known of the movements of the water in the Gulf of Maine, these arrows would of themselves be strong evidence of a general tendency inward and northward along the western shores of Nova Scotia and out to the southeastward past Cape Cod and the Nantucket Shoals region for the summer and autumn months when the

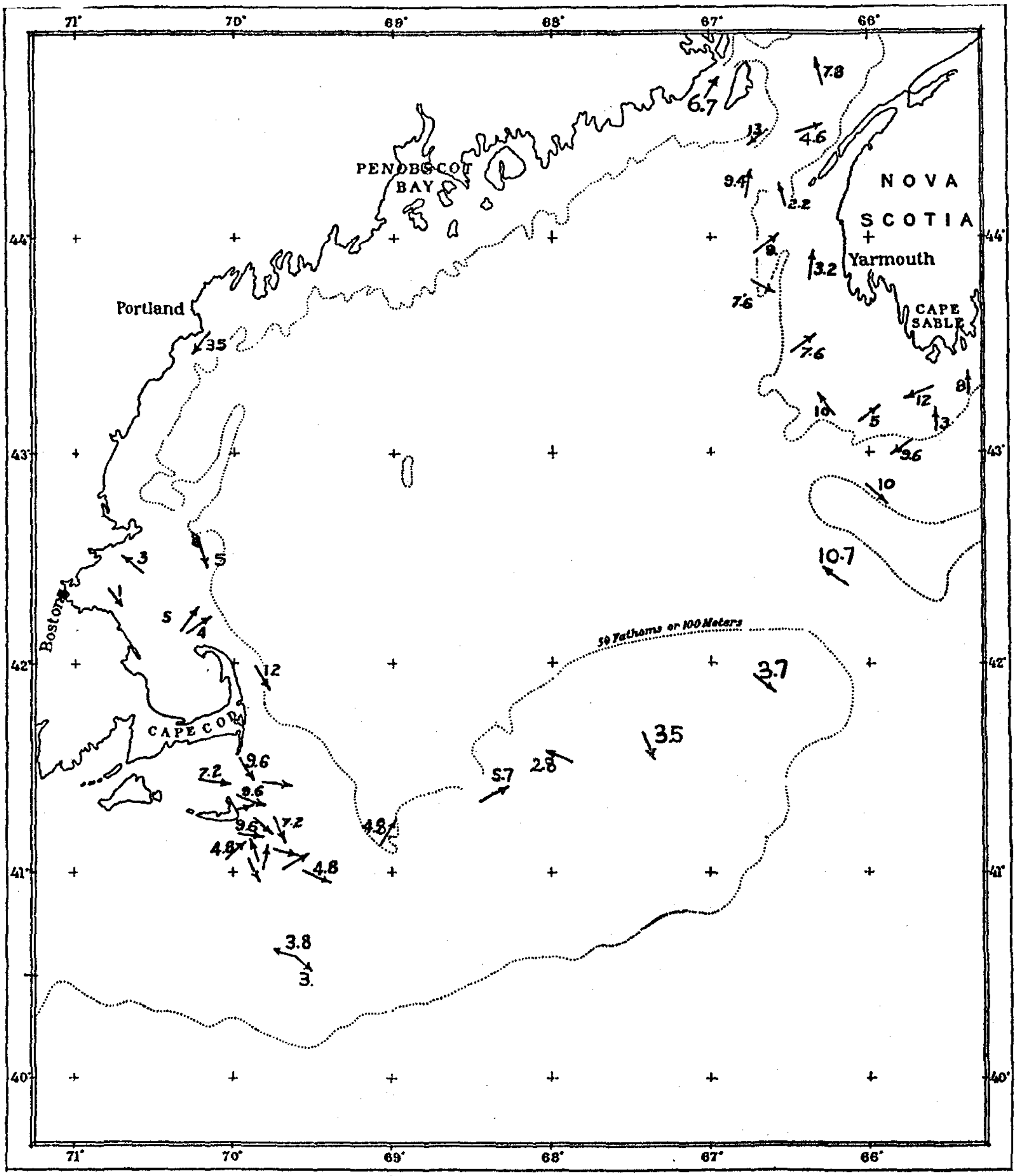

FIG. 173.—Direction and velocity, in miles, of the non-tidal current, per tidal day of 24 hours and 50 minutes, at stations of the United States Coast and Geodetic Survey and of the Tidal Survey of Canada. The feathered arrow is for the one *Albatross* station (20051)

current measurements were taken.[54] Mavor (1922, p. 109) has already emphasized the inward movement thus indicated around Nova Scotia and so into the eastern side of the Gulf of Maine. The drift to the westward past Cape Sable is shown to be irregular, however, and perhaps intermittent, for a very rapid dominant drift toward the west of about 12 miles per day, at Dawson's station R in the offing of Cape Sable, contrasts with contrary and much weaker resultant currents at two localities nearby (Dawson's stations P and Q). In the same way the water in the offing of Shelburne was setting strongly in toward the shore on June 25 to 29, 1907, showed no dominant drift in any direction at a neighboring station two weeks later,[55] but was drifting toward the southwest at a rate of about 8 miles per day on July 27 to 28, 1914 (Bigelow, 1917, p. 203, station 10231; current measurements at 6 meters depth with Ekman current meter).

The most that can be said is that the current arrows show some movement to the westward past the cape at times during the summer.

The general tendency northward along the western shores of Nova Scotia, toward the Bay of Fundy, is decidedly impressive, because not one of the arrows, as calculated from Dawson's tables (1908), runs counter to this rule, the only exceptions being two (his stations L and M), which point almost directly in toward the land. The arrows also show the water drifting into the Bay of Fundy along its southern (Nova Scotian) side, then turning northward toward New Brunswick and out again to the eastward and southward of Grand Manan. In the channel on the northern side of the latter, however, the water has been found to set inward toward the Bay of Fundy, suggesting a clockwise circulation around Grand Manan, which corroborates the local report that the flood current predominates over the ebb along the eastern part of the coast of Maine (Coast Pilot).

It is unfortunate that no measurements of currents are available for any points between the Bay of Fundy, on the east, and Portland lightship, to the west, for the tides run strong along this sector of the coast line.

At Portland lightship the currents are weak but slightly rotary (United States Coast and Geodetic Survey, 1923, p. 69).

The Coast and Geodetic Survey has supplied the following statement of the dominant (nontidal) set for several 29-day series at this location (lat. 43° 31′ 30,″ long. 70° 05′ 38″).

Duration of series	Rate per day (24 hours) in miles	Direction	Duration of series	Rate per day (24 hours) in miles	Direction
Oct. 3-31, 1913	11.3	S. 67° W.	July 1-29, 1919	2.4	N. 62° E.
Nov. 1-29, 1913	9.6	S. 31° E.	Aug. 1-29, 1919	2.2	S. 74° W.
Nov. 30-Dec. 28, 1913	11.3	S. 11° W.	Sept. 1-29, 1919	.5	N. 47° E.
June 1-29, 1919	4.3	S. 36° W.	Oct. 1-29, 1919	1.7	N. 58° E.

---

[54] So far as I have been able to learn, the only winter measurements made in the Gulf of Maine have been at Nantucket Shoals Lightship and one *Albatross* station off Gloucester (station 20051, p. 857).

[55] The resultant drifts for these two stations (Dawson, 1905 and 1908, statations S and T) are taken from Mavor's chart (1922, Pl. IV).

It is natural to think of the wind as partly responsible for these variations in the direction and velocity of the drift, and this is borne out by the following table giving the wind movements and directions at Portland, Me., for each month, and the resultants calculated therefrom by traverse tables.[56]

Month	Wind movement, miles								Resultant
	N.	NE.	E.	SE.	S.	SW.	W.	NW.	
October, 1913	2,471	449	597	813	667	574	264	1,247	N. 2° W., 2,030.
November, 1913	933	132	425	442	915	1,736	664	1,701	S. 84° W., 2,274.
December, 1913	1,848	443	235	232	208	1,422	942	2,255	N. 50° W., 3,697.
June, 1919	362	464	836	400	1,904	584	348	875	S. 3° E., 1,290.
July, 1919	382	186	551	411	2,094	826	1,013	624	S. 28° W., 2,279.
August, 1919	382	382	623	505	1,455	863	535	983	S. 33° W., 1,247.
September, 1919	690	575	485	462	2,088	638	504	1,097	S. 27° W., 1,118.
October, 1919	695	407	449	679	1,116	870	758	1,020	S. 73° W., 1,073.

When the directions and velocities of winds and currents are compared for the individual months it becomes clear that the drift is not purely a wind current, though considerably affected by the wind. With winds prevailing from anywhere between north and west, the drift has a southerly component, driven eastward and offshore by strong west winds (as in November, 1913), but setting toward the southwest, when the average wind direction is between north and west. It is when drifting southward (whether with an easterly or a westerly component) during periods when winds prevail between west and north that the surface set attains its greatest daily velocities of 9 to 11 miles per day. By common knowledge this applies also during northeast winds. During the one month (June, 1919) when south winds prevailed, the current ran, none the less, toward the southwest, though held back by the head wind to an average rate of only about 4 miles per day. The dominant drift was also very slow (0.5 to 2.4 miles per day) during the three months when southwesterly winds prevailed, setting against the wind (WSW.) for one month, but with the wind (between north and east) during the other three.

According to this correlation between current and wind, the direction of the nontidal current at this station is between WSW. and SE. and reaches a considerable velocity when westerly or northerly winds prevail; but its inherent stength is so small that southerly winds greatly reduce its velocity, or may even reverse it and produce a slow surface drift toward the northeast.

The wind table for Portland (p. 965) shows that the average direction of the wind there, from early autumn until April, is between northwest and a few degrees south of west.[57] Consequently we may assume that the dominant sets recorded at the lightship for the months of October, November, and December are representative for autumn, winter, and for the first two months of spring. These combined (by the traverse tables) give a resultant movement toward the south and west (S. 15° W.) at an average rate of about 8 miles per day. In spite of the prevalence of southwest winds in summer the resultant of the combined drifts for June, July, August,

---

[56] From data supplied by the United States Weather Bureau. The directions are those from which the wind blows, as in every-day parlance.

[57] Calculated on a time-percentage basis.

and September (similarly representative of that season) is a very slow set toward the southwest at less than 1 mile per day. If all the sets for all the months be combined, the resultant drift is toward the south by west ½ west (S. 18° W.) and its average daily rate about 3½ miles per day.

The underlying dominant drift at Portland lightship is thus shown to be southerly, so far as the general transference of water is concerned, and it is so shown on the chart. Westerly winds may give it an offshore (easterly) component; and persistent southwesterly winds, such as prevail in summer, may reverse the drift, driving the surface water to the northward and eastward. Such reversals, however, are only temporary, and while operative produce drifts much slower than the dominant southerly movement. It is only while the nontidal current is setting toward the southern half of the compass that it has velocities of 4 miles per day or greater.

No measurements have been made of the currents between Portland lightship and Cape Ann, but observations taken by the United States Coast Survey at a point 10 miles southward from Cape Ann, on September 27 and 28, 1877 (U. S. Coast Pilot, 1911, p. 151), showed a dominant set of about 3 miles per day toward the WNW. (N. 66° W.) for that particular 24 hours. Fourteen miles to the southeastward of this we found a dominant set of about 5.4 miles per day toward the SSE. (S. 26° E.) at a depth of 5 meters (with the Ekman meter) on March 1 and 2, 1920 (station 20051, p. 857). These drifts, approximately at right angles to each other, probably represent the dominant tendency at their respective locations more closely than might have been expected of one-day sets, because drift-bottle experiments also indicate a tendency inshore and into Massachusetts Bay from the inner of these two stations (Coast Guard station), southerly across the mouth of the bay from the outer (p. 890).

At Boston lightship (situated near the head of Massachusetts Bay, about 9 miles off the mouth of Boston Harbor) there is a very slow dominant drift toward the eastward, a 29-day series of observations (from September 24 to October 22, 1913) giving a resultant of about 2.6 miles per 24 hours toward the S. 6° E., while a second 58-day set (October 28 to December 19, 1913) showed a dominant drift of about 1 mile per day toward the N. 24° E.[58] These two combined point to a general dominant movement of the surface stratum toward the SSE. (S. 25° E.) at the rate of slightly less than 1 mile per day, and it is so shown on the chart (fig. 173). A dominant set outward from the head of the bay toward its mouth is thus indicated in its southern side, but one governed so much by the direction of the wind that the surface water may make but a short distance good in this general direction over a considerable period.

The dominant drift at a station in the channel, between the tip of Cape Cod and Stellwagen Bank, where the tidal currents were measured by the Coast Survey on August 24 and 25, 1877 (Coast Pilot, 1911, p. 151; lat. 42° 07′, long. 70° 15′), was toward the N. 53° E. at a rate of about 4 miles per day, with about 5 miles per day (2.5 miles for 12 tidal hours) toward the N. 36° E. on the southern side of Stellwagen Bank, a few miles to the northward, on September 17, 1855 (Coast Pilot, 1911, p. 151; lat. 42° 10′, long. 70° 16′).

---

[58] Information supplied by U. S. Coast and Geodetic Survey.

The directions and velocities given on the chart (fig. 173) for the stations off Cape Cod and in the region of Nantucket Shoals are copied direct from the Coast Pilot (1912, chart to face p. 9; based on observations taken by the U. S. Coast and Geodetic Survey). A south-southeasterly drift of about 12 miles a day at a station 7 miles off Nauset Light illustrates the general tendency toward a southerly movement of the water along Cape Cod, mentioned in the Coast Pilot. Observations taken at the Pollock Rip lightship and at Round Shoal lightship, at the entrance to Nantucket Sound, from June 20 to September 14, 1911, have also brought out dominant drifts toward the southeast at rates, respectively, of 9 to 10 and 2 to 3 miles per 24 hours. By this evidence, corroborated by bottle drifts (p. 886), the surface water sets southerly across and out of the eastern end of Nantucket Sound, not into the latter. This is corroborated by an east-southeasterly set of about 7 miles per 24 hours, recorded at a station 4 miles within the sound (2 miles south of Handkerchief Shoal lightship).

Sets of varying duration, taken by the Coast and Geodetic Survey at 11 stations in the general region of Nantucket Shoals, show a general dominant set between south and east, roughly paralleling the chief axis of the shoal ground, at rates varying from about 2 miles per day to about 14 miles (average about 3 miles). However, this is complicated by evidence of subsidiary eddying movements, such as might be expected over this uneven bottom, where strong tidal currents are complicated by rips and deeper channels.

Earlier studies pointed to the conclusion that the tidal currents at a point about 16 miles to the eastward of Nantucket light vessel are not only rotary but run at an equal velocity at all hours (Coast Pilot, 1912, p. 10); and it seems to have been taken generally for granted that there is no dominant set at the lightship, which is situated about 10 miles to the southward of the 40-meter contour of the shoals and 42 miles SSE. from Nantucket Island (lat. 40° 37′, long. 69° 37′), but that the currents there are purely tidal. This, however, is contradicted by 19 sets of current measurements, each of 29 days' duration, taken at this lightship by the United States Coast and Geodetic Survey in the months of June, July, August, September, October, November, December, February, March, April, and May of the years 1911, 1912, and and 1914, tabulated below.[59] In 13 cases a dominant set results toward the north and west; a set toward the south and east in four; and one series showed no appreciable set in either direction, as tabulated.

Dominant set at Nantucket lightship for various months

Month and year	Direction of dominant set	Drift per 24 hours	Month and year	Direction of dominant set	Drift per 24 hours
June, 1914	N. 46° W	2.2	September-October, 1913	N. 89° W	5.3
June-July, 1914	N. 55° W	2.2	Do	N. 80° W	8.2
June-July, 1911	N. 5° E	1.1	October, 1913	N. 86° W	5.3
July, 1914	N. 53° W	2.7	November, 1913	S. 68° E	2.4
July, 1911	N. 25° W	1.9	December, 1913	S. 44° E	4.0
August, 1914	N. 45° W	4.8	February, 1914	S. 51° E	2.9
August, 1911	N. 53° W	3.8	March, 1914	S. 40° E	1.0
August-September, 1911	N. 45° W	2.4	April, 1914	N. 75° W	1.4
September, 1914	N. 74° W	7.4	May, 1914	N. 62° W	4.3

---

[59] Data supplied by the U. S. Coast and Geodetic Survey.

Analysis of these sets shows a dominant drift toward the north and west (average direction about NW. by W.) during the spring, summer, and early autumn, averaging about 3.4 miles per day; but about as strong a southeasterly set (3 miles daily) during the late autumn, winter, and early spring, averaging about S. 50° E. in direction. If January and February be credited with about the same dominant drift as is recorded for December and March, the average set of water for the year works out at about 1.3 miles per day toward the N. 74° W. The rate has averaged lowest (less than 0.1 knot) from March through June, and drifts as strong as 0.2 knot have been recorded only during the months from August to December, a fact of some interest in connection with the discharge of surface water from the gulf (p. 974). This series of observations gives evidence of a considerable balance of movement of water toward the WNW. past the southern slopes of Nantucket Shoals, and whether the set be in that direction or toward the southeast, it is away from the gulf in either case.

This seasonal reversal in the direction of the dominant current is probably caused by the wind, with the southeasterly drift of winter reflecting the prevalence of strong northwest winds at that season; but the fact that the summer drift toward the west or northwest is not parallel with the prevailing southerly and southwesterly winds, but at right angles to them, reveals the dominant tendency for the water here to move westward.

Current measurements taken at eight stations along the southern rim of the the Gulf of Maine by the United States Coast and Geodetic Survey in 1877 show in each case a considerable nontidal resultant; and the indicated drift at any one of these may have been affected by the wind, for all were of short duration. However, they prove so consistent with the theoretic expectation of a clockwise movement around a shoal (p. 972) that they are probably representative of the prevalent summer state. The resultant drifts, as calculated by Mitchell (1881, p. 189, table 8), are as follows:

Station	Latitude		Longitude		Region	Directions	Velocity per 24 hours[1]
	°	′	°	′			*Miles*
1	41	10	68	55	South Channel	N. 31° E.	4.5
2	41	21	68	23	Northwest slope of Georges Bank	N. 79° E[2]	5.7
3	41	31	67	52	West side of Georges Shoals	N. 70° W[2]	2.8
4	41	36	67	24	East side of Georges Shoals	S. 14° E.	3.5
5	41	56	66	28	East end of Georges Bank	S. 42° E.	3.7
6	42	25	66	08	Eastern Channel	S. 76° W?	6.0
6	42	25	66	08	Do.	N. 51° W	10.7
7	42	50	65	56	South side of Northern Channel	S. 51° E.	7.3
8	43	04	65	41	North side of Northern Channel	S. 50° W.	4.7

[1] The U. S. Coast and Geodetic Survey writes that "resultant," in Mitchell's (1881, p. 189) original account, refers to the set for a tidal day of 24 hours and 50 minutes. This is reduced here to the set per 24 hours.

[2] The dominant drift is given as southeasterly at station 2, northeasterly at station 3, by Harris (1907, chart 7), and in the 1912 edition of the Coast Pilot (1912, chart to face p. 9); but a fresh calculation of the nontidal set at these stations by the Coast and Geodetic Survey shows a very good agreement with Mitchell's results.

These drifts indicate a general movement of the water northwestward around the western side of Georges Bank and southeastward over the eastern side, which is corroborated by bottle drifts (figs. 174, 176). They also suggest a subsidiary clockwise movement around the shoal part of the bank, drifting northward around its western flank and southward past the eastern flank. Drifts into the Gulf of Maine basin, at considerable velocities, result from the two stations in the center of the Eastern Channel.

At the time these observations were made the Northern Channel seems to have been dominated (as basins generally are in our latitudes) by an anticlockwise drift, southwesterly (toward the Gulf of Maine) in its northern side and southeasterly (away from the gulf) in its southern side. This latter drift, with the inward current in the Eastern Channel, suggests that Browns Bank was then the center of a clockwise eddy.

Current measurements also were taken in the center of the gulf, near Cashes Ledge (lat. 42° 53′, long. 68° 54′), on September 1 to 4, 1875, through a period of 58 hours, from which Harris (1907, pl. 7) has deduced a southerly set of about 4 miles per day. This agrees with the clockwise circulation to be expected around Cashes Ledge, this station being situated on its southeastern slope. Examination of the original data (supplied by the U. S. Coast and Geodetic Survey), however, makes it more likely that the dominant set varied with the wind there during the period of observation. The first 48 hours of the set (which apparently covered two tidal periods, because extending from "no current" to "no current") show a resultant toward the S. 26° W. of about 4 miles per 24 hours, as Harris represents it; but this period includes 8 hours (in groups of 3, 1, and 4) when no readings were taken, but during at least four of which the current almost certainly had an easterly component, judging from the stage of the tide as indicated by the veering of the current. The successive hourly directions also proved much more nearly rotary for the second tidal period than for the first, and with wide variation in its velocity while running in corresponding directions. It is wisest, therefore, to attempt no deduction of the dominant direction of the set from these data.

SUMMARY

The current measurements so far taken in the gulf when combined indicate the following circulatory movements: In the eastern side of the gulf the tendency is northward along Nova Scotia into the Bay of Fundy in its southern side, northward toward New Brunswick, and out of the bay along the south side of Grand Manan, with a counterflow into the bay via the Grand Manan Channel.

There is a gap in the observations for the coast section between Grand Manan and Cape Elizabeth. Off the latter the general set is southerly, though often deflected or temporarily reversed by the wind.

Two drifts are indicated in the region of Massachusetts Bay—one anticlockwise around its coast line and the other southerly across its mouth and down along Cape Cod. The drift is out to the eastward from Nantucket Sound, generally southerly and easterly past Nantucket Shoals. The records taken at Nantucket Lightship show a veering to the west and northwest around the shoals in summer, though not in winter. Two clockwise movements are suggested farther east—one around Georges Bank as a whole and a smaller one around its shoalest part.

In general, the dominant set has been found most rapid in the region of Cape Cod and Nantucket Shoals, averaging about 8 miles daily. The average velocity (about 7 miles per 24 hours) is nearly as great for the stations along the west coast of Nova Scotia and in the Bay of Fundy; but the resultant set into this side of the gulf is not so rapid, because most of the stations show components either to the west or to the east. Perhaps 5 miles per day approximates the rate at which a bottle might be expected to drift northward along Nova Scotia by this evidence.

EXPERIMENTS WITH DRIFT BOTTLES

Measurements with the current meter, such as have just been discussed, give both the direction and the rate of the dominant set, as well as of the tidal currents, at that particular place and time, assuming always that the observations are taken at frequent enough intervals and extended over a sufficient period of time.

The setting free and recovery of a drift bottle can never yield information so definite, because only the two end points of its journey are known, the route it has traveled from the one to the other always remaining a matter for deduction. Our drift bottles, furthermore, reflect the dominant movement of the uppermost stratum of water only; a fathom or two deep, at most, for the bottles with the longest drags. Neither does the drift of a bottle necessarily reproduce the drift that would have been followed by a particle of water, because the bottle floats on the surface, while the water may sink to lower levels by vertical currents, while new water may well up to the surface from below to take its place.

Because only the end points of the drifts are known and the intervening tracks can only be assumed, their value depends on a number of factors, especially on their consistency, one with another; the length of time they are adrift; the extent of the oceanic area covered; and on general information from other sources as to the local currents. In all these respects the Gulf of Maine has proved an especially favorable region for the study of the dominant circulation by the drift-bottle method. Since all the drifts from all the lines set out have, without exception, proved reducible to one scheme, entirely consistent with the current measurements (p. 866) and with general report as to the dominant set along various parts of the coast, with temperature and salinity, with the distribution of the plankton, and with the internal hydrostatic forces (p. 936), I believe they may be taken as representing the main features usually prevailing in spring, late summer, and early autumn.

The greater the time interval between release and recovery, the greater does the uncertainty become, because the longer the bottle is afloat, the greater distance it may have covered in its journey—i. e., the farther its track is apt to have diverged from the direct point to point line. By this same reasoning, when bottles are released in numbers the time interval becomes an important factor in deducing their probable tracks. If, for example, bottles released near Cape Elizabeth were to drift repeatedly to a point in Nova Scotia in as short a period as bottles released at Mount Desert, it is a fair assumption that the latter have diverged enough from the direct route to make their journey approximately as long as that of the former, assuming, of course, an approximately equal rate of drift for both. I should also point out that in a region where the tidal currents are as strong as they are in the Gulf of Maine, little information as to the *dominant* drift is to be had from a bottle until it has been adrift through several tidal periods. Consequently, when a bottle set adrift within 3 or 4 miles of shore at the beginning of the flood tide is recovered on the beach it does not mean that a dominant inshore set brought it in, but simply that it drifted and stranded with the tide.

These remarks are elementary, but are introduced here because, in conversation, I have found a very general tendency to ascribe a direct drift to any drift bottle.

BOTTLES SET OUT IN THE BAY OF FUNDY

The first systematic attempt to plot the dominant or nontidal circulation of any part of the gulf by the use of drift bottles was undertaken by the Atlantic (St. Andrews) biological station of the Biological Board of Canada in the summer of 1919, when 396 bottles were set adrift on lines crossing the Bay of Fundy, with results so positive that they are extremely welcome for the light they throw on the returns from the several series subsequently released in the open gulf by the Bureau of Fisheries. The complete data of localities of release and recovery are given by Mavor (1922), who has also discussed the probable tracks in such detail that a brief summary will suffice here.

The recoveries[61] may be divided into two groups—first, from within the Bay of Fundy, and second, from the Gulf of Maine.[62]

Bottles picked up within the Bay of Fundy were all set out in August and September, 1919, along lines at right angles to the general axis of the bay. Five bottles, set out at distances of 1 to 10 miles from shore on a line running northwest from Brier Island, at the mouth of the bay, and picked up along its Nova Scotian shore after drifts of 25 to 65 miles, show a definite set inward along the southern side of the bay consistent with the current measurements that have been taken there (Mavor, 1922, p. 116, fig. 13). One of these traveled at a rate of more than 4 nautical miles per day. It seems, however, that this inward drift involved only a narrow belt, probably not more than 6 or 7 miles wide at the time, because only one bottle from the next line to the west (one set adrift about 7 miles from the shore of Digby Neck) took this route, while two others released closer in to the land drifted across the bay to the New Brunswick shore and to Grand Manan.

Most of the recoveries from all the other lines were from points on the New Brunswick shore; a few were from the neighborhood of Grand Manan and a few (to be considered later) were in the Gulf of Maine outside the bay. Mavor's (1922) analysis brings out the interesting fact that the bottles that were picked up farthest east on the New Brunswick shore[63] were all set out in the southern side of the bay within 12 miles of the Nova Scotian shore.

The bottles set out in the southern side of the bay (several lines) thus exhibit one or the other of two rather definite tendencies. Those set adrift near the Nova

---

[61] Only those reported within 4 months after the bottles were set out are considered here.

[62] Mavor (1922, p. 116) states that "all the drift bottles which have been recorded from outside the Bay of Fundy were picked up in the Gulf of Maine." Two also have been reported from Europe (Mavor, 1921; Moor [Mavor], 1921).

[63] Between Musquash Harbor (long. 66°15'W.) and St. John.

Scotian shore at the mouth of the bay, or inward to Digby Gut, tended to drift eastward, hugging the southern coast. Those set afloat more than 5 to 10 miles out from land in the southern side of the bay rarely stranded on that shore, but usually drifted northward across the bay to the New Brunswick shore. It is evident that they did not go far up the bay, for only one bottle was picked up east of St. John, while most of the recoveries of bottles set out on the Nova Scotian end of the innermost line were west of the longitude at which they were set out.

Bottles set out in the northern side of the Bay of Fundy showed a westerly drift, the majority of recoveries coming from the New Brunswick shore west of Point Lepreau (especially concentrated in the region of Passamaquoddy Bay), with some from the southern and eastern sides of Grand Manan.

The southern edge of the inflowing current in the southern side of the bay hugged the shore—witness the stranding of bottles along Nova Scotia. Its outer (offshore) edge, on the contrary, showed as evident a tendency to veer, anticlockwise, across the bay toward the New Brunswick shore, and so to eddy westward, made evident by the tendency of bottles from the Nova Scotia side to strand farthest east (inward), along New Brunswick, and for bottles set out in the northern side of the bay to follow the coast line of New Brunswick farther to the westward.

Some idea of the routes followed by bottles crossing from the Nova Scotian to the New Brunswick side of the bay can be gained from the relative lengths of the intervals between release and recovery,[64] when these prove as consistent as they did in this instance. Mavor (1922, p. 116) has already commented on the fact that the bottles set out on the Nova Scotian end of a line abreast of Point Lepreau (his line G) averaged longer afloat than those set out on the New Brunswick end, suggesting that they took a longer route, going up on the Nova Scotian side and down on the New Brunswick side. The time intervals between release and recovery for bottles drifting from Nova Scotia to New Brunswick were also longer for those set out nearest the mouth of the bay (25 to 48 days) than for those set adrift farther in the bay (8 to 22 days), with a discrepancy much wider than the varying width of the bay would account for. Bottles set out on the southern end of the innermost line and picked up eight days later on the New Brunswick side must have followed a comparatively direct route in their crossing. A longer time interval for bottles set out nearer the mouth of the bay points to a more extended circling drift; but the fact that on the whole bottles set out farther and farther east along the Nova Scotian side fetched up farther and farther up the bay in the New Brunswick side is evidence that the south-north drift was of considerable breadth.

A cross section of the Bay of Fundy from Nova Scotia to Grand Manan would thus have shown a rather sudden transition, at the time, from a current flowing toward the southwest in the northern side to a northeast drift in along the southern shore. The fates of four bottles that were set out close together on a line abreast of Point Lepreau, but were picked up far apart and on opposite sides of the bay 37 to 70 days later, locates the boundary of these two currents nearer Nova Scotia than New Brunswick (Mavor, 1922, p. 116).

---

[64] Always remembering that a bottle may lie a long time on some seldom-visited beach.

These bottle drifts justify Mavor's (1922) general conclusion that in the summer of 1919 the water was drifting in along the southern side of the bay, circling northward across to the New Brunswick shore about abreast of St. John, setting west and southwest along New Brunswick and out of the bay past the southern side of Grand Manan. This, as he points out (1922, p. 116), is entirely consistent with the dominant set resulting from Dawson's current measurements; more consistant, indeed, than one might have expected of observations of these two sorts taken several years apart in such tide-swept waters.

The drift westward along New Brunswick, according to Mavor's analysis, was at a rate of at least 5 nautical miles per day. This, with the rates for the bottles that drifted inward along the Nova Scotian shore (p. 868), suggests a general daily rate of 4 to 5 miles for the periphery of the Bay of Fundy eddy.

Fifteen of the bottles set out in the Bay of Fundy in 1919 were picked up outside the bay in the Gulf of Maine—2 from the June series and 13 from the August series. The two June bottles, however, represent a much larger percentage than do the August recoveries; for only 10 bottles were set out in June, and these were the only ones picked up, whereas 220 were set out in August, most of the recoveries coming from within the Bay of Fundy. None of the September bottles (75 in number) were picked up in the Gulf of Maine.

The two June bottles were put out, respectively, 14 and 18 miles south of Grand Manan on the 18th. One was picked up at Bailey's Mistake (a cove on the north shore of the Grand Manan Channel) about midway of its length; the other was recovered in Penobscot Bay. Both of these bottles undoubtedly passed out of the bay in the outflowing current along the south side of Grand Manan; but the one circled Grand Manan, to be caught up in the indraft demonstrated by current measurements for the Grand Manan Channel; while the other, put out only 4 miles farther south, escaped this eddy and traveled westward along the coast of Maine. There is every reason to suppose that the 13 August bottles also went out of the Bay of Fundy along the south side of Grand Manan, for they show very uniform drifts. One was returned from Jonesport, Me., one from Schoodic Head, near Mount Desert, and all the rest from the Massachusetts Bay region and Cape Cod. Bottles from the innermost as well as from the outermost lines in the Bay of Fundy (Mavor's lines D and G) partook of this drift (curiously enough, however, none from the intermediate line).

Mavor (1922, p. 118) has emphasized the uniform time intervals of 7 of the 11 bottles that were picked up in Massachusetts Bay 73 to 80 days after being put out. This, with the fact that so large a proportion of all the bottles picked up outside the Bay of Fundy within four months after being set adrift were found along so short a stretch of the coast line, is evidence enough of a very definite surface drift from the northeastern to the southwestern side of the gulf during the late summer and early autumn of 1919; and the recovery of two bottles on the eastern coast of Maine makes it probable that this line of drift lay rather close in to the shore as far as the mouth of Penobscot Bay. However, since none were found between Penobscot Bay and Cape Ann they seem to have followed tracks farther out from the land along this sector of the coast line.

The distance from the Bay of Fundy to Cape Cod being about 220 miles, these bottles, as Mavor points out, must have drifted at an average rate of at least 4 miles per day. Actually, the rate was no doubt somewhat more rapid than this, because the track probably followed is approximately 260 miles, at the smallest reckoning.

The regional distribution of the recoveries in the Massachusetts Bay region is also interesting, none being from the shore line between Cape Ann and Plymouth, but seven scattered around the shores of Cape Cod Bay from Plymouth to the tip of the cape.[65] The hook of Cape Cod seems, therefore, to have acted as a sort of catch-basin for flotsam at the time these bottles were adrift, evidence that the set of surface water was then from north to south across the mouth of Massachusetts Bay, as it was in March, 1920 (current measurements at station 20051; p. 863), not around the shore line of the bay, as current measurements show it at times (p. 863).

Two bottles, evidently having crossed the mouth of the bay somewhat farther out, stranded on the outer shore of Cape Cod (near Pamet River Coast Guard Station and near South Wellfleet wireless towers), and one went to Monomoy Island at the southern angle of Cape Cod.

BOTTLES SET OUT IN THE GULF OF MAINE

The drifts of the bottles set out in the Bay of Fundy by the Biological Board of Canada in 1919 were so significant and agreed so well with the dominant set calculated from current measurements that the United States Bureau of Fisheries has since released 1,606 drift bottles in the Gulf of Maine and its tributary waters along the following lines, the returns from which are tabulated below:

DRIFT-BOTTLE RECORD, INCLUDING RECOVERIES UP TO SEPTEMBER 1, 1926

SERIES A: Bottles Nos. 1 to 300; two every half mile on a line running 125°, true, from Cape Elizabeth to the vicinity of Cashes Ledge, June 30 to July 1, 1922.

No.	Set out						Where found	Date, 1922	Interval
	Latitude			Longitude					
	°	′	″	°	′	″			*Days*
23	43	30	06	70	04	42	Small Point Harbor, east of Littlewood Island, Me	July 26	26
26	43	29	48	70	04	06	Between Richmond Island and Cape Elizabeth, Me	July 5	5
27	43	29	30	70	03	30	Near Bald Head, Small Point, Me	July 28	28
28	43	29	30	70	03	30	1 mile east of Cape Elizabeth Lighthouse	July 4	4
30	43	29	12	70	02	54	Northwest side of Monhegan Island	Aug. 16	47
32	43	28	54	70	02	18	Richmond Island Bay, Me	July 13	13
43	43	27	06	69	58	42	Woodwards Cove, Grand Manan Island	Oct. 12	104
52	43	25	57	69	56	18	Metinic Shoal (northwest of it)	Sept. 13	75
65	43	23	48	69	52	06	Loon Point, Jonesport, Me	Sept. 18	80
70	43	23	12	69	50	40	Chebeague Island, Me	July 25	25
72	43	22	54	69	50	18	Prouts Neck Beach. Scarboro, Me	do	25
75	43	22	18	69	49	06	Boothbay Harbor, Me	Aug. 1	32
76	43	22	18	69	49	06	5 miles east of Prouts Neck, Me., opposite Richmond Island	Sept. 10	72
79	43	21	42	69	47	54	Thompsons Point, Cundys Harbor, Me	do	72
83	43	21	06	69	46	42	Birch Point, Winnegance Bay, Me	Aug. 20	51
87	43	20	30	69	45	30	South Beach, Matinicus Island, Me	Oct. 12	103
88	43	20	30	69	45	30	Eastern Wolves Island, Bay of Fundy	do	103
90	43	20	12	69	44	54	Bald Head, Casco Bay, Me	July 25	25
98	43	00	19	69	42	30	¾ mile northeast from outer John's Island, near Swans Island, Me	Sept. 1	63
99	43	18	42	69	41	54	Bay of Fundy, Nova Scotia	Sept. 18	80
105	43	17	48	69	40	02	1 mile west of Hartsville Breakwater, south shore of Bay of Fundy	Oct. 6	98
124	43	15	06	69	34	42	South side of Cedar Island, Isles of Shoals, N. H	Oct. 8	100

[65] White Horse Beach, Plymouth; Sagamore Highlands; Sagamore Beach; Scorton Beach; North Truro; and three between Wood End and Peaked Hill Bar Coast Guard Station.

No.	Set out						Where found	Date, 1922	Interval
	Latitude			Longitude					
	°	′	″	°	′	″			*Days*
127	43	14	30	69	33	30	2 miles off Hillsburn, Hants County, Nova Scotia	Sept. 28	90
128	43	14	30	69	33	30	New Meadows River, Casco Bay, Me	Sept. 15	77
153	43	10	36	69	25	42	1 mile north of Beaver River, county line [N. S. ?]	Oct. 26	118
165	43	08	48	69	22	06	Scotts Bay Beach, Nova Scotia	Oct. 21	113
190	43	05	12	69	14	54	Entrance of Grand Passage, Nova Scotia	Oct. 24	116
206	43	02	48	69	10	06	Digby Neck, Sandy Cove, Nova Scotia, Bay of Fundy side	Sept. 28	90
210	43	02	12	69	08	54	½ mile off west side of Isle au Haut, Me	Sept. 23	85
215	43	01	18	69	07	06	1½ miles east of Port Lorne Lighthouse, Nova Scotia	Nov. 23	146
222	43	00	24	69	05	18	Port Lorne, Nova Scotia	Oct. 21	113
230	42	59	12	69	02	54	Meteghan Cove, Nova Scotia	Nov. 14	135
241	42	57	24	68	59	18	Port Lorne, Bay of Fundy, Nova Scotia	Sept. 26	88
242	42	57	24	68	59	18	14 miles west-southwest from Digby, in Bay of Fundy, 3 miles offshore	Sept. 8	70
248	42	56	30	68	57	30	Broad Cove Breakwater, 2 miles from Point Prim Light, Bay of Fundy	Sept. 13	75
255	42	55	18	68	55	06	9 miles from Point Prim, Bay of Fundy	Sept. 28	90
264	42	54	06	68	52	42	Bay of Fundy shore of Long Island, at Central Grove, Nova Scotia	Sept. 19	81
280	42	51	42	68	47	54	Northwest from Salvages fog alarm, Nova Scotia	Sept. 5	67
284	42	51	06	68	46	42	Southern Point, Matinicus Island, Me	Oct. 11	103
299	42	48	42	68	41	54	Advocate Harbor Beach, Cumberland County, Nova Scotia	Oct. 15	107

Series B: Bottles Nos. 301 to 900; two every half mile, running 141° from the offing of Chatham, Cape Cod, 150 miles, July 4, 1922.

No.	Set out						Where found	Date, 1922	Interval
	Latitude			Longitude					
	°	′	″	°	′	″			*Days*
301	41	41	00	69	53	00	1½ miles north of Coast Guard station 41, Nausett Beach, Mass	July 11	5
302	41	41	00	69	53	00	Stonewall Beach, Chilmark, Mass. (east of Old Bull bell buoy)	Aug. 26	51
303	41	40	36	69	52	36	Sakonnet River, R. I	July 30	24
304	41	40	36	69	52	36	Chatham, Mass	July 9	3
308	41	39	45	69	51	48	Cuttyhunk, Mass	Sept. 10	66
309	41	39	24	69	51	24	West side of Nantucket Harbor, mouth of jetty	Dec. 31	180
311	41	39	00	69	51	00	60 miles south-southeast of Cape Cod Light	July 21	15
314	41	38	36	69	50	36	West end, Cuttyhunk Island	Aug. 7	32
317	41	37	48	69	49	48	On Beach near north lighthouse, Block Island	Aug. 11	36
331	41	35	00	69	47	00	¼ mile north of Gay Head, Mass	Aug. 6	30
333	41	34	36	69	46	36	On Beach near southeast light, Block Island	July 7	1
334	41	34	36	69	46	36	Newport Beach, Newport, R. I	Sept. 12	67
337	41	33	38	69	45	48	South side, Marthas Vineyard Island	July 23	16
343	41	32	36	69	44	36	Chilmark, south shore Marthas Vineyard	Aug. 29	53
348	41	31	48	69	43	48	5 miles north of Finis-terre Light, France	[1] Sept. 16	------
357	41	29	48	69	41	48	75 miles southeast from Cape Cod [light ?]	Oct. 3	88
358	41	29	48	69	41	48	Hampton, Annapolis County, Nova Scotia	Oct. 21	106
362	41	29	00	69	41	00	75 miles southeast ½ south from Cape Cod Light	July 12	5
376	41	26	12	69	38	12	Between Horseneck Beach and Barney's Joy Point	Sept. 10	65
389	41	23	24	69	35	24	Head of Miacomet Pond, Nantucket, Mass	Aug. 19	43
396	41	22	12	69	34	12	75 miles south-southeast from Cape Cod [light]	July 15	8
405	41	20	12	69	32	12	48 miles south-southeast from Cape Cod Light	do	8
422	41	17	00	69	29	00	12 miles south of Sakonnet Point light	Sept. 5	60
433	41	14	36	69	26	36	Hampton, 26 miles east of Digby, Nova Scotia	Sept. 27	82
435	41	14	12	69	26	12	Lat. 42° 07′ N., long. 66° 41′ W	Oct. 11	96
445	41	12	12	69	24	12	1½ miles west of U. S. Coast Guard Station 47, Muskeget	Aug. 10	34
447	41	11	48	69	23	48	300 yards east of boat house, Fishers Island, N. Y	Aug. 16	40
462	41	09	00	69	21	00	Near Port George, Nova Scotia	Oct. 20	105
484	41	04	36	69	16	36	South shore of Marthas Vineyard, east of No Mans Land	Sept. 12	67
510	40	59	24	69	11	24	72 miles southeast by east from Cape Cod Light	July 10	3
528	40	55	48	69	07	48	West shore, Mishaum Point, Mass	Aug. 13	37
536	40	54	12	69	06	12	East-southeast ½ mile from mouth of Vineyard Sound, Mass	July 30	23
541	40	53	00	69	05	00	South Beach, Katama Bay, Edgartown, Mass	Aug. 28	52
543	40	52	36	69	04	36	Georges Bank, lat. 41° 15′	Aug. 11	35
547	40	51	48	69	03	48	On beach, Nantucket, Mass	Aug. 20	44
548	40	51	48	69	03	48	4 miles southwest of Vineyard Sound Lightship, Mass	July 29	22
557	40	49	48	69	01	48	Katama Bay, Edgartown, Mass	Aug. 13	37
569	40	47	24	68	58	24	Near Buoy, Gay Head, Mass	July 20	22
580	40	45	24	68	56	24	1 mile east of U. S. Coast Guard Station 47, Mass	July 25	18
582	40	45	00	68	56	00	Southeast shore, Block Island, R. I	Sept. 12	67
584	40	44	36	68	55	36	Horseneck Beach, Mass	July 31	24
585	40	44	12	68	55	12	On Massachusetts and Rhode Island line	July 28	21
587	40	43	48	68	54	48	Off Grace Point, Block Island	Sept. 13	68
588	40	43	48	68	54	48	Penikese Island, Mass	Aug. 2	26

[1] 1923.

No.	Set out						Where found	Date, 1922	Interval
	Latitude			Longitude					
	°	′	″	°	′	″			*Days*
590	40	43	24	68	54	24	Crescent Beach, Block Island, R. I	Aug. 13	37
591	40	43	00	68	54	00	Middle Ground Shoal, Vineyard Haven, Mass	Aug. 9	33
593	40	42	36	68	53	36	Bathing Beach, Southampton, Long Island	Sept. 12	67
596	40	42	12	68	53	12	¼ mile north of Sakonnet Lighthouse, Sakonnet River, R. I	July 30	23
597	40	41	48	68	52	48	On Beach at Horseneck, Westport, Mass	Aug. 7	31
600	40	41	24	68	52	24	Tarpaulin Cove, Naushon Island, Mass	Aug. 26	50
602	40	41	00	68	52	00	Near Lighthouse, south beach, Gay Head, Mass	July 29	22
603	40	40	36	68	51	36	2½ miles northwest of Vineyard Sound Lightship, Mass	Aug. 1	25
604	40	40	36	68	51	36	Old Harbor Point, Block Island, R. I	Aug. 10	34
605	40	40	12	68	51	12	West Horseneck Beach, Westport, Mass	July 29	22
606	40	40	12	68	51	12	West shore Block Island, R. I	Aug. 19	43
608	40	39	48	68	50	48	Narragansett Pier, R. I	Aug. 7	31
609	40	39	24	68	50	24	North-northwest of Old Harbor Breakwater, east side, R. I	Aug. 4	28
611	40	39	00	68	50	00	1 mile north of Wasque Hill, Chappaquiddic Island, Mass	July 27	20
613	40	38	36	68	49	36	1 mile east of Coast Guard station 72, Long Island, N Y	Aug. 7	31
614	40	38	36	68	49	36	1½ miles West of Barney's Joy Point, Mass	July 29	22
615	40	38	12	68	49	12	5 miles below Edgartown, south shore Martha's Vineyard, Mass	Aug. 20	44
617	40	37	48	68	48	48	Pleasant View Beach, R. I	July 28	21
618	40	37	48	68	48	48	Westport Point, Mass	[1]Dec. 29	(2)
620	40	37	24	68	48	24	Horseneck, Beach, Mass	July 31	23
621	40	37	00	68	48	00	Horseneck Beach, Westport, Mass	do	22
622	40	37	00	68	48	00	Matunuck Beach, R. I	Aug. 8	32
624	40	36	36	68	47	36	Near Warren Point, Little Compton, R. I	July 29	22
627	40	35	48	68	46	48	Cornwall, England	[3]Aug. 14	(4)
628	40	35	48	68	46	48	3½ miles west of Montauk Light Station	Sept. 10	65
629	40	35	24	68	46	24	West Horseneck Beach, Mass	Aug. 1	25
630	40	35	24	68	46	24	South shore, Chilmark, Mass	Aug. 2	26
631	40	35	00	68	46	00	4 miles below Edgartown, south shore Marthas Vineyard, Mass	Aug. 6	30
634	40	34	36	68	45	36	2 miles northwest of Vineyard Sound Lightship, Mass	Aug. 1	31
635	40	34	12	68	45	12	1 mile southeast of Westport Harbor, Horseneck Beach, Mass	Aug. 7	31
637	40	33	48	68	44	48	3 miles south-southeast of Cuttyhunk Lighthouse, Cuttyhunk, Mass	July 28	21
638	40	33	48	68	44	48	Between North Light and New Harbor Channel, West Beach, R. I	Aug. 6	30
639	40	33	24	68	44	24	Halfway between Coast Guard Stations 66 and 67, Montauk, L. I	Sept. 16	71
641	40	33	00	68	44	00	On beach near Falmouth, Mass	Aug. 20	44
644	40	32	36	68	43	36	West end of Nashawena Island, Mass	July 29	22
645	40	32	12	68	43	12	½ mile southeast of light on beach, Block Island, R. I	July 7	1
646	40	32	12	68	43	12	Charlestown Beach, R. I	Aug. 5	29
647	40	31	48	68	42	48	10 miles west of Montauk Point, south side Long Island, N. Y	Aug. 7	31
648	40	31	48	68	42	48	Between Point Judith and Charleston, opposite East Island	Aug. 17	31
649	40	31	24	68	42	24	Sakonnet Point, R. I	Aug. 4	28
650	40	31	24	68	42	24	6 miles southeast from Sakonnet Point Light, R. I	Aug. 3	27
651	40	31	00	68	42	00	Little Compton, R. I	July 28	21
652	40	31	00	68	42	00	Easthampton, L. I	Sept. 12	67
653	40	30	36	68	41	36	Near Life Guard Station 65, Ditch Plains, Montauk, L. I	Sept. 9	64
654	40	30	36	68	41	36	½ mile east of Coast Guard Station 73, opposite Hampton Bays, N. Y	Sept. 11	66
655	40	30	12	68	41	12	East side of Block Island, R. I	Sept. 9	64
656	40	30	12	68	41	12	Sagaponack, L. I. northeast of Bridgehampton	Sept. 12	67
658	40	29	48	68	40	48	Gay Head, Mass	Sept. 3	58
661	40	29	00	68	40	00	1½ miles west of Charlestown, R. I. (?)	Sept. 17	72
662	40	20	00	68	40	00	1½ miles from light, south shore, Gay Head, Mass	Aug. 5	29
664	40	28	36	68	39	36	1 mile south of No Mans Land, Mass	July 28	21
665	40	28	12	68	39	12	Start Point, bearing north-northwest, 15 miles, England	[5]Sept. 19	(6)
666	40	28	12	68	39	12	West Beach, Horseneck, South Westport, Mass	Aug. 7	31
668	40	27	48	68	38	48	3½ miles from light, south shore, Gay Head, Mass	Aug. 5	29
669	40	27	24	68	38	24	2 miles north of Coast Guard Station 172, Kitty Hawk, N. C	Sept. 26	81
676	40	26	12	68	37	12	Coast Guard Station 176, near Manteo, N. C	Sept. 30	85
679	40	25	24	68	36	24	1 mile north of Coast Guard Station 165	Oct. 1	86
680	40	25	24	68	36	24	¼ mile north of Coast Guard Station 171	Sept. 22	77
684	40	24	36	68	35	36	1 mile north of Coast Guard Station 170	do	77
686	40	24	12	68	35	12	Near Coast Guard Station 179	Sept. 27	82
688	40	23	48	68	34	48	1 mile north of Coast Guard Station 176	Sept. 30	85
695	40	22	12	68	33	12	Kitty Hawk, N. C	Sept. 27	82
700	40	21	24	68	32	24	1½ miles west of Coast Guard Station 56, Green Hill, R. I	Sept. 12	67
702	40	21	00	68	32	00	8 miles west of Montauk Lighthouse, Long Island, N. Y	Sept. 19	74
703	40	20	36	68	31	36	1½ mile south of Coast Guard Station 170	Sept. 21	76
707	40	19	48	68	30	48	Near life-saving station, east beach, Montauk, L. I	Sept. 12	67
718	40	17	48	68	28	48	2½ miles east of Quonochontaug life-saving Station, R.I	Sept. 13	68
724	40	16	36	68	27	36	Edgartown Harbor, Edgartown, Mass	Oct. 15	100
727	40	15	48	68	25	48	1½ mile south of Coast Guard Station 9	[7]Mar. 4	(8)
728	40	15	48	68	25	48	2¼ miles north of Coast Guard Station 170, on beach	Sept. 22	77
731	40	15	00	68	25	00	The Azores	(9)	(10)
732	40	15	00	68	25	00	Off Gooseberry Neck, near Westport Harbor, Mass	Sept. 3	58

[1] 1923.

[2] One year 4 months and 22 days.

[3] 1926.

[4] Four years 1 month and 7 days.

[5] 1924.

[6] Two years 2 months and 12 days.

[7] 1923.

[8] Seven months 25 days.

[9] July, 1923.

[10] About 1 year.

No.	Set out		Where found	Date, 1922	Interval
	Latitude	Longitude			
	° ′ ″	° ′ ″			Days
739	40 13 24	68 23 24	2 miles south of Coast Guard Station 170, Duck, N. C	Sept. 29	84
745	40 12 12	68 22 12	West end of Baileys Beach, Newport, R. I	Sept. 13	68
749	40 11 24	68 21 24	Grand Canary Island	[1]Apr. 1	(2)
752	40 11 00	68 21 00	Southeast by south ½ south, 35 miles from No Mans Land	Sept. 20	75
753	40 10 36	68 20 36	6 miles southwest of Gay Head, Mass	Sept. 6	61
762	40 09 00	68 19 00	Point O Wood, Fire Island, Long Island, N. Y	Oct. 8	93
770	40 07 24	68 17 24	Lat. 41° 20′ 45″, long. 70° 38′ 30″	Sept. 4	59
775	40 06 12	68 16 12	2 miles east of Coast Guard Station 70	Sept. 20	75
777	40 05 48	68 15 48	½ mile south of Coast Guard Station 169	Oct. 14	99
779	40 05 24	68 15 24	1 mile south of Coast Guard Station 181	Sept. 27	112
787	40 03 48	68 13 48	Roughley, Sligo Bay, Ireland	[3]July 18	(4)
790	40 03 24	68 13 24	South shore of Marthas Vineyard, Mass	Sept. 4	59
802	40 01 00	68 11 00	South Beach, Edgartown, Mass	Aug. 29	53
804	40 00 36	68 10 36	Southwesterly shore of Marthas Vineyard, Mass	Sept. 7	62
806	40 00 12	68 10 12	¾ mile on the shore northeast from the breakwater, Sakonnet Point, R. I	Sept. 6	61
822	39 57 00	68 07 00	1 mile south of Coast Guard Station 173	Sept. 28	83
824	39 56 36	68 06 36	Horseneck Beach, Westport, Mass	Sept. 16	71
835	39 54 12	68 04 12	1 mile below Bodies Island Lighthouse, N. C	Oct. 2	87
837	39 53 48	68 03 48	½ mile north of Coast Guard Station 177	do	87
839	39 53 24	68 03 24	In Bay at Nantucket, Mass	Nov. 22	141
844	39 52 36	68 02 36	10 miles southwest by west of Sankaty light, Nantucket, Mass	Aug. 28	52
845	39 52 12	68 02 12	9 miles north of Bodies Island light Station	Sept. 18	73
890	39 43 24	67 53 24	South side of Marthas Vineyard, Mass	Oct. 1	86
900	39 41 24	67 51 24	South Beach, Marthas Vineyard, Edgartown, Mass	Aug. 28	52

[1] 1924.
[2] One year 8 months and 24 days.
[3] 1923.
[4] One year 11 days.

Series D: Bottles Nos. 1501 to 1600; two bottles every half mile on a line running 150° from Bakers Island, off Mount Desert, for 25 miles, August 6, 1923.

No.	Set out		Where found	Date, 1923	Interval
	Latitude	Longitude			
	° ′ ″	° ′ ″			Days
1503	44 13 19	68 10 25	Duck Island, Me	Aug. 8	2
1504	44 13 19	68 10 25	Near Baccaro lighthouse, Shelburne County, Nova Scotia	Oct. 18	73
1506	44 12 53	68 10 05	Comeau Cove, Digby County, Nova Scotia	Oct. 7	62
1510	44 12 01	68 9 25	Great Duck Island, Me	Aug. 8	2
1511	44 11 35	68 9 05	Winter Harbor, Me	[1]July 19	
1515	44 10 43	68 8 25	Point of outer Long Island, Me	Aug. 8	2
1521	44 9 25	68 7 25	Kennebunk Beach, Me	Sept. 7	32
1523	44 8 59	68 7 05	8 miles southeast of Isle au Haut, Me	Aug. 7?	(?)
1530	44 7 41	68 6 00	Salmon River, Digby County, Nova Scotia	Dec. 17	133
1531	44 7 15	68 5 45	East side Petite Passage, Digby County, Nova Scotia	Oct. 16	71
1541	44 5 05	68 4 05	West side Egg Rock light, Hancock County, Me	Sept. 11	36
1546	44 4 13	68 3 25	Deep Cove, Isle au Haut, Me	Sept. 14	39
1547	44 3 47	68 3 05	Salmon River Beach, Digby County, Nova Scotia	Oct. 9	64
1550	44 3 21	68 2 45	Scudish Island, Me	Sept. 10	35
1551	44 3 00	68 2 45	Pubnico Harbor, Nova Scotia	[1]Jan. 4	151
1553	44 2 29	68 2 05	1¾ miles WNW. of Matinicus, Me	Sept. 12	37
1554	44 2 29	68 2 05	Clark Island, Me	Sept. 9	34
1557	44 1 37	68 1 25	Pubnico Point, Nova Scotia	[1]Jan. 4	151
1563	44 0 19	68 0 25	Pleasant Cove, Digby County, Nova Scotia	Oct. 8	63
1565	43 59 53	68 0 05	States Point, St. George, Me	Sept. 9	34
1566	43 59 53	68 0 05	Wooden Ball Island, Me	Sept. 11	36
1568	43 59 27	67 59 45	Meteghan River, St. Marys Bay, Digby County, Nova Scotia	Oct. 7	62
1576	43 57 43	67 58 25	3 miles west from Petit Manan light, Me	Sept. 13	38
1581	43 56 25	67 57 25	West side of Grindstone Neck, Winter Harbor, Me	Sept. 8	33
1584	43 55 59	67 57 05	Haycocks Harbor, Washington County, Me	Nov. 7	93
1587	43 55 07	67 56 25	Near Port George, Annapolis County, Nova Scotia	Nov. 2	88
1599	43 52 31	67 54 25	Near bell buoy, Burnt Island, Me	Sept. 10	35
1600	43 52 31	67 54 25	Northeast Matinicus	Sept. 8	33

[1] 1924.

Series E: Bottles Nos. 1701 to 1800; two every half mile along a line running 125° from Cape Elizabeth whistling buoy, for 25 miles, August 4, 1923.

No.	Set out						Where found	Date, 1923	Interval
	Latitude			Longitude					
	°	′	″	°	′	″			Days
1702	43	32	00	70	12	00	Beachwood, Me	Sept. 7	31
1712	43	30	35	70	09	10	Siasconset, Mass	Dec. 24	139
1720	43	29	27	70	6	54	Clifford's Cove, Long Island, Nova Scotia	Oct. 20	74
1721	43	29	10	70	6	20	4 miles southeast Seguin light, Me	Sept. 8	32
1726	43	28	36	70	5	12	Entrance Grand Harbor, New Brunswick, Nova Scotia	Nov. 26	111
1728	43	28	19	70	4	48	New River Beach, Charlotte County, New Brunswick, Canada	Oct. 22	76
1731	43	27	45	70	3	40	North Beach, Chatham, Mass	Dec. 6	121
1732	43	27	45	70	3	40	New Meadows River, Me	Sept. 14	38
1733	43	27	28	70	3	06	Mascabin Point light, New Brunswick, Canada	Oct. 21	75
1734	43	27	28	70	3	06	Pond Island, Casco Bay, Me	Oct. 1	55
1740	43	26	37	70	1	24	Shore of Round Pond Harbor, Me	Nov. 2	77
1763	43	23	23	69	54	36	Salmon River, St. Marys Bay, Nova Scotia	Nov. 5	90
1764	43	23	23	69	54	36	Centreville, Digby County, Nova Scotia	Oct. 9	63
1768	43	22	49	69	53	28	Bay of Fundy shore, Digby County, Nova Scotia	Oct. 10	64
1769	43	22	32	69	52	54	Comeau Cove, Digby County, Nova Scotia	Oct. 10	64
1773	43	21	58	69	51	46	Big Wood Island, Grand Manan, Nova Scotia	Oct. 2	56
1780	43	21	07	69	50	04	Bay of Fundy, Brier Island, Digby County, Nova Scotia	Nov. 4	79
1792	43	19	25	69	46	40	Metinic Island, Me	Oct. 10	64
1793	43	19	08	69	46	06	Sheepscot River, Me	Sept. 10	34

Series F: Bottles Nos. 1601 to 1700; two bottles every half mile along a line running 99° from Thatchers Island, Cape Ann, for 25 miles, August 9, 1923.

No.	Set out						Where found	Date, 1923	Interval
	Latitude			Longitude					
	°	′	″	°	′	″			Days
1635	42	36	22	70	19	23	Yarmouth Harbor, Yarmouth County, Nova Scotia	Oct. 18	60
1636	42	36	22	70	19	23	Port Maitland, Yarmouth County, Nova Scotia	Oct. 12	64
1645	42	36	02	70	15	58	Cockeritt Passage, Shelbourne County, Nova Scotia	Oct. 13	65
1648	42	35	58	70	15	17	15 miles north of Yarmouth Cape, Nova Scotia	Dec. 25	138
1672	42	35	10	70	7	05	East side Digby Gut, Nova Scotia	Nov. 2	85
1677	42	34	58	70	5	15	Dogs Bay, Roundstone West, County Galway, Ireland	[1] Jan. 2	------
1692	42	34	30	70	0	15	East of Preston Littlehampton, Sussex, England	[2] Sept. 25	------

[1] 1925. [2] 1924.

Series G: Bottles Nos. 1801 to 1900; two every half mile on a line running 73° from a point half a mile off the radio towers at South Wellfleet, Cape Cod, for 25 miles, August 16, 1923.

No.	Set out						Where found	Date, 1923	Interval
	Latitude			Longitude					
	°	′	″	°	′	″			Days
1815	41	56	03	69	52	40	Nauset Harbor, Mass	Sept. 12	27
1826	41	56	48	69	49	36	Nauset Lighthouse, North Eastham, Cape Cod, Mass	Aug. 18	2
1881	42	00	57	69	31	20	Eastern edge of Georges Bank, latitude 41° 50′, longitude 66° 0′	Oct. 14	59
1885	42	01	15	69	30	06	Bally Teique Bay, Kilnare Quay, County Wexford, Ireland	[1] Sept. 20	------
1892	42	01	42	69	28	15	Tiverton, Digby County, Nova Scotia	[1] Jan. 12	149

[1] 1924.

Series H: Bottles Nos. 1 to 85, placed in Nantucket and Vineyard Sounds in 1924, as follows:

1. On a line from Great Point, Nantucket Island, N. 10° W., running about one-half mile west of Handkerchief Shoal lightship to within about 1½ miles of the coast of Cape Cod. Bottles dropped approximately one-third mile apart. Bottle

No. 1 was dropped nearest Great Point at 11.17 a. m., August 4. Bottle No. 45 was dropped nearest the mainland at 12.45 p. m.

2. On a line from Succonesset Point to Cape Pogue. Bottle No. 46 was dropped nearest Succonesset Point at 10.17 a. m., August 5, while No. 67 was dropped nearest Cape Pogue at 10.59 a. m.

3. On a line from Pasque Island to Menemsha Bight. Bottle No. 68 was dropped nearest Pasque Island at 12.04 p. m., August 6, and bottle No. 85 was dropped nearest shore in Menemsha Bight at 12.38 p. m.

No.	Set adrift		Recovered	
	Date, 1924	Place	Date, 1924	Place
2	Aug. 4	From Great Point north 10° west ⅔ mile.	Oct. 4	Point Pleasant Beach, N. J.
3	...do	From Great Point north 10° west 1 mile	Sept. 29	1 mile east of Mecox station, Bridgehampton, Long Island, N. Y.
14	...do	From Great Point north 10° west 4⅔ miles.	Sept. 22	East Hampton, Long Island Beach.
19	...do	From Great Point north 10° west 6⅓ miles.	[1] Mar. 4	Eorabus, Bunessan, Mull, Argyle, Scotland.
27	...do	From Great Point north 10° west 9 miles.	Sept. 30	Lonelyville, Fire Island, N. Y.
28	...do	From Great Point north 10° west 9⅓ miles.	Oct. 7	About 72d Street, Holiday Beach, N. J.
31	...do	From Great Point north 10° west 10⅓ miles.	Sept. 29	Beach Haven, N. J.
37	...do	From Great Point north 10° west 12⅓ miles.	Aug. 22	In Bucks Creek, South Chatham, Mass.
38	...do	From Great Point north 10° west 12⅔ miles.	Aug. 20	Harwichport, Mass.
39	...do	From Great Point north 10° west 13 miles.	Aug. 7	1 mile west of Monomoy Coast Guard station (south of Chatham, Mass.).
41	...do	From Great Point north 10° west 13⅔ miles.	Aug. 11	Forest Beach, South Chatham, Mass.
42	...do	From Great Point north 10° west 14 miles.	Aug. 9	Hardings Beach light, Chatham Bay, Mass.
43	...do	From Great Point north 10° west 14⅓ miles.	Aug. 16	½ mile from Hardings Beach light, West Chatham, Mass.
44	...do	From Great Point north 10° west 14⅔ miles.	Aug. 9	Bucks Creek, South Chatham, Mass.
45	...do	From Great Point north 10° west 15 miles.	Aug. 10	South Chatham, Mass.
46	Aug. 5	From Succonesset Point south ⅓ mile	Aug. 26	4 miles southeast of Rose and Crown Buoy, Nantucket Shoals Mass.
47	...do	From Succonesset Point south ⅔ mile	Aug. 16	1 mile off Wiano Point, Cape Cod, Mass.
49	...do	From Succonesset Point south 1⅓ miles	Aug. 11	West side of Great Island Point, Hyannis Harbor, Mass.
50	...do	From Succonesset Point south 1⅔ miles	Aug. 10	Near Hyannis Lighthouse, South Hyannis, Mass.
51	...do	From Succonesset Point south 2 miles	Aug. 29	Mouth of Bass River, Cape Cod, Mass.
52	...do	From Succonesset Point south 2⅓ miles	Aug. 9	Between Marthas Vineyard and Succonesset Point, Mass.
53	...do	From Succonesset Point south 2⅔ miles	Aug. 18	West side of Hyannis Harbor, Mass.
55	...do	From Succonesset Point south 3⅓ miles	Aug. 10	West Beach, Hyannisport, Mass.
56	...do	From Succonesset Point south 3⅔ miles	Sept. 11	Bass River, Mass.
63	...do	From Succonesset Point south 6 miles	Aug. 31	Dennisport Beach, Cape Cod, Mass.
64	...do	From Succonesset Point south 6⅓ miles	Aug. 26	Foot of Morey Lane, Siasconset, Mass.
66	...do	From Succonesset Point south 7 miles	[2] Dec. 17	At entrance to Chatham Harbor, Mass.
67	...do	From Succonesset Point south 7⅓ miles	Nov. 10	1 mile west of the Green Hill Coast Guard station (R. I. ?).
68	Aug. 6	From Pasque Isle south ⅓ mile	Aug. 18	Northeast shore of Cuttyhunk Island, Mass.
69	...do	From Pasque Isle south ⅔ mile	Aug. 14	2 miles north of Woods Hole, Mass.
71	...do	From Pasque Isle south 1⅓ miles	Aug. 7	¼ mile northeast of Cedar Tree Neck, Vineyard Sound, Mass.
72	...do	From Pasque Isle south 1⅔ miles	Sept. 21	Extreme end of Tuckernuck Island, Mass.
74	...do	From Pasque Isle south 2⅓ miles	Sept. 22	Brant Beach, N. J.
76	...do	From Pasque Isle south 3 miles	Aug. 14	4 miles northwest of Vineyard Sound Lightship.
79	...do	From Pasque Isle south 4 miles	Aug. 27	Menemsha Bight, Vineyard Sound, Mass.
80	...do	From Pasque Isle south 4⅓ miles	Aug. 10	East Passage, Narragansett Bay, R. I.
81	...do	From Pasque Isle south 4⅔ miles	Sept. 29	1 mile north of Sea Isle City, N. J.
82	...do	From Pasque Isle south 5 miles	Sept. 30	Hereford Inlet, Anglesea, N. J.
83	...do	From Pasque Isle south 5⅓ miles	Aug. 11	Ribbon Reef, ½ mile west of buoy.

[1] 1926

[2] 1924.

SERIES I: Bottles Nos. 1 to 60, set adrift in Massachusetts and Cape Cod Bays, February 6 and 7, 1925, by the *Fish Hawk*, cruise No. 6. (For station record, see p. 1004.)

No.	Set out							Where found	Date, 1925	Interval
	Hour	Latitude			Longitude					
		°	′	″	°	′	″			Days
15	12.45 p. m.	42	12	00	70	23	30	Near radio station, Nantucket	June 14	128
22	2.50 p. m.	42	03	18	70	14	42	Fire Island Coast Guard station, N. Y.	July 4	87
25	3.40 p. m.	42	00	45	70	11	50	Beach, Provincetown, Mass	Feb. 11	5
26	do	42	00	45	70	11	50	Pilgrim Heights, Mass	Feb. 26	20
27	do	42	00	45	70	11	50	East end of breakwater, Provincetown, Mass	Feb. 12	6
28	4.10 p. m.	41	58	12	70	10	48	Pickett Wharf, Provincetown, Mass	Feb. 14	8
29	do	41	58	12	70	10	48	C. L. Birch's store, Provincetown, Mass	Feb. 11	5
30	do	41	58	12	70	10	48	Can factory wharf, Provincetown, Mass	do	5
32	4.40 p. m.	41	55	30	70	09	30	Beach at Provincetown, Mass	Feb. 12	6
33	do	41	55	30	70	09	30	Beach at North Truro, Mass	Feb. 11	5
34	5.35 p. m.	41	52	18	70	10	30	East Harbor, Provincetown, Mass	do	5
35	do	41	52	18	70	10	30	Eastern cold-storage wharf, Provincetown, Mass	do	5
36	do	41	52	18	70	10	30	Smiths Bathing Beach, Mass	Feb. 12	6
37	6.00 p. m.	41	49	30	70	11	15	Provincetown Harbor, Mass	Feb. 11	5
38	do	41	49	30	70	11	15	On beach, Provincetown Harbor, Mass	Feb. 14	8
39	do	41	49	30	79	11	15	Provincetown Harbor, Mass	Feb. 12	6
40	6.52 p. m.	41	52	27	70	15	24	North Truro Beach, Cape Cod Bay, Mass	Feb. 17	11
42	do	41	52	27	70	15	24	Bay shore, North Truro, Cape Cod, Mass	Feb. 22	16
43	7.15 p. m.	41	56	00	70	18	30	Beach Point, Provincetown Harbor, Mass	Feb. 23	17
44	do	41	56	00	70	18	30	Provincetown Harbor, Mass	Feb. 18	12
74	10.45 a. m.	42	07	18	70	36	36	29 miles from Eastern Point, Stellwagen Bank	Feb. 16	10
78	11.00 a. m.	42	09	30	70	38	15	Surfside, south shore, Nantucket	June 30	144
85	12.50 p. m.	42	16	06	70	42	30	Freeport, Digby County, Nova Scotia	July 2	146
89	1.10 p. m.	42	18	15	70	44	00	28 miles east-southeast from Thatchers Island		

SERIES J: Bottles Nos. 91 to 101, set out in Ipswich Bay and off Cape Ann by the *Fish Hawk*, April 7, 1925.

No.	Set out							Fish Hawk station	Where found	Date, 1925	Interval
	Hour	Latitude			Longitude						
		°	′	″	°	′	″				Days
95	3.20 a m.	42	49	30	70	40	00	23	¼ mile west of Race Point, Cape Cod	Apr. 21	14
96	do	42	49	30	70	40	00	23	¼ mile southeast of Race Point, Cape Cod	Apr. 24	17
97	4.30 a. m.	42	46	00	70	40	00	21	2 miles off Cutler, Me	July 21	105
99	6.10 a. m.	42	38	00	70	33	00	29	2 miles north of Brant Rock, Mass., Coast Guard station	Apr. 29	22

SERIES K: Bottles Nos. 102 to 141, set out in pairs by the *Fish Hawk* in Massachusetts Bay, May 20 to 22, 1925, cruise No. 13 (p. 1004).

No.	Set out							Fish Hawk station	Where found	Date, 1925	Interval
	Hour	Latitude			Longitude						
		°	′	″	°	′	″				Days
103	6.41 a. m.	42	18	15	70	44	00	17	Dennisport, Mass	June 6	17
106	9.10 a. m.	42	16	54	70	30	30	18A	3 miles northwest of Race Point Light, Cape Cod	May 26	6
108	11.15 a.m.	42	05	00	70	35	00	14	1¼ miles north of Pamet River Coast Guard station, Cape Cod.	May 30	10
109	do	42	05	00	70	35	00	14	Coast Guard station, Provincetown, Mass	May 25	5
112	3.10 p. m.	41	56	00	70	18	30	6A	Race Point, Mass., Coast Guard station	June 1	12
113	do	41	56	00	70	18	30	6A	South Beach, Edgartown, Mass	July 24	65
114	4.45 p. m.	41	49	30	70	11	15	7	6 miles east of Gurnet Light, Plymouth, Mass	May 29	9
115	do	41	49	30	70	11	15	7	South Truro, Mass	May 26	6
117	5.55 p. m.	41	55	30	70	11	15	6	5 miles west of Race Point, Cape Cod	May 31	11
118	5.50 a. m.	42	05	30	70	17	00	4	Nauset Beach, near Coast Guard station, Eastham, Mass.	July 12	52
120	7.00 a. m.	42	09	30	70	19	30	3	75 miles southeast by south from Cape Cod Light	June 12	22
126	12.55 p. m.	42	23	30	70	15	30	32	1¼ miles West of Race Point Coast Guard station, Cape Cod.	May 27	6
127	do	42	23	30	70	15	30	32	2 miles off Peaked Hill bar, Cape Cod	do	6
136	7.10 a. m.	42	30	15	70	43	15	36	Marblehead Neck, Mass	July 15	54
137	do	42	30	15	70	43	15	36	Pea Island, Nahant, Mass	June 1	10
139	8.25 a. m.	42	28	00	70	48	00	37	¼ mile east of Tinkers Island, Marblehead, Mass	May 31	9
140	9.20 a. m.	42	24	15	70	52	15	38	Lynn Beach, Mass	May 27	5
141	do	42	24	15	70	52	15	38	Long Island, Boston Harbor, Mass	May 28	6

Series L: Bottles Nos. 1901 to 1941, set out by H. C. Stetson on a line running 75° for 10 miles from Dry Salvages Beacon, off Cape Ann, 1 bottle every one-fourth mile, April 19, 1926. First bottle put out at 7 a. m.; last bottle at 9.11 a. m.

No.	Distance out from starting point	Where found	Date, 1926	Interval
	Miles			*Days*
1904	1	1 mile east of Madakket Coast Guard station, Nantucket Island	June 30	70
1907	1¾	Monomoy Point, Mass	June 7	49
1911	3	South shore of Marthas Vineyard, between Gay Head and Edgartown	July 4	74
1913	3¼	2 miles south of Chatham Light, Mass	May 30	30
1915	3¾	1 mile north of Pamet River Coast Guard station, Cape Cod	June 26	66
1916	4	1 mile north of Old Harbor Coast Guard station, Chatham, Mass	May 27	38
1917	4¼	Beach near Hummock Pond, Nantucket	June 2	44
1918	4½	South shore, Nantucket, near radio station	Sept. 8	142
1919	4¾	1½ miles west of Race Point Coast Guard station, Cape Cod	May 21	32
1922	5½	Lepreau Harbor, Charlotte County, New Brunswick	July 24	94
1923	5¾	Harts Island, Port Clyde, Me	July 15	85
1927	6¾	12 miles below Digby Gut, Nova Scotia, 1 mile offshore	Aug. 16	119
1937	9¼	10 miles west of Brier Island, Digby County, Nova Scotia	July 3	73
1941	10	¼ mile from Weymouth Light, Digby County, Nova Scotia	July 7	77

Series M: Bottles Nos. 1942 to 1970, set every one-half mile on a line from light buoy off Manomet Point, Mass., to Wood End, Provincetown, by Henry C. Stetson, April 21, 1926. First bottle put out at 11 a. m.; last bottle at 3.30 p. m.

No.	Distance set out from Manomet	Where found	Date, 1926	Interval
	Miles			*Days*
1945	1½	Wood End Coast Guard station, Provincetown	May 22	31
1946	2	Provincetown Bay, Provincetown, Mass	May 3	12
1949	3½	Wood End station, Provincetown, Mass	Apr. 28	7
1953	5½	Provincetown Bay, Mass	June 12	52
1956	7	3 miles north of Wood End station, Provincetown, Mass	Apr. 28	7
1960	9	⅛ mile south of Race Point Light, Cape Cod	June 9	49
1961	9½	Race Point Light, Provincetown, Mass	Apr. 23	2
1963	10½	Race Point Light station, Provincetown, Mass	May 10	19
1964	11	Near Race Point Light, Provincetown, Mass	May 2	11
1965	11½	2 miles north of Wood End Light, Provincetown, Mass	do	11
1967	12½	1 mile south of Race Point, Provincetown, Mass	May 12	21
1968	13	Wood End Run, Provincetown, Mass	May 15	24

Series N: Bottles Nos. 1971 to 1980, set out by Henry C. Stetson every one-half mile on a line running 244° for 5 miles from a point 1 mile west of the mouth of Pamet River, Truro, Mass., April 21, 1926. Outer bottle set out at 3.55 p. m.; innermost bottle at 4 p. m.

No.	Distance set out offshore	Where found	Date, 1926	Interval
	Miles			*Days*
1974	4	½ mile south of Wood End Coast Guard Station, Provincetown, Mass	Apr. 24	3
1975	3½	1 mile off Church Point Light, St. Marys Bay, Digby County, Nova Scotia	July 9	79
1978	2	Off Wood End Light, Provincetown Mass	Apr. 29	8
1980	1	Seeleys Cove, 5 miles west of Beaver Harbor Light, Charlotte County, New Brunswick	July 22	92

SERIES O: Bottles Nos. 1952 and 1981 to 2000, set out on July 18, 1926, by T. E. Graves, on a line running 107° from Cape Neddick, Me., for 9 miles, 1 bottle every one-half mile. First bottle (No. 1952) put out at 8.17 a. m.; last bottle (No. 2000) at 10.44 a. m.

No.	Distance set out from Cape Neddick	Where found	Date, 1926	Interval
	Miles			*Days*
1982	1½	Kenwood Bridge, Salem, Mass	Aug. 4	17
1985	3	10 miles southeast by south from Thatchers Island, Mass	Aug. 3	16
1987	4	do	do	16

GENERAL DISCUSSION OF THE RECOVERIES

With the Bay of Fundy experiments as a guide, it was natural to expect a considerable number of the bottles released in the Gulf of Maine on the several lines off Mount Desert, Cape Elizabeth, and Cape Ann, in 1922 and 1923, to be picked up in the Massachusetts Bay region. This, however, did not prove to be the case. Not a single bottle from any of these series has been found anywhere between Cape Ann and the southern elbow of Cape Cod, and only five of them south of Kennebunkport. It is therefore evident that the dominant surface drift was not the same in the summers of 1922 and 1923 as it was in 1919, but drifts of the 1919 type were recorded for series L and O, as described below.

The most striking aspect of the experiments carried out in all these summers is that more than 30 per cent of all the recoveries of bottles put out north of the southern angle of Cape Cod have been from the Bay of Fundy and Nova Scotia, which (if these were the only data available on the circulation of water in the gulf) would obviously suggest a drift from south and west to north and east. However, as we have just seen, the bottle drifts of 1919 and of 1926, on the contrary, point to an anticlockwise current skirting the shores of the gulf from northeast to southwest, and salinities (p. 910), temperatures (p. 918), and the distribution of the plankton (p. 923) all point in the same direction. It therefore becomes necessary to reduce these apparently contradictory lines of evidence to a rational order, which may best be done by analyzing the results for the years 1922 to 1926 regionally, not chronologically, to test whether they prove consistent, one with the other. The dominant sets of the surface water are shown rather clearly for the southwestern part of the gulf by the lines off Cape Ann, in Massachusetts Bay, off Cape Cod, and in Vineyard and Nantucket Sounds. These, therefore, may be considered first, leaving until later the study of the more puzzling drifts of the bottles set out in the northern side of the gulf.

SOUTHWESTERN SERIES

These bottles were set out off Cape Ann, in Massachusetts Bay, off Cape Cod, and to the southward of the latter.

The Cape Cod line of July, 1922 (line B), proved, in some ways, the most instructive of all, for out of these 600 bottles, 131, or 22 per cent, were picked up within

4 months. The line may be divided into three sections, according to the localities of recovery: First, an inner section, from Cape Cod across the mouth of Nantucket Sound and skirting the easterly edge of Nantucket Shoals; second, a middle section, from the shoals out nearly to the edge of the continent; and third, the outer end of the line to the seaward of the continental edge.

Ten bottles out of the 250 set out along the inner section were picked up to the eastward, three of them on the Nova Scotian shore of the Bay of Fundy, one on the northeastern part of Georges Bank, and five (after short drifts) in the south channel and along the northwestern side of Georges Bank (fig. 174).[66] This last group of recoveries is especially instructive as evidence that the surface water to the south and southeast of Cape Cod was setting in a southeasterly direction at the time. Bottle No. 362, picked up 40 miles to the southeast of the place of its release, after 5 days' drift, and Nos. 396 and 405, found 30 miles away after 8 days, can hardly have diverged from a direct line except to follow the spiral tracks induced by the veering tidal currents of this region, unless the dominant set was more rapid at the time than other experiences in the gulf would suggest.[67] A southeasterly set is also indicated in this general region by the current measurements carried out by the United States Coast and Geodetic Survey (p. 864).

The uniformity of these southeasterly drifts makes it likely that the bottles that went from the inner end of line B to the eastern end of Georges Bank and to Nova Scotia also drifted in a southeasterly direction at first, veering to the eastward—i. e., anticlockwise.

It seems that this inner section of line B followed the boundary of demarkation between this southeasterly set and another drift directed more to the southward from the mouth of Nantucket Sound, veering westward past Nantucket Shoals, because 20 bottles from this section were picked up along the southern coast of New England. The fact that current measurements show a general southeasterly set over Nantucket Shoals and a summer set to the west and northwest at the lightship a few miles farther south, makes it more likely that these bottles rounded the shoals than that they crossed the latter.

It is a question of considerable interest whether 11 bottles, spaced across the eastern entrance to Nantucket Sound, which were picked up along the south shores of Nantucket, Marthas Vineyard, and of New England between Buzzards Bay and and Block Island, drifted directly westward through Nantucket and Vineyard Sounds or whether they also traveled southward around Nantucket Island and Shoals. Of course, a positive answer can not be given; but it seems hardly conceivable that some of them would not have been picked up afloat in the sounds or stranded along shore there if they had gone through, because these beaches are thronged with vacationists. Actually, however, not one of the bottles from line B was found along the northern coast of the sounds, and only one of them on the northern shore of Nantucket, 159 days after it was set afloat. One, however, after 30 days afloat, was found 1 mile inside Gay Head at the western end of Marthas Vineyard, where many species of tropical fishes have been recorded in summer. Thus, it seems almost certain that

---

[66] One bottle from this section went to France.

[67] Bottle No. 510 was reported on the northwest slope of Georges Bank, 50 miles from where it was set out, within 3 days. This ostensible drift is so rapid, however, that some error in the reported locality seems probable.

this group of bottles went out around Nantucket.[68] Bottle No. 536 journeyed to the south shore of Marthas Vineyard (85 miles) at a rate of at least 4 miles per day.

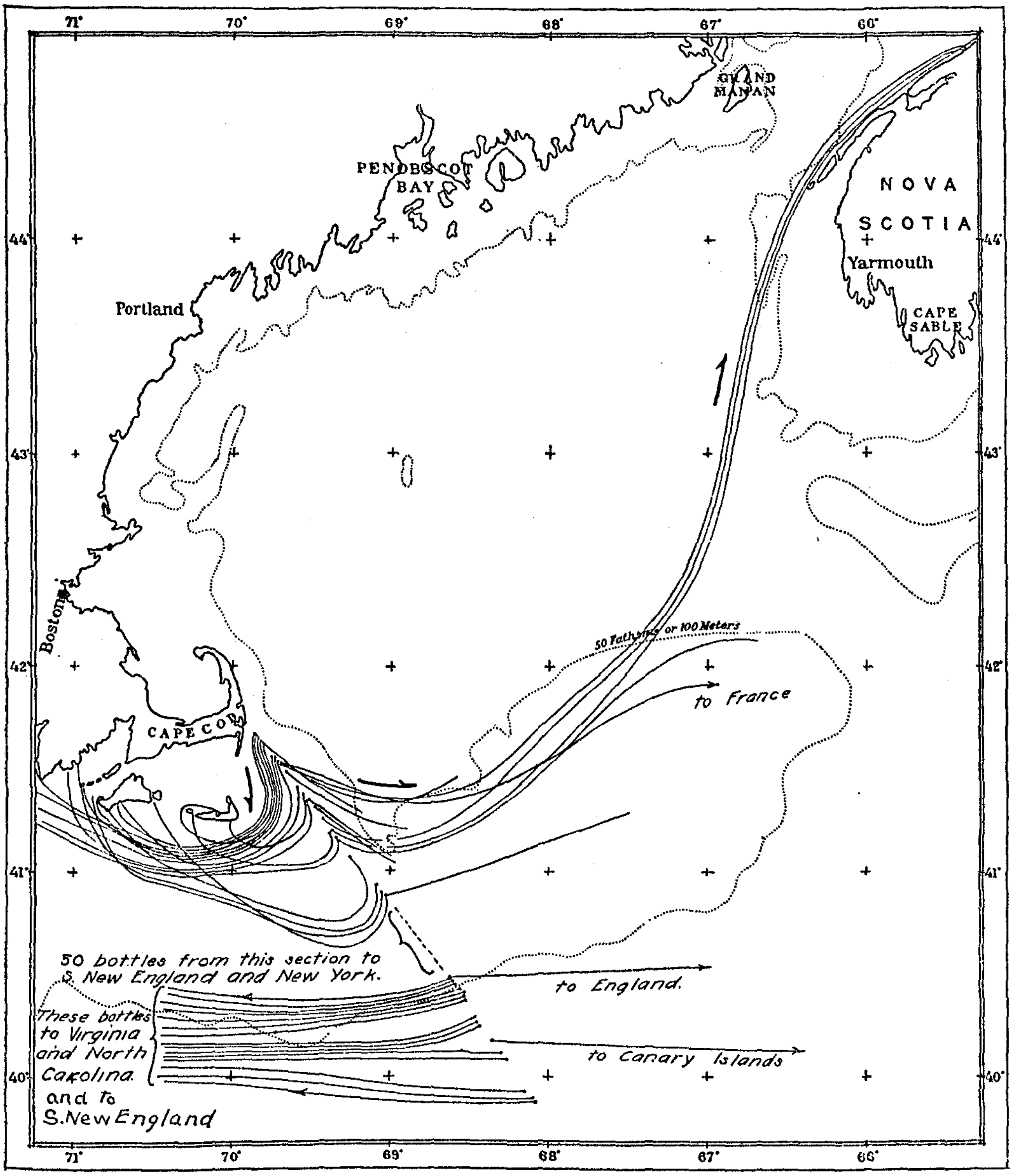

FIG. 174.—Assumed drifts of representative bottles recovered from line B, set out off Cape Cod, July 6 to 8, 1922. ●, place of release.

The mid-section of line B (lat. 40° 50′ to lat. 41° 30′) was clearly involved in this same set, veering clockwise around Nantucket Shoals, because 50 of these bottles out of a total of 103 were picked up along the shores of southern New England, from

---

[68] The assumed routes for this group of bottles are laid down on the chart without reference to Nantucket Shoals. Actually however, the complex tidal currents among these banks and through the channels between them must give a very circuitous route to any flotsam in that region.

Nantucket westward, and along the eastern half of Long Island, New York, the great majority on the south shore of Marthas Vineyard, at the mouth of Buzzards Bay, and near Block Island.

This percentage of recoveries is larger than for any considerable section of any one of the other lines along which drift bottles have been put out in the Gulf of Maine, so large, in fact, that representatives only can be shown on the chart (fig. 174). With the recoveries condensed in so short a section of the coast line, it is obvious that these bottles came within the grip of a very definite current setting northward and inshore, probably around the shoals.

The alteration along line B, from westerly drifts at the inshore end to easterly and westerly both from the next section of 40 miles, and then to westerly again from the mid-section, is clear evidence that the line followed the boundary between the Gulf of Maine eddy and the clockwise drift around the shoals to the west just stated, locating the southern boundary of the former at about latitude 40° 50′.

This westerly drift certainly involved the water right out to the edge of the continent, because 22 bottles from the outer section of line B (including the outermost of all, set adrift 40 miles out from the 200-meter contour) were picked up between Nantucket Island and Fire Island Beach on Long Island, N. Y. Seventeen of these outer bottles (10 from just inside and 7 from just outside the continental edge) were found on the North Carolina beach, a few miles north of Cape Hatteras,[69] after time intervals averaging 85 days (73 to 112 days). The mean distance traveled by this last group of bottles (if they followed a straight line) is about 410 miles—slightly longer by their probable route—giving a minimum rate of nearly 5 miles per day. It is probable, also, that the time intervals between the dates of setting out and recovery correspond very closely to the periods when actually afloat, because the sector of beach on which they stranded is continuously and closely patrolled by the Coast Guard stations.

Some further light is thrown on the tracks that the bottles of this last group followed on their journey, by recoveries set adrift a few days later along a line (C) running southeasterly from New York, 111 of which were picked up between Delaware Bay and Cape Hatteras. Most of those that reached the North Carolina coast from the outer part of this line were spaced from a point about 45 miles from the New Jersey coast out to a point some 40 miles beyond the edge of the continent, as marked by the 100-fathom contour. It is therefore fair to assume that the bottles from the Cape Cod line that drifted farthest south likewise passed Delaware Bay within a few miles (one way or the other) of the continental edge, where they would have intersected the New York line.

The fact that so many of the other bottles from the same outer section of the Cape Cod line drifted inshore, to strand along southern New England, makes it likely that this whole group of bottles set northwestward, in over the outer part of the continental edge at first, and then separated, some veering to the westward and southwestward along the outer part of the shelf, others turning northward toward the coast. There must also have been a rather direct drift of surface water in that direction from the offing of Nantucket Shoals, and so in toward the land, at the time, for if the bottles that traveled that route had gone far west before turning

---

[69] Scattered from False Cape to a point 9 miles north of Hatteras Light.

north the New York line would have been involved in this same drift and so have stranded along the coast of Long Island to the east of Fire Island lighthouse, where only three of them actually were found.

The combined evidence of these Cape Cod and New York lines thus points to a dominant movement of the surface water along the edge of the continent, westward and southward from the offing of Nantucket to Cape Hatteras, but complicated by a clockwise eddy movement in toward the land west of Nantucket Shoals, just where flotsam from the so-called "Gulf Stream" (gulf weed and various tropical animals) most often drifts in to the coast. No such tendency for the surface water to set inshore from the outer part of the continental shelf is reflected in the drifts to the west of this, however, not a single bottle from the Cape Cod line having been found between New York and Chesapeake Bay, though bottles from the New York line were picked up all along this 250-mile sector.

No further discussion of the bottles set out off New York is called for here, as they do not immediately touch the Gulf of Maine, except to emphasize that neither they nor the Cape Cod line afford any evidence whatever of surface water entering the gulf around Nantucket from the southwest. It has long been known that the southern angle of Cape Cod marks a rather abrupt faunal division between the waters of Nantucket and Vineyard Sounds, on the one hand, and the more boreal Gulf of Maine, on the other. It is obvious that a division of this sort, with no change of latitude, is associated with the nontidal circulation of the water.

It was to check the evidence of the drifts from line B and measurements with current meters (p. 864) pointing to a set of water outward from the eastern end of Nantucket Sound, and so toward the southeast, that lines H (p. 875) were set out along three sections of the sounds during August, 1924.

Thirty-seven of these 85 bottles have been recovered within the sounds, along the outer shores of Nantucket, and still farther west, but not one of them within the limits of the Gulf of Maine.

The drifts from the western end of Marthas Vineyard (Pasque Island to Menemsha Bight) may be passed over briefly. Eleven of these were picked up—1 on Cuttyhunk Island, 2 in Vineyard Sound, 1 on Tuckernuck Island, 1 within Buzzards Bay, 2 at the mouth of the latter, 1 in Narragansett Bay, and 3 on the Rhode Island shore (fig. 175). It is not easy to reconstruct the probable paths of all of these.

The series was set adrift on the first of the ebb, which sets westward here through Vineyard Sound and northward from the latter through the "holes" between the Elizabeth Islands into Buzzards Bay. It is probable that the bottles found in Buzzards Bay and on Cuttyhunk went north through Quick's Hole, because they were put out close to Pasque Island at about high water and would soon have been carried in that direction by the ebb. If this line had been put out on the flood instead of at the beginning of the ebb it would probably have been carried far enough up the sound before the tide changed to come within the easterly set that appears to dominate Nantucket Sound. Actually, however, most of these bottles must have drifted westward for the first 5 or 6 hours, carrying them about to the mouth of Vineyard Sound, where a division evidently took place. Two bottles from the northern end seem to have been carried back into the sound by the next flood, one of them to be picked up two days later on the Marthas Vineyard shore, 6 miles to the east of where it was put out, the other on Tuckernuck Island, between Nantucket and Marthas Vineyard, after 46 days.

The others, from the southern end of this line, seem to have been carried far enough out of the sound on the first ebb to escape the next flood back again. The two that were picked up at the mouth of Buzzards Bay must have drifted on a comparatively direct route, for one was picked up after five and the other after six days. Evidently they came within the sweep of the Buzzards Bay tides. The bottles that went to New York and New Jersey must have escaped this. The one that was picked up at the entrance to Narragansett Bay only five days after it was put out evidently followed a route directly westward, making it a fair assumption that the three others set afloat close by, which went to New Jersey, also traveled via the same route, paralleling the coast.

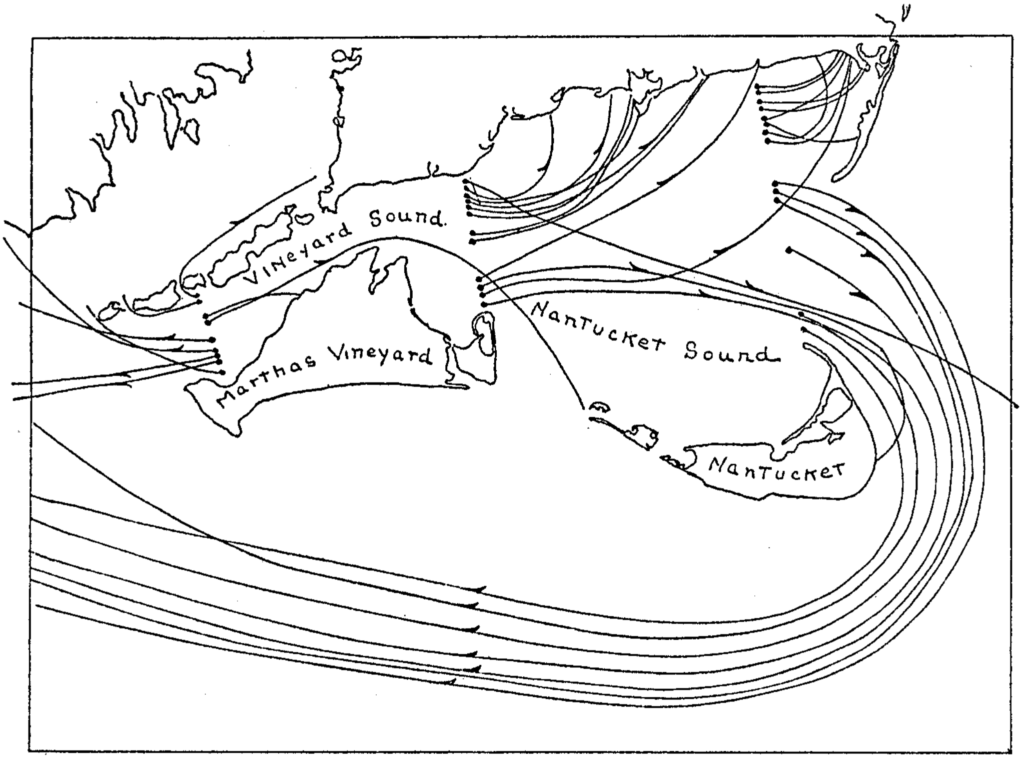

FIG. 175.—Assumed drifts of representative bottles recovered from lines H, set out in August, 1924. ●, place of release

It would be an instructive experiment to put bottles out on this same line early on the flood tide, so that they would journey eastward, up the sound at first, not out of it, so to determine what net movement results from tides whose velocity (1.7 to 2.5 knots at strength) is so great that "a certain part of the water, at least, travels a distance of one-half or more of the length of Vineyard Sound during a single phase of the tide." (Sumner, Osburn, and Cole, 1913, p. 36.) The earlier current tables published by the United States Coast and Geodetic Survey (Coast Pilot, 1912, Appendix I) indicate a net westerly drift of the water along the axis of Vineyard Sound at a rate of about 2 miles per 24 hours, the easterly movement averaging about 3½ miles during the flood, the westerly ebb about 4½ miles. More recent information, however, does not substantiate this, ebb and flood being given as approximately equal along the axis of the Sounds in the current tables for 1924 (United States Coast and Geodetic Survey, 1923); and the fact that considerable quantities of gulf weed so often drift into Vineyard Sound and through into Nantucket Sound in the summer season points rather to a net movement inward into the former from the westward.

The returns from the line next to the east (Succonnesset Point to Cape Pogue; fig. 175) are consistent with a dominant set from west to east along the southern side of Nantucket Sound, because all but one of the recoveries were to the eastward of where the bottles were set out—9 of them from points along its northern shores as far as Chatham; 1 close to Rose and Crown Buoy outside the sound, about 11 miles east of Nantucket Island; 1 from the southeast shore of Nantucket; and 1 from the coast of Rhode Island. Bottles from all parts of the line stranded along the north shore, and the drifts that went out of the sound were from both ends of the line (the bottle picked up near Rose and Crown Shoal was thrown out closest to Succonnesset). This suggests that all traveled eastward at first, as would naturally happen, as they were put out one to two hours after low water; but this first flood, running at an average rate of about 1 knot, can only have carried these bottles 4 or 5 miles east.

It is possible, of course, that the bottles that went from this line to the eastern side of Nantucket and to Rose and Crown Shoal passed out of the sound via the Tuckernuck Channel; but the more direct route eastward is the more probable when these drifts are studied in connection with the line put out across the eastern end of the sound.

Fourteen bottles from this line were recovered, 6 of which (set out abreast the channel between Nantucket and Monomoy) made long journeys to Long Island, New York, and New Jersey, while 8 bottles set out behind Monomoy Island were picked up along the coast near by, between Harwichport and Monomoy. This division, and the fact that the only bottles from this line that were recovered within the sound were those just mentioned, makes it fairly certain that the bottles that made the long journeys did not go westward through the sound, but drifted eastward out of the latter at first and then veered clockwise to the southward and so around Nantucket by the same general route followed by bottles set out off the mouth of the sound in 1922 (line B, p. 880), and so continued westward, paralleling the coast, to the points where they were finally picked up.

This division between the drifts followed by the bottles from the southern and northern parts of the line clearly reflect a tidal difference. All were put out two to three hours before high water; but while the first group was carried eastward by the flood and out of the sound, the second group was caught up in the current flooding northward into Chatham Roads. The fact that so many then stranded there, instead of coming out again with the ebb, and that so many bottles from the line next to the west were found along the northern shore of the sound, shows that the bight inclosed between Monomoy Point (with its submarine extension in Handkerchief Shoal) and the south shore of Cape Cod is the site of a subsidiary anticlockwise eddy, as might be expected from the trend of the coast and from the contour of the bottom.

The combined evidence afforded by the drifts from the two lines last discussed points unmistakably to an easterly set as dominating the southern side of Nantucket Sound, with a net movement of the surface water out through the channel between Great Point and Monomoy. The time intervals for the bottles picked up at Rose and Crown Shoal and on the east shore of Nantucket (21 days in each case) show a daily rate of at least 1½ to 2 miles in this direction at the time.

With none of the bottles from Nantucket Sound reported within the Gulf of Maine, but abundant evidence of drifts veering to the south and west around Nantucket Island and Shoals, it is established with reasonable certainty that the outflow from Nantucket Sound usually shares in the clockwise eddy movement away from the gulf, which involved the water to the southeast of Cape Cod in 1922 (p. 880) and which is indicated by the measurements made of the currents along the eastern side of Nantucket Shoals (p. 864).

The fact that three bottles set out in Nantucket Sound in 1924 were picked up in New Jersey, whereas none of the bottles set out abreast the mouth of the sound in 1923 were reported so far west, suggests that those that passed eastward out of the sound in 1924 then drifted far enough southward to become involved in the drift followed by the bottles put out on the middle section of the Cape Cod line in the year before. An interesting annual difference thus appears in this respect.

If this general type of circulation prevails as constantly from year to year and throughout the summer season, as the bottle drifts suggest, it goes far to explain the fact that tropical fishes, planktonic animals, and floating plants (notably gulf weed), which are so commonly swept from the "Gulf Stream" into Vineyard Sound, only exceptionally enter the gulf around Cape Cod. Passing out of Nantucket Sound to the eastward by the same route followed by the drift bottles, their course would then veer to the southward and so away from the gulf, not into the latter.

An earlier paragraph, the reader will recall, points out that several bottles from the inner (northern) end of line B, set out of Cape Cod in July, 1922, were carried eastward into the Gulf of Maine, though the majority were swept away from the gulf, locating the division between these two circulating movements (p. 882).

Series G was set out normal to the coast, about midway of Cape Cod, in August, 1923 (p. 875), in the hope of throwing more light on the southern side of the eddying circulation that dominates the surface waters of the Gulf of Maine. Only 5 out of the 100 have been recovered, this being the lowest percentage of recoveries for any of the lines. Two of them, put out, respectively, 4 and 6 miles from the land, were picked up at Nauset near by, one within 2 days after it was set adrift. One bottle, set afloat about 20 miles out at sea, was found 2 months later (October 14) floating on the eastern edge of Georges Bank (fig. 176); one launched 5 miles farther out was reported 5 months later from Tiverton, Digby County, on the Nova Scotian shore of the Bay of Fundy, near its mouth; and a fifth, also from the outer end of the line, picked up in Ireland in September a year later, completes the brief list (p. 875).

Evidently the outer bottles on this line (but not the inner) took part in a drift of the same sort as carried several bottles, set out southeast of Cape Cod in 1922, across to the eastern part of Georges Bank, to the Bay of Fundy, and to France (fig. 174), so that a set in this direction is to be expected in the southern side of the gulf in summer.

The measurements taken of the currents in the region of Georges Bank (p. 865; fig. 173) suggest that this group of bottles held to the northward of the shoal part of Georges Bank (Georges and the Cultivator Shoals) in their journey, and that a separation of the tracks evidently occurred to the eastward of the latter, some of the bottles then veering southward across the eastern side of Georges Bank, where one was recovered from each year's series (1922 and 1923) 96 and 59 days, respectively, after release.

The two bottles (one from each year's series) that went from close to Cape Cod to Europe (one to France, the other to Ireland, after a year's journey) probably followed much this same route, continuing on out to sea until they came within the influence of the general North Atlantic drift. Bottle No. 543, which was set out in the South Channel on July 7, 1922, and picked up just south of Georges Shoal 35 days later, was probably caught up in the tidal circulation over that shoal ground.

These Georges Bank drifts are good evidence that the bottles that went to the Bay of Fundy from the two Cape Cod lines (B and G; figs. 174 and 176) likewise skirted the northern side of the banks, continuing eastward until they became involved in the current setting northward into the eastern side of the gulf, which has been developed by Mavor (1922) from Dawson's measurements of currents (p. 861; fig. 173). The Bay of Fundy would then be their most likely destination; and the fact that they stranded on its Nova Scotian shore, just as did several of the bottles that Mavor set out at the mouth of the bay in 1919 (p. 868; Mavor, 1922), makes it likely that they, too, drifted in close along its southern side.

The three bottles that drifted from the offing of Cape Cod (line B) to the Bay of Fundy in 1922 were picked up after intervals, respectively, of 82, 102, and 105 days—an average of 97 days. Their probable route (figs. 174 and 176) being about 300 miles, a daily journey of slightly more than 3 miles is indicated. An interval of 59 days for bottle No. 1881, set out off Cape Cod on August 7, 1923, and picked up on the eastern edge of Georges Bank, points to about this same rate as probable; but bottle No. 435, from the Cape Cod series of the year previous, was not picked up on the eastern part of Georges Bank until 96 days after it was set out, though its journey along the general route it may be assumed to have followed was no longer. Another bottle from the same section of this same Cape Cod line was found on the western slope of Georges Bank, only about 50 miles distant from where it was set adrift, after it had been afloat for 88 days. It would be interesting to know whether it had circled to and fro over the banks during that long period. The only bottle from the Cape Cod line of 1923 (line G) that was reported from the Bay of Fundy was either longer afloat or lay longer on the shore before it was noticed, the interval between its release and recovery being 149 days, or less than 2 miles per day.

RECOVERIES FROM THE CAPE ANN AND MASSACHUSETTS BAY LINES

Only 7 of the 100 bottles set out off Cape Ann in August, 1923 (line F; p. 875), have ever been heard from. Five of these were found scattered along the Nova Scotian coast of the gulf and of the Bay of Fundy from Cockerwit Passage, in Pubnico Bay (near Cape Sable), to Digby Gut, and two went to Europe (fig. 176). Time intervals of 65 days (between release and recovery) to Pubnico, 60 days to Yarmouth, 64 days to Port Maitland, and 85 days to Digby Gut suggest a somewhat more direct route to Nova Scotia than was followed by the Cape Cod series of the year previous, because it is not likely that they traveled more than 3 or 4 miles per day until they approached Nova Scotia, where their daily rate may have increased to 5 to 6 miles (p. 867; fig. 173). The probable tracks laid down on the chart (fig. 176) are based on an assumed rate of about 3 miles per day, corresponding to the bottles that drifted from the Cape Cod line (line B) to the Bay of Fundy in 1922 (p. 887).

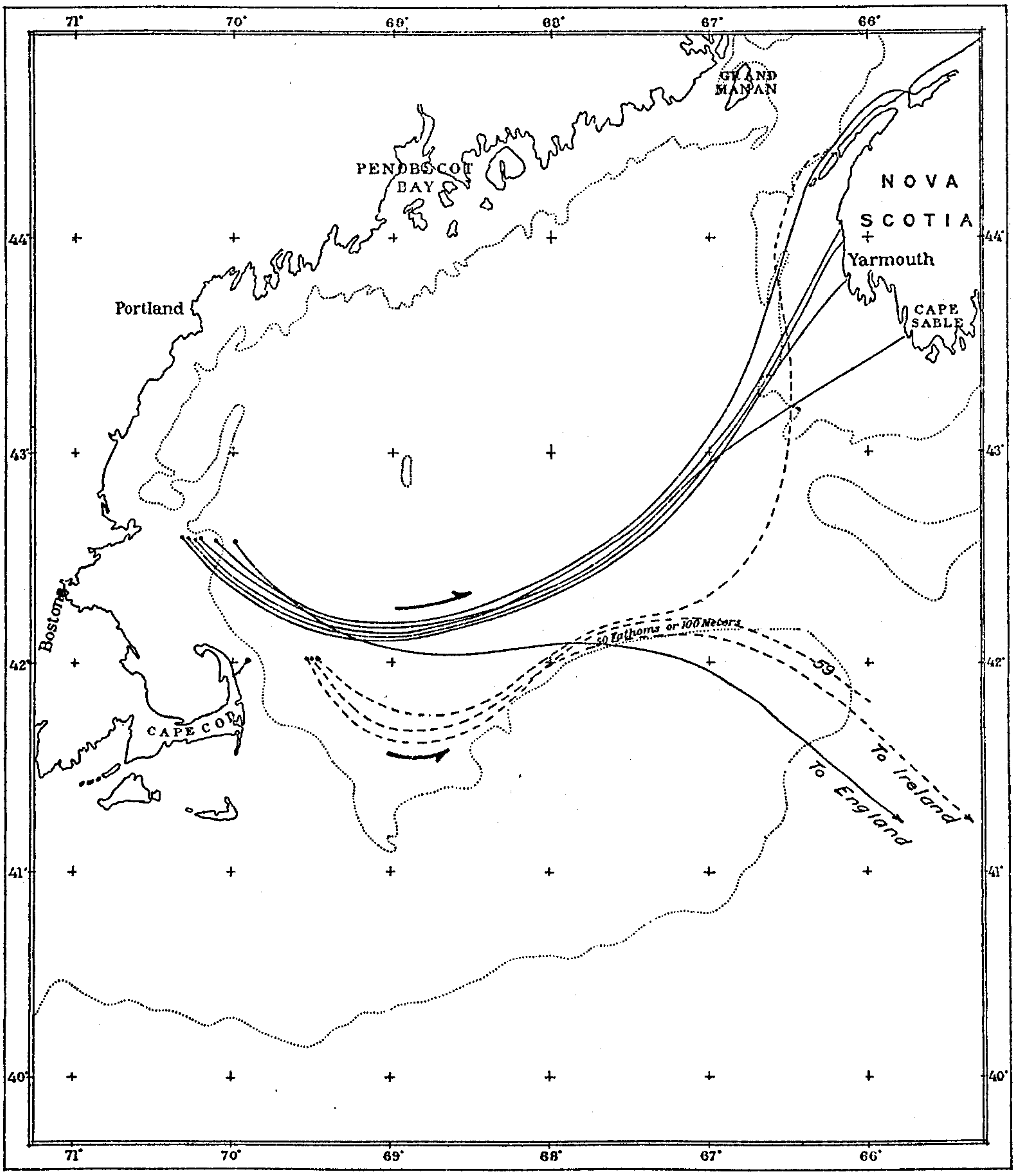

FIG. 176.—Assumed drifts of bottles recovered from lines F (solid curves) and G (dotted curves), set out off Cape Ann and Cape Cod, August 9 and 16, 1923. ●, place of release

If these drifts from the offing of Cape Ann to Nova Scotia stood alone, it would be impossible to tell whether their tracks diverged to the left of the direct line along the coast or to the right across the southern side of the basin. Comparison, however, with the bottles that went to the same general destination and eastward along Georges Bank from the Cape Cod lines (figs. 174 and 176) makes the second alternative much the more likely; and when we add the fact that not a single bottle from any of these three lines has ever been found along the coast between Cape Cod and the Bay of Fundy, contrasting with the number of recoveries scattered around the southern and eastern peripheries of the gulf from Georges Bank to the Bay of Fundy, the anticlockwise movement from the offing of Massachusetts Bay around the southern side of the basin and along its offshore rim, as indicated on the charts, seems fully demonstrated for the summers of 1922 and 1923.

The small number of recoveries from the Cape Ann line shows that only those that kept farthest north on this eastward journey came within the influence of the veering drift toward Nova Scotia. This is still more certainly true of the bottles set out off Cape Cod in 1923 (line G). To all intents and purposes these were entirely south of this set, for only odd ones among them were caught up by it. Such of the bottles as dispersed farther to the south from both these lines no doubt drifted to the Georges Bank region, and so, probably, out into the open Atlantic, either circling around the eastern end of the bank or crossing it, probably by the same tracks as were followed by the bottles that went to Europe. The fact that all the recoveries from outside the Gulf of Maine, for the Cape Cod and Cape Ann lines of 1923, were from the other side of the Atlantic, contrasting with the large number of bottles that went west from the line south of Cape Cod in 1922, is sufficient evidence that the eddy movement that carried the latter involved only the western part of Georges Bank at the time. In short, bottles from these lines, which drifted out of the Gulf of Maine in 1923, did so in a southeasterly direction across the eastern end of Georges Bank, traveling to the northward and eastward of its shoal ground.

Of course, it is possible that bottles found along western Nova Scotia after long intervals—say 100 or more days—may have followed this same route at first but then have been caught by an indraft through the Eastern Channel (p. 866). However, we have no positive evidence of this, and the chance that any bottle would be involved in the set toward Nova Scotia after it had once drifted south of latitude 42° is evidently very slight.

It is interesting to find that the bottles that drifted from west to east across the southern side of the gulf from the Cape Cod and Cape Ann lines tended to go far up the Bay of Fundy in 1922, but stranded near its mouth and along the Nova Scotian coast to the southward in 1923. Apparently the northerly set, which dominates the eastern side of the gulf, hugged that coast more closely in the one year than in the other, perhaps reflecting the prevalent winds at the time; but a difference of this sort is trivial, contrasted with the uniformity of these drifts and of those to the eastern part of Georges Bank, just discussed.

In 1919, the reader will recall, bottles from the Bay of Fundy stranded in Cape Cod Bay, marking a set into the latter; but in 1923 the Cape Ann line, by contrast, showed a drift past the mouth of Massachusetts Bay, not into the latter, proving a periodic variation, with the dominant movement following around the coast line of the bay in some summers and passing it as a sort of back water at other times. It was in the hope of throwing further light on this secular alternation, especially in its bearing on the involuntary migrations of fish eggs and larvæ, that series I and K were set out in the bay in February and May, 1925, and series L, M, and N in April, 1926 (p. 877).

Twenty-three (26 per cent) of the February series of 90 bottles have been recovered. Recoveries from bottles set out off the Plymouth shore were distributed as follows: One (No. 74) from Stellwagen Bank, 28 miles off Gloucester; one from an equal distance out in the basin of the gulf (fig. 177); two from Nantucket; one from the Nova Scotian shore of the Bay of Fundy;[70] and one, put out close to the tip of Cape Cod (No. 22), went to Fire Island, New York.

These drifts, combined, show a definite surface set out of the southern side of the bay, dividing off Cape Cod, where some bottles took the southern route down past Nantucket, and so westward (which so many bottles from the Cape Cod line (line B) followed in July, 1922), while one, at least, was caught up in the southern side of the Gulf of Maine eddy, reproducing the drifts of bottles from the Cape Ann line of 1923 (p. 887).

The bottles set out in the eastern side of Cape Cod Bay followed a surprisingly definite set eastward and toward Provincetown, no less than 16 out of 21 stranding in that harbor or near by (all of them to the east and most of them well to the north of where they were set adrift) after intervals of 5 to 17 days (usually 5 or 6). Drifts of this sort suggest an anticlockwise movement of the surface water around Cape Cod Bay, with a subsidiary eddy of the same sort in Provincetown Harbor, which finally caught them up as they set northward along the inner shore of the cape.

Ten bottles set out in Ipswich Bay on April 7 (series J) give definite evidence of a southerly set around Cape Ann and into Massachusetts Bay, one of them having been found at Brant Rock, a few miles north of Plymouth, and two near Race Point, at the tip of Cape Cod, after intervals of 14 to 22 days. A fourth, picked up at Cutler, Me., at the western entrance to the Grand Manan Channel after 106 days, apparently had followed the southern side of the Gulf of Maine eddy, veering southeast, east, and northeast, and so paralleling the drift of bottles set out off Cape Ann in 1923 (line F; p. 887) and at about the same daily rate. A rather definite anticlockwise drift around the Massachusetts Bay region is thus indicated for winter and early spring by the combined drifts of the February and April series, its southern edge involving Cape Cod Bay but with the water farther north setting more to the eastward and so out past Cape Cod.

This same type of circulation is still more clearly reflected by the drifts of 40 bottles put out in Massachusetts Bay on the 20th to the 22d of that May (series K), drifts so easily interpreted as to demand rather detailed study. Eighteen of these were recovered—the largest percentage (45) for any series yet set out in the Gulf of Maine.

Following around the bay from north to south we find one or two bottles set out off Manchester[71] drifting to Marblehead and Nahant, while one bottle set

---

[70] Freeport, Digby County.

[71] About 3 miles west of Gloucester.

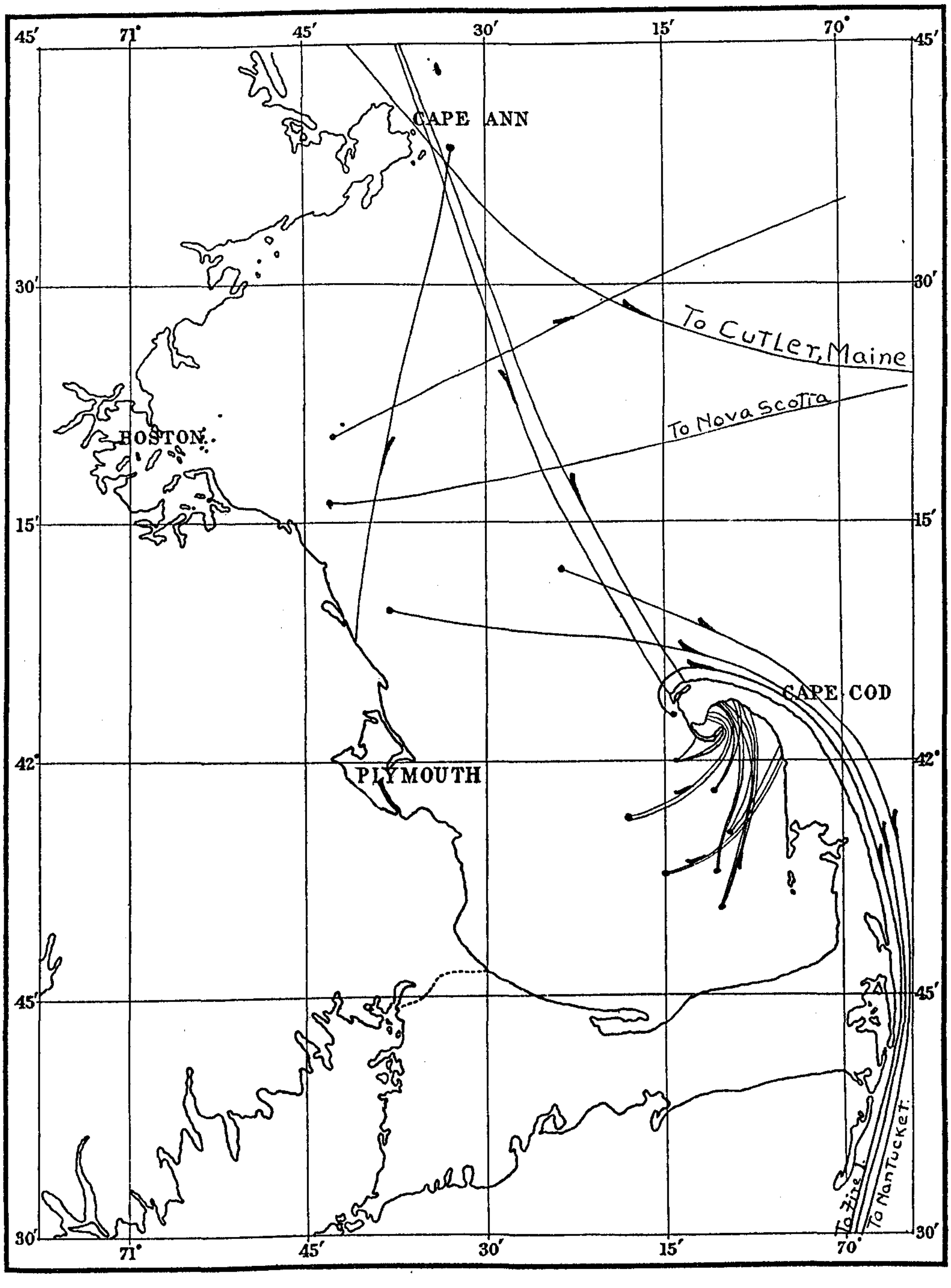

FIG. 177.—Assumed drifts of bottles recovered from Series I, set out in Massachusetts Bay, February 6 and 7, and in Ipswich Bay, April 7, 1925 (Series J). ●, place of release

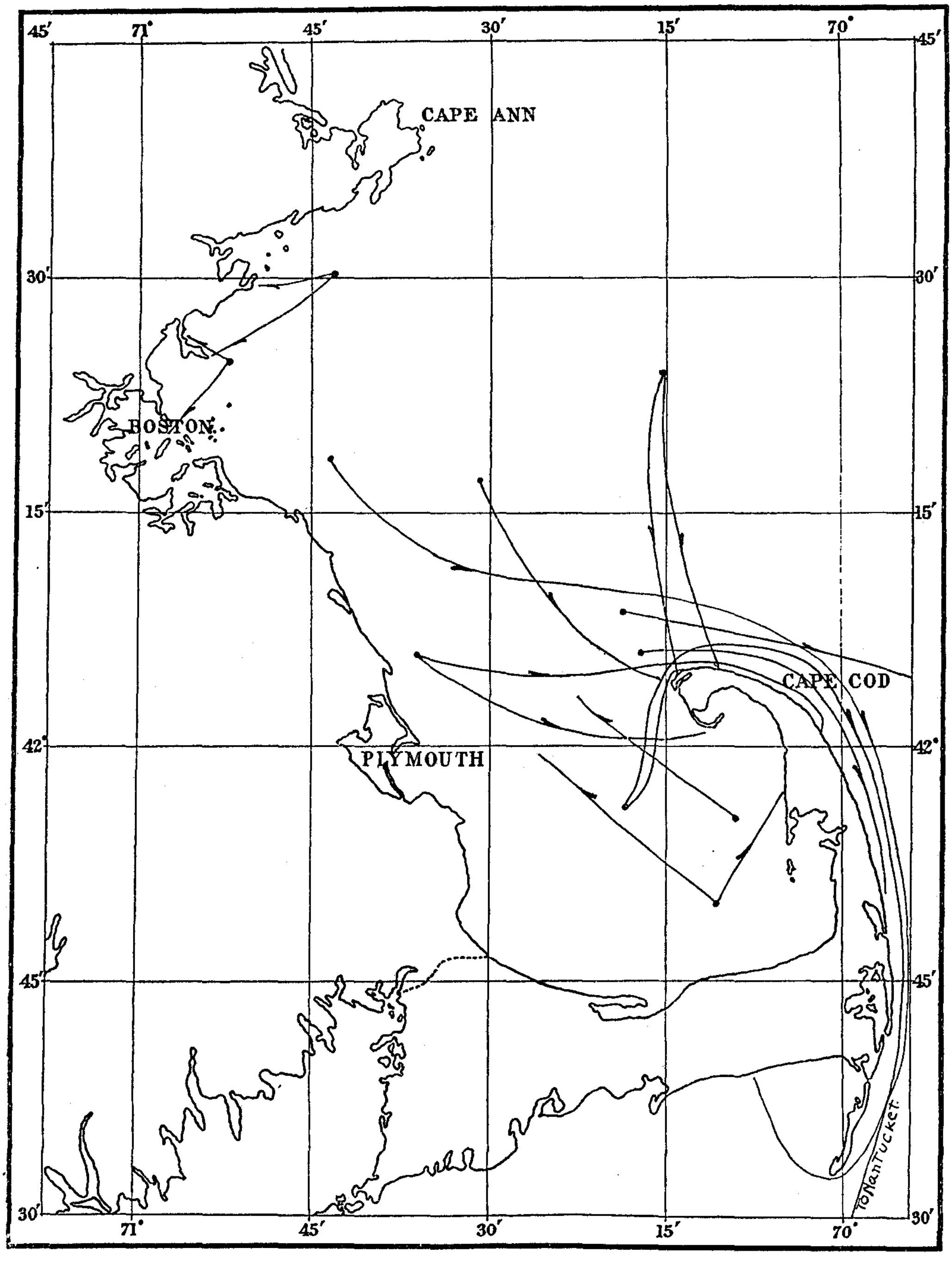

FIG. 178.—Assumed drifts of representative bottles recovered from series K, set out in Massachusetts Bay, May 20 to 22, 1925. ●, place of release

out near Nahant drifted west into Boston Harbor,[72] reflecting a definite set inward along the northern shore of the bay. On the other hand, bottles that were set out in the central part of the bay and at its mouth showed a tendency to drift southeastward, either to leave the bay or to be caught up at the tip of Cape Cod. Thus, one launched near Boston lightship reached Dennisport, on the south shore of Cape Cod (fig. 178); one set afloat on the southern side of Stellwagen Bank was picked up 75 miles east of Cape Cod Light 22 days later; while a third drifted from the offing of Race Point, at the tip of the cape, to Nauset Beach, some 16 or 17 miles down its outer shore. One of a pair set out in the western side of the bay a few miles north of Plymouth also rounded Cape Cod, but the other, also drifting eastward, stranded at Wood End, near Provincetown, while one from the center of the bay and two from its mouth, midway between the capes, were picked up on the beach at the tip of Cape Cod or floating near by.

The anticlockwise set, so clearly indicated by the drifts so far discussed from this series, was also shared by bottles set out in the eastern side of Cape Cod Bay; for all recoveries from this group were to the northward of where the bottles were set out. Two of them went out around the cape, one stranding at its tip but the other continuing southward past Cape Cod to Nantucket. One bottle set out off Wellfleet and another off Billingsgate Island would probably have followed a similar route if they had not been intercepted; for they went northwestward and were picked up midway between Plymouth and Provincetown after 9 and 11 days afloat. The companion bottle from the Billingsgate station (*Fish Hawk* station 7), however, was evidently caught in a different tidal current, for it went northeast to the Truro shore (fig. 178).

These Massachusetts Bay studies were continued by series L to N, set out in April, 1926, by Henry C. Stetson (p. 878). Twelve of the 41 bottles put out off Cape Ann (series L, fig. 179) have been recovered. One of these was from Race Point, at the tip of Cape Cod, in 32 days; four were from the outer shore of Cape Cod, south to Monomoy, in 30 to 66 days; two were from the south shore of Nantucket Island, near the western end, after 44 and 70 days. This general tendency southward across the mouth of Massachusetts Bay and so down past Cape Cod recalls the drifts of bottles from Ipswich Bay and out of Massachusetts Bay the spring before. The parallel between the two years is made complete by three returns from Nova Scotia at the mouth of the Bay of Fundy from the series of 1926 and one from the New Brunswick shore of the bay.

One of these Cape Ann bottles went to Point Clyde, at the western entrance to Penobscot Bay. Without the southern drifts just listed, for comparison, the tracks followed by these bottles to the Bay of Fundy would be conjectural. The former, however, make it as clear as evidence of this sort ever can that the general route was southward at first, with a division off Cape Cod, whence some continued southward but others were carried in an eddying course eastward and northward around the basin of the gulf. The Port Clyde recovery alone is puzzling, but the time interval (85 days) is sufficient to allow of a circuitous journey in its case also.

---

[72] Another stranded close by.

The line (M) set out at the mouth of Cape Cod Bay from Manomet Point, Plymouth, to Provincetown, on April 21, 1926, showed an unmistakable movement of the water eastward, for 12 of the 28 were picked up near the tip of Cape Cod between Provincetown and Race Point, one passing out of the bay and thence southward to Nantucket. Two of the bottles set out off Truro (series N) also drifted to the tip of the cape at Wood End, the entrance to Provincetown Harbor.

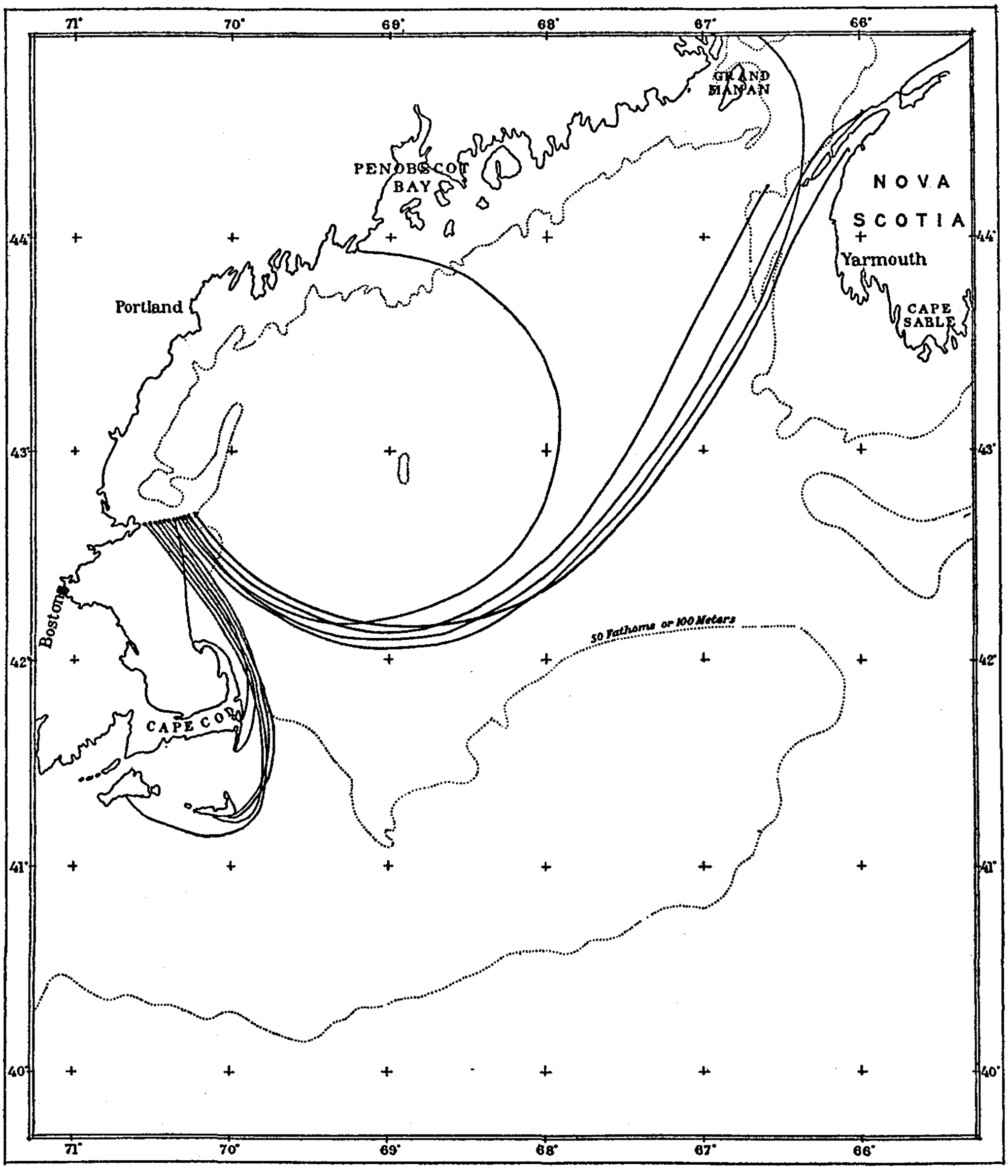

FIG. 179.—Assumed drifts of representative bottles recovered from Series L, set out off Cape Ann by H. C. Stetson, April 19, 1926. ●, place of release

In weighing the significance of drifts of this sort, when bottles are set out so close to land, due consideration must be given to the stage of the tide. In this instance all the bottles that showed a drift toward the north were set out on the flood tide, so that they must have traveled up the bay at first. Consequently, the fact that they stranded where they did indicates a predominance of ebb over flood, or in other words, a drift out of Cape Cod Bay along the eastern side.

Before leaving the bottle drifts in Massachusetts Bay, I should emphasize the fact that not one of them is clockwise, but that all can be safely interpreted anticlockwise within the bay or from north to south across its mouth and so down past Cape Cod.

At first sight the evidence (by bottle drifts) of a dominant set out of Cape Cod Bay around Cape Cod, and so southward along the outer shore of the latter, might seem contradicted by the physiography of the cape; for, as Davis (1896) has shown, the so-called "Province lands," which form its tip, were built up by the transference of sand along shore from the south. In fact, the existence of the sand spit known as Wood End, which incloses Provincetown Harbor on the southwest, is sufficient evidence of beach-drifting inward toward the bay, not outward from the latter, as the bottle drifts demand. However, this apparent contradiction vanishes on closer analysis. Beach-drifting[73] is effected chiefly by the longshore component of wave action.

A glance at the chart will make it clear that winds from the only direction (between north and southeast) that can drive a sea against the tip of the cape heavy enough to move much sand necessarily produce a wave current westward around its extremity. This would be the case even if the current a few hundred yards out (tidal or not tidal) were making in the opposite direction, perhaps carrying our drift bottles with it. Neither the tidal nor the nontidal currents scour the shore line here violently enough to be of more than minor importance.[74]

Thus, beach drifting may be constantly in one direction, but the dominant set of the water as constantly the opposite only a short distance out at sea; and it seems sufficiently established that this is the case at the tip of Cape Cod.

Farther south along the cape beach-drifting acts in the same direction as the nontidal drifts, both making to the southward.

The drifts from series O (set out near the coast, about midway between Cape Ann and Cape Elizabeth, on July 18, 1926, by T. E. Graves) proved consistent with these Massachusetts Bay drifts (as, also, with the drifts from the Bay of Fundy in 1919) for the three recoveries so far reported were all from the southward—two from Cape Ann and the other from the north shore of Massachusetts Bay at Salem.

DRIFTS OF BOTTLES SET OUT OFF CAPE ELIZABETH AND OFF MOUNT DESERT

The drifts so far discussed have proved so consistent, both regionally and from year to year, that the type of circulation which they represent may safely be taken as characteristic of the southern and southwestern parts of the gulf. The drifts of bottles put out off Cape Elizabeth and Mount Desert have proven equally consistent among themselves, though interpretation has not been so easy.

---

[73] Johnson (1919 and 1925) has proposed this convenient term for the longshore transference of sand or other débris.

[74] For an illuminating discussion of the relative importance of wave and other currents in causing beach-drifting, see Johnson (1919; 1925, p. 505).

We may first consider the outer half of the Cape Elizabeth line of 1922 (line A, p. 871, fig. 180) as the easiest to understand. Sixteen of these 150 bottles were recovered, as follows: Outer coast of Nova Scotia (Scotts Bay), 1; vicinity of Cape Sable, 1; mouth of Penobscot Bay, 2; western shore of Nova Scotia and southern shore of the Bay of Fundy, 12. Thus, the net drift for the great majority of these bottles was toward the east and northeast. The fact that so many of them stranded along the same sector of the Nova Scotian coast where bottles from the Cape Ann and Cape Cod lines have been picked up (figs. 174 and 176) makes it likely that they, too, veered from southeast to east in their journey across the gulf, to continue northeastward along the Nova Scotian coast in the drift shown there by current measurements (p. 861). The rapid drift of one bottle from the outer part of this line (No. 280) to the Salvages Ledges (about 25 miles east of Cape Sable), where it was picked up 67 days after release, points similarly to a rather direct track toward the east at first; for it can not have followed a very circuitous route unless it drifted faster than is at all likely. It is on these bases that the probable drifts are laid down on Figure 180.

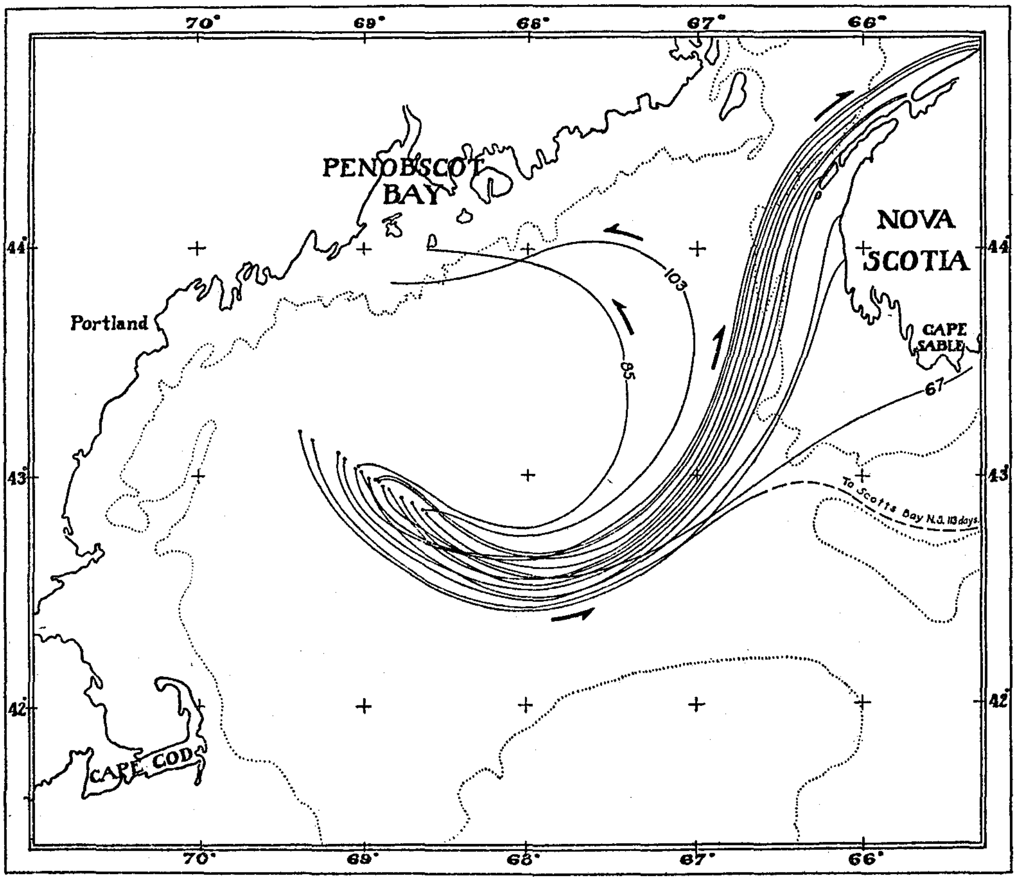

FIG. 180.—Assumed drifts of bottles recovered from the outer half of series A, set out off Cape Elizabeth, July 1, 1922. ●, place of release

Why the bottle last mentioned (No. 280) escaped the drift setting northward toward the Bay of Fundy is not clear. However, that it did escape, to continue eastward, proves that the surface current that sometimes flows westward past cape Sable was not active at the time. On the other hand, the fact that only two bottles of all this group were found on the outer Nova Scotian coast east of the cape, while so many turned toward the Bay of Fundy, is conclusive evidence that there was no general flow past the latter, but that its offing was comparatively a dead water at the time so far as any nontidal current is concerned.

It is not possible to reconstruct the track of the "Salvages" bottle in its rounding of the cape; it may have held farther offshore than its line, as laid down on the chart, would suggest, and then have veered inshore again. Bottle No. 165, which drifted from a point a few miles inshore of Cashes Ledge to Scotts Bay, 50-odd miles beyond Cape Sable, may have been caught up in the Nova Scotian eddy, judging from the considerable interval between release and recovery (113 days).

More interesting, in connection with the general circulation of the Gulf of Maine, are the two bottles (Nos. 210 and 284) that went from the outer section of line A to the mouth of Penobscot Bay. The direct route for these would be to the north, of course, but it is most unlikely that they followed such a course at right angles to the general easterly drift followed by the other bottles that went to Nova Scotia from this same section of the line. The fact that they were afloat about as long (85 and 103 days) as several of the bottles that reached the Bay of Fundy[75] also makes it likely that all the bottles of this group drifted southeastward and eastward at first. On this basis the most reasonable explanation for the eventual separation is that while most of the bottles approached the Bay of Fundy close enough to the Nova Scotian shore to be swept inward, reproducing the drifts of Mavor's bottles in 1919 (p. 868), others, circling on a shorter radius, hence following a more northerly route, crossed the mouth of the Bay of Fundy instead of entering it, were picked up in the current that flows out of the bay past Grand Manan, and so were carried westward again. This is made the more likely by the fact that several drift bottles put out in the Bay of Fundy in 1919 traveled by this same route to points along the Maine coast, one of them to the same destination (Penobscot Bay; p. 870). It is probable, therefore, that the two bottles that went from the vicinity of Cashes Ledge to Penobscot Bay in 1922 made a partial, anticlockwise circuit, which brought them well over toward the eastern side of the gulf en route, so that they approached their eventual destination from the east or southeast, not directly from the south.

The route of the Matinicus bottle is carried the farther eastward of the two on the chart (fig. 180), because of its longer interval; but there is no means of knowing whether this apparent difference is actually significant.

On the whole, the most instructive feature of this group is the uniformity of the drifts and the very definite and comparatively rapid movement of the water which these show along a narrow track from the center of the gulf to the Nova Scotian side of the mouth of the Bay of Fundy.

---

[75] No. 190 to Grand Passage, 116 days; No. 206 to Digby Neck, 90 days; No. 241 to Port Lorne, 88 days; No. 242 to the offing of Digby, 70 days; Nos. 248 and 255 to the vicinity of Point Prim, 75 and 90 days; No. 264 to Long Island, at the mouth of the Bay of Fundy, 81 days; No. 299 to Advocate Harbor, Nova Scotian shore of the Bay of Fundy, 107 days.

The inshore half of the Cape Elizabeth line of 1922 (line A, fig. 181) is more puzzling. These recoveries fall into four groups, so distinct and so far separated that the bottles must have scattered widely within a short time after they were put out. Four bottles from the outer half of the section went to the Bay of Fundy; three others were picked up along the coast of Maine between Jonesport and the western entrance to Penobscot Bay, the same sector to which several bottles drifted from the Bay of Fundy in 1919; one went southward to the Isles of Shoals, off Portsmouth; and six were found in Casco Bay or along the coast a few miles to the eastward of it. The recoveries from the inner end of the line were all from near-by localities, either in the Casco Bay region or along the southern shore of Cape Elizabeth.

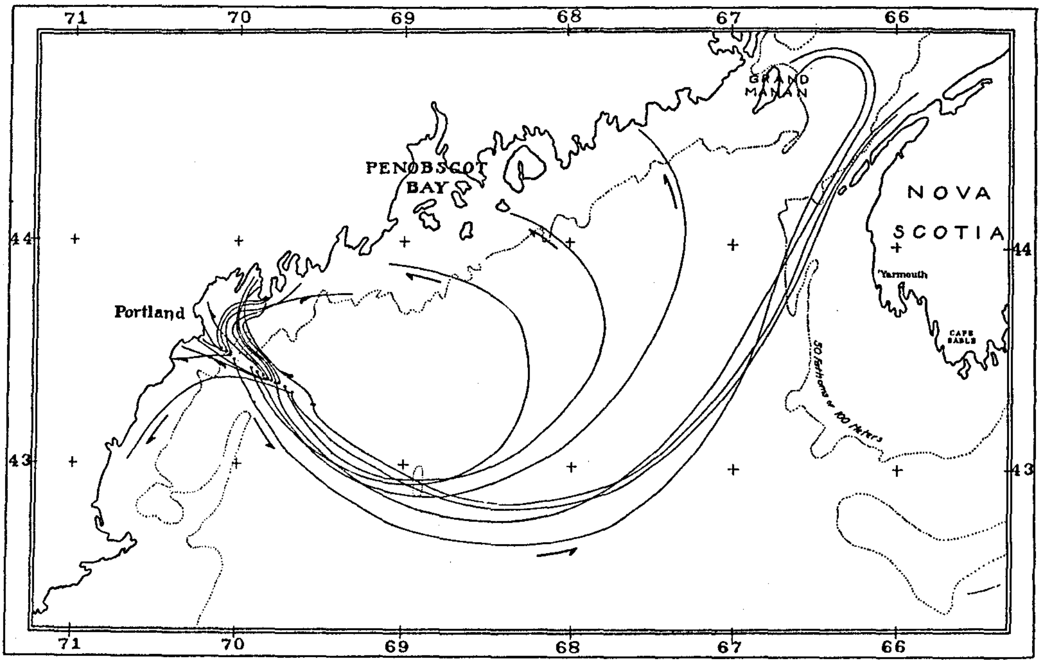

FIG. 181.—Assumed drifts of bottles recovered from the inshore half of Series A, set out off Cape Elizabeth, June 30, 1922. ●, place of release

If the two halves of line A be compared (figs. 180 and 181), it is at once evident that the percentage of bottles that went to Nova Scotia was much greater (14 bottles) for the outer than for the inner half, and that all the bottles that traveled this route were set out more than 10 miles from the land. If the drifts from the inner end of line A had been the only evidence available, the natural conclusion would have been that their general set was eastward along the coast of Maine. The evidence of the other series discussed so far forbids this, however. In the first place, the Bay of Fundy series of 1919 drifted in the opposite direction (p. 870), as several bottles set off Mount Desert in 1923 did, also (p. 902). Furthermore, all the bottles from the Cape Cod, Cape Ann, and Cape Elizabeth lines that were recovered in the Bay of Fundy region were reported from so short a sector of the coast that they must have followed a very uniform track, which for the Cape Ann and Cape Cod lines veered unmistakably through southeast; east, and northeast (p. 889). The time intervals are consistent with this, also, the great majority ranging between 70 and 105 days, irrespective of which line the bottle in question was launched from. For any of the bottles from the Cape Elizabeth line to have reached the southern shore of the Bay of Fundy by the alternative route via the coast of Maine and through the Grand Manan Channel would have involved a drift from north to south across the Bay of Fundy directly contrary to the dominant set established there by Mavor's (1922) experiments with drift bottles, as well as by measurements of currents (p. 861). Such an explanation would also be contrary to the time intervals, for the two bottles that went from the offing of Cape Elizabeth to Grand Manan and to The Wolves (Nos. 43 and 88) and were not reported until 103 and 104 days after release, while two others, set afloat near by (Nos. 99 and 105), were reported from the Nova Scotian side of the Bay of Fundy in 80 to 98 days.

By this reasoning the bottles that went to Penobscot Bay from the inner end of line A, and to the coast of Maine farther to the eastward, may safely be credited with essentially the same route as those that reached this same sector of the coast from the outer end of this line, circling anticlockwise at first toward the Bay of Fundy, to return westward again. The time intervals between release and recovery (80 days for No. 65, picked up at Jonesport; 63 days for No. 98, reported near Swans Island; and 103 days for No. 87, found at Matinicus) favor this interpretation.

The general uniformity, both of localities of recovery and of time intervals, for the outer two-thirds of line A, indicates a well-developed, dominant set of the anticlockwise sort just outlined. This, however, seems hardly to have affected the surface water within 15 miles of the land at the time, judging from the regional dispersion of the returns from the inner end of line A and from the fact that the time intervals between release and recovery vary widely for these, quite independent of the distances which this group of bottles made good. Thus we find intervals ranging from 25 to 77 days for 7 bottles that were picked up in the Casco Bay region, 15 to 30 miles from the points of launching, and 5 to 72 days for 5 bottles recovered along the southern side of Cape Elizabeth after journeys of 8 to 23 miles. One was found at Monhegan Island (35 miles) in 47 days, but another, reported from Damiscove (25 miles), was not found until 75 days had passed.

Of course, little stress can be laid on the time interval for any one bottle, because there is no knowing how long it may have lain on the shore, overlooked; but our general experience suggests that if bottles are not reported comparatively soon after stranding they are either broken or buried in windrows of seaweed and never after heard from at all. Consequently, when time intervals vary widely for bottles drifting only a short distance to a coast as frequented as the Casco Bay region is, contrasting with uniformity of intervals for bottles journeying right across the gulf, it is obvious that the former did not follow as definite a set as the latter. On the whole, the regional distribution of the localities of recovery for the inner end of this Cape Elizabeth line trends eastward across Casco Bay, pointing to an irregular eddying drift in that direction as involving the mouth of the latter. Cape Elizabeth, however, seems to have bounded this eddy on the south at the time, witness the several strandings to the south of the cape (fig. 181); the fact that one bottle, set out about midway of line A was recovered at the Isles of Shoals after 100 days points to some movement of surface water southward along the coast sector between Cape Elizabeth and Cape Ann.

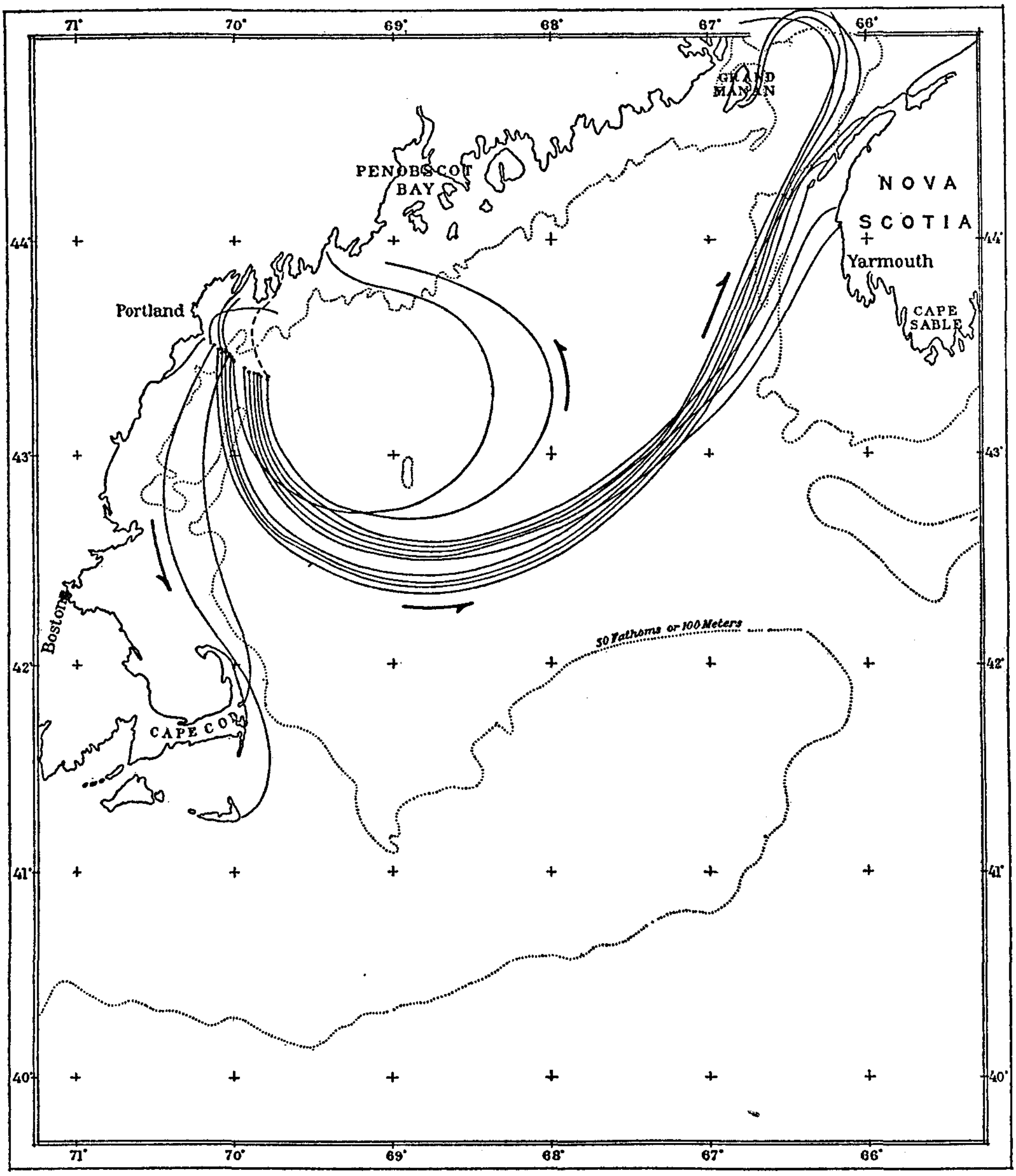

FIG. 182.—Assumed drifts of representative bottles recovered from Series E, set out off Cape Elizabeth, August 7, 1923. ●, place of release

The drift of a second line of bottles set adrift off Cape Elizabeth a year later (in August, 1923; series E, p. 874) showed much the same grouping as that just described for the corresponding line of 1922 (series A). Two recovered from the outer part of the line were from the west coast of Nova Scotia (fig. 182); three were from the entrance to the Bay of Fundy, on the Nova Scotian side; two were from the New Brunswick side of the Bay of Fundy; and three were from the southern side of Grand Manan; totaling 9 per cent of the number set out. These drifts so closely reproduce (in their regional distribution) the recoveries of bottles set afloat farther out along this same line the year before (line A; fig. 181) and off Cape Ann in 1923 (fig. 176) that most of them, no doubt, followed a uniform route, at least in their journey northward toward the mouth of the Bay of Fundy.

It is evident that most of the bottles from line E moved offshore from the time of their release, otherwise more strandings would have been reported from the coast line to the southward. However, the fact that one of them was recovered at Nantucket, a second on the outer shore of Cape Cod, and a third at Beachwood, Me. (Nos. 1702, 1712, and 1731; intervals, respectively, of 138, 121, and 34 days), makes it probable that they followed a southeasterly course at first. Negative evidence to the same effect results from the fact that only two bottles from this line were found anywhere along the coast of Maine between Seguin Island and the Bay of Fundy, contrasting with the considerable number of recoveries from Nova Scotia. Had the set been eastward along the coast of Maine, such as would be represented by a straight line between the points of release and recovery, a considerable number of recoveries might have been expected along that 140-mile sector, where the tide draws strongly into the numerous bays, bringing in large amounts of drift of all kinds. It is fair to assume, also, that the route across the gulf was about as long for series E as for the Cape Ann series, because three of the latter were reported from Nova Scotia after intervals as brief as any from the northern lines; one, namely from Yarmouth, in 60 days; another from Port Maitland in 64 days; and one from Cockerwit Passage in 65 days (p. 875). However, it seems that the Cape Elizabeth groups swung east before reaching the Cape Ann line, because so many more of the former reached Nova Scotia than of the latter; i. e., that on the whole the two groups of bottles followed different routes until they converged toward the eastern side of the gulf.

The repetition, from year to year, of drifts most easily reconcilable with an anticlockwise eddying set argues strongly in favor of the prevalence of this type of circulation around the southern side of the basin of the gulf. Only one drift (No. 1773) from the two series so far launched off Cape Elizabeth (series A and E) has been hard to reconcile with this; because, if the date of recovery is correctly stated, its time interval from the offing of Cape Elizabeth to Grand Manan (56 days) is smaller than for any other bottle that crossed from the western side of the gulf to the Bay of Fundy. Granting it a direct journey, this means a daily rate of 2.7 miles, or at least 4.7 miles if it followed the eddying route, which is more likely.

The time intervals between the dates of release and recovery for bottles drifting from the offing of Cape Elizabeth to Nova Scotia averaged considerably shorter in 1923 (56 to 111 days; average 75 days for line E) than in 1922 (75 to 146 days; average 103 days for line A). Taken at its face value, this difference would point either to a more rapid rate of travel or to a more direct route, which in this case would mean veering more directly eastward. It seems more likely, however, that the difference is not as significant as it might appear, but that the discovery of the bottles and the local interest aroused thereby stimulated a closer scanning of the Nova Scotian shores in 1923, so that the bottles were found soon after they stranded, instead of lying on the beach perhaps for a week or more. The fact that one bottle, which drifted right up the Bay of Fundy to Advocate Harbor at Cobequid Point, at its head, was picked up in 107 days affords direct evidence to this effect, the distance on the assumed track being more than 250 miles.

With this uncertainty introducing a source of error that may be very considerable, I have not thought it justifiable to assume a shorter route for the bottles drifting to the mouth of the Bay of Fundy in 1923. The probable routes within the Bay of Fundy of such bottles from line E as entered the latter are laid down on the chart (fig. 182) to accord with the drift bottles set out there by Mavor in 1927 (i. e., crossing it from south to north and then continuing to veer westward to Grand Manan), because this type of circulation seems sufficiently established there.

Line E reproduces the corresponding series of the preceding year (line A), not only in the preponderance of drifts to Nova Scotia and in the uniformity of the tracks probably followed, but also in the recovery of one bottle at Metinic Island, off the western entrance to Penobscot Bay (No 1792), and of another at Round Pond Harbor, a few miles farther to the west (No. 1740). The time intervals for these (respectively, 64 and 77 days) correspond as closely as could be expected with 63 and 103 days for the two bottles (Nos. 98 and 284) that drifted to this same sector the year before (figs. 180 and 181), and hence suggest the equally circuitous offshore route laid down on the chart. However, it is possible that the two bottles in question (Nos. 1740 and 1792) actually circled in the opposite direction (i. e., clockwise), drifting inshore at first in company with four others that were picked up in Casco Bay and a few miles to the east of it, then continuing eastward along the coast, perhaps through the channels between the islands. The fact that one bottle (No. 1793) from the outer end of line E was found in Sheepscott River[76] after 34 days lends likelihood to this possibility.

The Cape Elizabeth series for the two years, however, illustrate an annual difference of another sort; namely, that the coastal belt, 10 to 15 miles broad next the cape, was a sort of deadwater in 1922 (p. 899), while in 1923 the general dominant set governed closer in to the coast.

BOTTLES SET OUT OFF MOUNT DESERT, AUGUST, 1923

The drifts of the bottles of the Mount Desert line can be approximated only if they are taken in conjunction with the several series discussed so far. Standing by themselves they would be self-contradictory, for 8 were recovered at significant distances to the westward (figs. 183 and 184); 11 were recovered at significant distances to the eastward; and 6 others at points close to where they were released. The easterly drifts so far reported all lead to the coast of Nova Scotia, except for one to the coast of Maine at the western entrance to the Grand Manan Channel (No. 1584, Haycock Harbor, Washington County). By themselves, these would naturally suggest a set to the northeast from the offing of Mount Desert, but analysis makes this most unlikely.

The fact that these Nova Scotian recoveries are distributed along the same sector of the coast line where bottles from the Cape Elizabeth, Cape Ann, and Cape

---

[76] Stated in the returns as "Sheepshead" River.

Cod lines have stranded would of itself be strong evidence that the routes of all had converged into one general and rather definite track some distance before they reached the land. In this respect the correspondence between the Mount Desert line of 1923 and the outer half of the Cape Elizabeth line of 1922 (series A, fig. 180) is as close as could have been expected had all these bottles been launched on the same line and on the same day. In fact, this correspondence extends even to the odd bottles that diverged from the majority grouping, one or two having reached

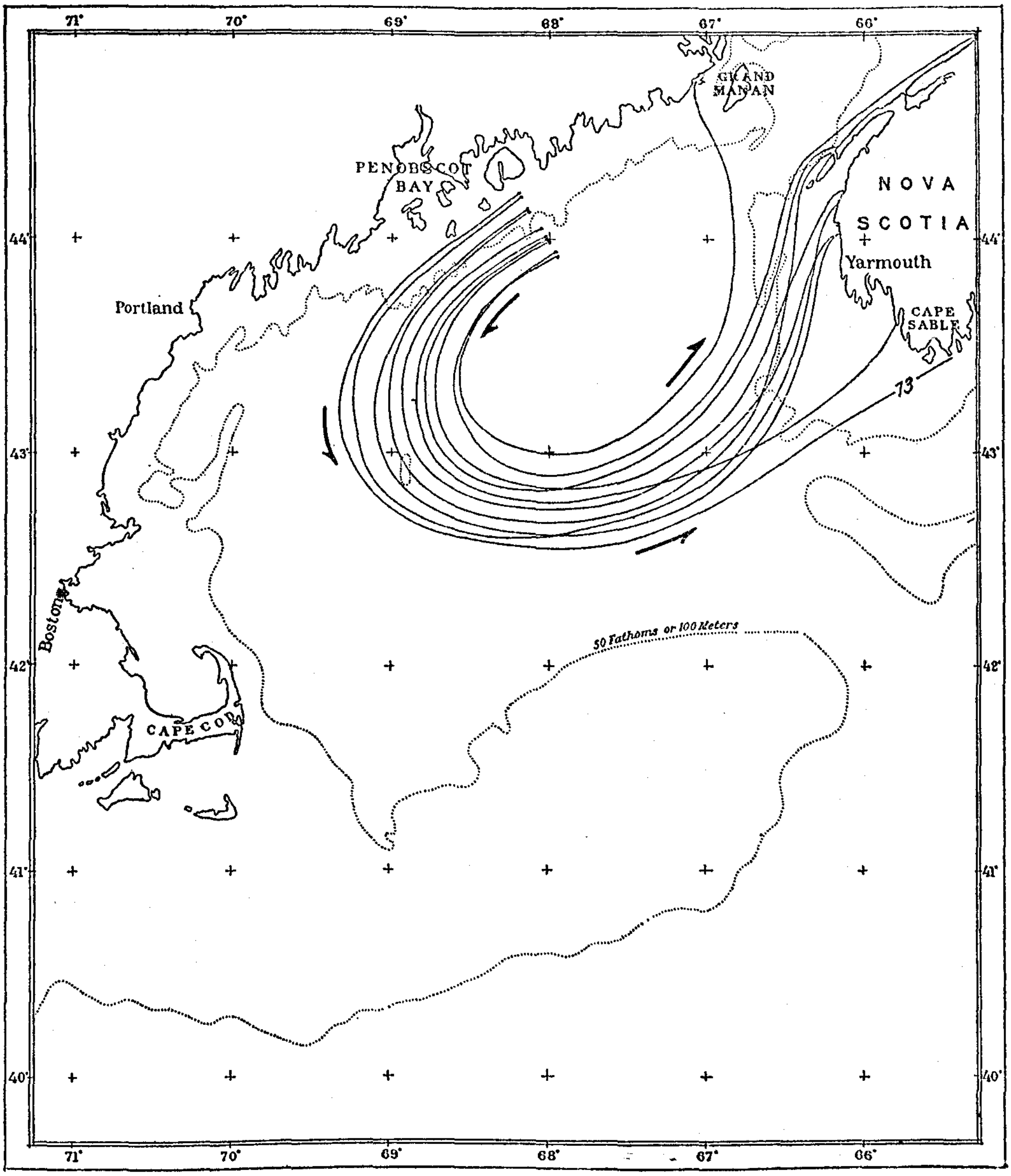

FIG. 183.—Assumed drifts of representative bottles recovered to the eastward from Series D, set out off Mount Desert Island, August 6, 1923. ●, places of release

the vicinity of Cape Sable, and one or two found along the coast of Maine well to the eastward, in each instance. In the case of the drifts that cross the gulf, this track, I believe, is now definitely proven to approach the Bay of Fundy from the south or southwest, by the evidence just detailed.

The relationship which distance traveled bears to time interval between release and recovery also argues for a circuitous route for the bottles that went to Nova Scotia from the Mount Desert line, because the average distance for all of them, in a direct line, would be only about 85 miles, though the times range from 62 to 88 days for 8 of 10[77] (averaging 70 days). Evidence of this sort must, of course, be used with discrimination, because there is no knowing how long a bottle lies on the beach before it is noticed. When the results prove reasonably consistent, however, some trust can be put in them. In the present connection we have as a standard for comparison the Nova Scotian drifts from the lines set out off Cape Elizabeth. The distance (in a direct line) is only about one-half as great from Mount Desert to Nova Scotia as from Cape Elizabeth. The two lines of 1923 were set out only one day apart, and there is no reason to suppose that bottles from one line would be consistently overlooked while bottles from the other would be soon found. Consequently, it is reasonable to assume that some of the Mount Desert bottles would have been found a month or more before the first were reported from the Cape Elizabeth line, unless they had journeyed by a very circuitous route. Actually, however, the first four recoveries for the former were on October 7 to 9; the first three of the latter on the 9th and 10th. Allowing the one day's difference in the dates when the two series were put out, we have the rather surprising fact that the time intervals for these two groups, launched almost 100 miles apart, were the same almost to a day, though the strandings were scattered along more than 20 miles of coast line between Yarmouth, Nova Scotia, and the mouth of the Bay of Fundy.

The time intervals for the Nova Scotian drifts as a whole, from these two series, also correspond much more closely than the difference in direct distance would have suggested as probable, averaging about 75 days for the Cape Elizabeth series (extremes of 56 to 111 days; p. 875) and about 70 days for the Mount Desert group (62 to 151; p. 874).

The percentage of recoveries is not only of the same general order of magnitude for the Mount Desert line as for the Cape Elizabeth line of 1923 (respectively, 28 and 19 per cent), but the Nova Scotian and Fundian returns formed almost the same proportion of the total for the former (36 per cent of the total returns) as for the latter (42 per cent).

The most reasonable explanation for this correspondence between the two series, and the only explanation that fits all the facts just outlined, is that the journey to Nova Scotia covered about as long a distance for the Mount Desert bottles as for the Cape Elizabeth bottles, and that the former drifted southwestward at first, to join the general route of the latter group from west to east across the gulf.

Bottle No. 1584, set adrift about 25 miles out from Mount Desert Island and picked up at Haycocks Harbor, on the north shore of the Grand Manan Channel, 93 days later, probably followed the same general track as the bottles that went to

---

[77] Three others (Nos. 1530, 1551, and 1557), which were not picked up until 133 and 151 days had passed, may have lain unnoticed on the beach or drifted in and out along the shore with the tides.

Nova Scotia. It may have entered the south side of the Bay of Fundy, come out again past Grand Manan, and then circled the western end of the latter and so into the channel, as would be compatible with the current measurements in that region. Or it may have circled northward past the mouth of the bay but close enough to Grand Manan to be caught up in the indraft into the channel.

The general conclusion that all this group of bottles followed an eddylike course and did not drift directly eastward is directly corroborated by nine bottles from this same line, picked up to the westward along the coast of Maine. The fact that these were set out at intervals from the inner end of the line to the outer is evidence that the surface was involved in this movement for at least 25 miles out from the land.

Two bottles from the inner end of the line, picked up on Great Duck Island two days later, may have made their journey on the tide, for they were set out early in the ebb,[78] which sets toward the southwest here. A greater distance covered (10 miles) makes it likely that bottle No. 1515, which went to Long Island (also to the westward), made its landfall on the second tidal period; and it is certain that No. 1521, which went from the inner end of the line to Kennebunk, Me. (a distance of about 107 miles in a direct line), in 32 days, was carried with a very definite drift, for its rate was not less than 3½ miles per day. The daily rate of another bottle (No. 1523), which went from the mid section of the line to a point 8 miles southeast of Isle au Haut, 31 miles away, was ostensibly much more rapid, for it was reported as picked up the day after it was set out. This date, however, can hardly have been correct. Allowing one day's error (which is probably the correct explanation), the daily rate would be about 7 miles to the westward.[79]

The rapidity of these westerly drifts, which can not be disputed, makes it likely that four other bottles that went from this line to the entrance to Penobscot Bay and to St. Georges River, a few miles farther west (Nos. 1553, 1565, 1566, and 1599), but were not found until after 35 to 38 days afloat, were drifting to and fro with the strong tides of Penobscot Bay for some days before they stranded and were noticed.

It is impossible, of course, to determine how far any given bottle, which moved westward from the Mount Desert line but did not soon strand, may have paralleled the coast before veering offshore toward the center of the gulf, but it is probable that most of them did so somewhere between the longitudes of Penobscot Bay and Cape Elizabeth. Had their general route led farther westward, more bottles from the Cape Elizabeth line might have been expected to show a southerly drift than the few actually so reported (p. 901).

Some few bottles from the Mount Desert line, hugging the shore line closest, may have crossed the Cape Elizabeth line, but the time intervals between release and recovery make it more likely that all that went across the gulf from the offing of Mount Desert passed to the seaward of the outer end of the Cape Elizabeth line—i. e., more than 25 miles offshore—and it is so indicated on the chart (fig. 182).

---

[78] It was high tide at Southwest Harbor at 6.26 a.m. on that day; the bottles in question (Nos. 1503 and 1510) were put out shortly afterwards.

[79] Assuming that it was picked up in the afternoon.

The tracks of three bottles from the mid section of line D, which were picked up at the eastern entrance to Frenchmans Bay, and one other that went to the vicinity of Petit Manan, are more puzzling. Ostensibly these point to short easterly drifts of 8 to 12 miles, and the time intervals are so uniform (33 to 38 days)[80] that all of them seem to have followed approximately the same route, though set out some miles apart. However, the time between release and recovery is so long for direct journeys so short, when contrasted with the rapidity with which other bottles set out near them drifted in the opposite direction, that it seems virtually certain that they followed a roundabout route. Judging from the facts that many more bottles stranded to the westward and that all of this series (D) were set out on the ebb, it is probable that the four bottles in question also drifted westward at first. Their most likely route would then be into Blue Hill Bay with the next flood, around Mount Desert Island, and so out again through Frenchmans Bay, to strand about Schoodic Promontory and to the eastward of it. Such a drift would be consistent with the clockwise circulation to be expected around Mount Desert Island, on theoretic grounds (p. 970). In short, the bottles set out off Mount Desert in 1923 afford definite proof of a set westward along the coast of Maine but no clear evidence of any longshore set in the opposite direction.

On the basis of the foregoing analysis, the most reasonable explanation of the localities where bottles from the Mount Desert, Cape Elizabeth, Cape Ann, and Cape Cod series of 1923 were recovered, and of the periods of time between the dates they were set afloat and later were picked up, is that bottles from all three lines moved in tracks eddying counterclockwise through southwest, through east, to north, and veering on successively shorter and shorter radii of curvature. Thus, the few bottles from the two southernmost lines, which were found on the Nova Scotian coast, probably traveled easterly from the time they were set out (southeast at first, then east and northeast), but the farther north and east along the coast bottles were put out, the more they tended to circle to the right of a direct course. It is also likely that while the breadth of the track covered by all the bottles in the western side of the gulf was something like 100 miles, they tended to converge into a narrower track as they approached the eastern side of the gulf.

In August, September, and October of 1922 and 1923 the center of this eddylike circulation seems to have been situated 40 to 60 miles south of Mount Desert Island, over the northeastern extension of the deep trough of the gulf.

The fact that the great majority of the recoveries from Nova Scotia and from the Bay of Fundy were from a rather short stretch of coast leads to the conclusion that no matter on which line the bottles in question were released, all those that drifted across the gulf finally came within the influence of the same south-north current, hugging close to the eastern shore. On no other assumption, I believe, is it possible to reconcile the facts just stated with the time element (p. 904) and with the current measurements that have been taken in that side of the gulf (p. 861).

The recoveries on the coast of Maine already discussed point to a division of this northerly set before it reaches the Bay of Fundy, the greater volume entering the bay along its southern shore, but offshoots (which may be only intermittent)

---

[80] No. 1511 was picked up in Winter Harbor 11 months later, a period so long that there is no way of estimating how far it may have traveled en route, or how long it may have lain on the strand.

from its western side recurving to the left across the mouth of the bay. Flotsam drifting in this branch may then come under the influence of the drift setting eastward into the right-hand side of the Grand Manan Channel. But only one bottle can so be classified, while five seem to have passed by the channel in their rounds to Penobscot Bay.

It is interesting that only two bottles from any of the several series[81] have been recovered along the coast sector between Petit Manan and the western entrance to the Grand Manan Channel, although many must have passed by. Judging from this, such parts of the dominant surface drift as veers westward past Grand Manan does not usually strike the coast of Maine in summer until it has passed the longitude of Mount Desert Island.

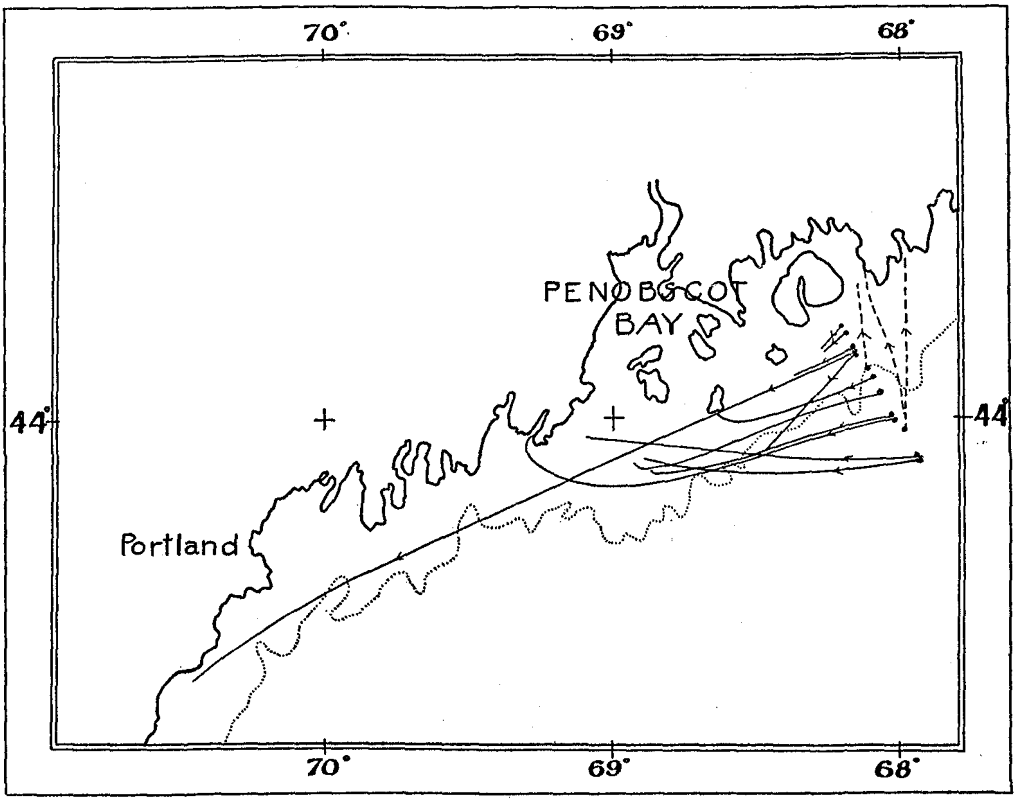

FIG. 184.—Assumed drifts of bottles recovered to the westward and inshore from Series D, set out off Mount Desert Island, August 6, 1923. ●, places of release

The circulatory scheme just outlined reconciles the bottle drifts for 1923 with those of the bottles set out in the Bay of Fundy in the summer of 1919, except that the latter certainly hugged the coast more closely in their westward and southward journey, else so many of them would hardly have been embayed behind Cape Cod. In this respect the summer of 1919 paralleled the April and July currents of 1925

---

[81] One set out in the Bay of Fundy in August, 1919 (Mavor, 1922, bottle no. 181); the other (no. 65) from the inner part of the Cape Elizabeth line of July, 1922.

and 1926, which carried bottles past Cape Ann, from Ipswich Bay into Massachusetts Bay (pp. 890, 893).

In the summers of 1922 and 1923 so many more bottles were picked up along Nova Scotia than in the western side of the gulf (a difference hardly accidental, because the coast line between Cape Elizabeth and Cape Cod is much frequented) that the surface water was evidently moving more offshore in the western side of the gulf, inshore in the eastern, than was the case in 1919.

BOTTLES PUT OUT OFF WESTERN NOVA SCOTIA

In 1926 the Biological Board of Canada put out four sets of bottles (each of 120) off Yarmouth, Nova Scotia, in July, August, September, and October, and Dr. A. G. Huntsman has contributed a summary of the recoveries in advance of his publication of the detailed results.

The great majority of returns from all the sets were from the Nova Scotian side of the Bay of Fundy, scattered from St. Marys Bay, at the mouth, to Minas Basin and Chignecto Bay, at the head. Six others crossed to the New Brunswick shore of the bay; five were picked up at Grand Manan; two went to the coast of Maine, one to Cape Cod; and two went in the opposite direction, eastward, past Cape Sable to Cape Negro and the vicinity of Shelburne, Nova Scotia.

As a whole, these drifts demonstrate the northerly drift along western Nova Scotia into the southern side of the Bay of Fundy, and up it. The New Brunswick recoveries show the anticlockwise movement within the bay, brought out by Mavor's (1923) experiments (p. 868). The drifts to Maine and Cape Cod are in line with the westerly and southerly drifts of bottles from the Mount Desert and Cape Elizabeth lines.

By what counterdrift the two bottles that went to the eastward escaped the Gulf of Maine eddy and came within the influence of the Scotian eddy is not clear.

DRIFTS OF BOTTLES ENTERING THE GULF FROM THE EASTWARD

The northerly drift along the Nova Scotian side of the gulf to the Bay of Fundy and its anticlockwise eddying continuation along the coast of Maine are further illustrated by the destinations reached by a considerable number of bottles that entered the gulf from lines set out off the outer coast of Nova Scotia by the Biological Board of Canada in the summers of 1922, 1923, and 1924. The following data have generously been contributed by Doctor Huntsman in advance of publication.

Two bottles from a line set out southeast across the continental shelf from Brazil Rock on July 17, 1922, were picked up along the western coast of Nova Scotia; 8 in the Bay of Fundy; and 2 circled farther westward, 1 of them to Winter Harbor and the other continuing past Mount Desert to the neighboring Long Island. The localities of release were scattered from 2 to 59 miles out from Brazil Rock, and none of the bottles set adrift farther out were reported from the gulf.

The bottle that went to Long Island made so rapid a drift (45 days from release to recovery) that no doubt it passed across the mouth of the Bay of Fundy. The Winter Harbor bottle, with 77 days, may have entered and circled the bay.

The next summer a series roughly at right angles to this last was set out on a line running northeastward from the western end of Browns Bank. Fourteen of these were reported from the Gulf of Maine; 6 of them scattered along the west shore of Nova Scotia; 7 were from widely separate localities in the Bay of Fundy, from its mouth to its head, after intervals of 64 days and upward; and 1 was from Penobscot Bay, Me. The drifts are thus much the same as those of the preceding summer, hugging the Nova Scotian coast to the Bay of Fundy. The time interval for the Penobscot Bay bottle was so long (113 days) that it, too, may have entered and circled the bay.

Twelve bottles from lines set out off Country Harbor, off Beaver Island, and off Cape Canso, Nova Scotia, were also reported from the Gulf of Maine (all of them from Yarmouth and northward along the western coast of Nova Scotia) and from the two sides of the Bay of Fundy. Only a single bottle from these eastern lines has yet been reported from the western side of the gulf—one set adrift a few miles off Sable Island by the Ice Patrol cutter *Tampa* on April 18, 1924, and picked up at Gloucester, Mass., 118 days later. The distance in a direct line being about 450 miles and something like 500 miles by the probable route around the northern side of the gulf, this bottle made an unusually rapid journey.

Since the preceding was written, Doctor Huntsman has contributed a summary of five monthly series, each of 200 bottles, set out offshore from Brazil Rock (off Cape Sable), July to October, 1926. Twenty-six of the 35 returns from the July set were close by, five from the Nova Scotian shore of the Bay of Fundy, and two from the New Brunswick side. The 46 returns from the August series were similar, except that the proportion of near-by returns was smaller (16); of returns from St. Marys Bay and the Nova Scotian shore of the Bay of Fundy larger (29). Fifteen of 23 returns from the lines of September 1 were again from this same sector of the Bay of Fundy region, three from the New Brunswick shore, and five between the point of release and Cape Sable. Three of the 15 returns from the series of September 27, however, were from the eastward (Shelburne to Port Mouton), nine near where set out, and only three from the Bay of Fundy. The series of October 20, again, gave 50 per cent of returns (six) near-by, four returns to the eastward (Negro Harbor to vicinity of La Have River), with two, only, from the western coast of Nova Scotia within the Gulf of Maine.

In sum, the evidence of a general northward drift hugging the Nova Scotian side of the gulf to the Bay of Fundy, and of its continuation westward as far as Penobscot Bay, is made cumulative by these drifts into the gulf.

The Brazil Rock series of 1926 also show the following seasonal succession: In July and August the dominant movement from the offing of Cape Sable was into the Gulf of Maine, but by the end of September the Scotian eddy had spread westward far enough to involve some bottles from this line in drifts best interpreted as circling anticlockwise, first offshore and then in again to the coast, to the eastward.

Further details as to the tracks followed are to be expected in Doctor Huntsman's forthcoming account.

One other bottle is recorded by the United States Hydrographic Office (Pilot Chart for May, 1923; reverse No. 26) as showing a similar drift into the eastern side of the Gulf of Maine from its release, 34 miles south of Cape Sable, September 21, 1902, to its recovery near Yarmouth, Nova Scotia, 30 days later.

CIRCULATION OF THE SUPERFICIAL STRATUM AS INDICATED BY SALINITY

The distribution of salinity affords a valuable check on the correctness of the circulatory system of the surface stratum, deducible from the drift-bottle experiments and from current measurements. The physical state of the water, together with the horizontal and vertical distribution of density, is the only clue yet available to the nontidal circulation in the deep strata of the gulf.

The reader will find frequent references to this phase of the subject in the section devoted to the salinity (p. 701). The distribution of salinity, as a reflection of the circulation of the gulf, has also been discussed in such detail in earlier reports on the Gulf of Maine explorations (Bigelow, 1914 to 1922) that a brief statement will suffice here.

With the oceanic water outside the edge of the continent much salter than the water in over the banks or alongshore (a rule prevailing all along eastern North America from Florida to the Grand Banks) a high salinity becomes an excellent indicator of any indraft from offshore. On the other hand, the lines of dispersal for land water are to be learned from the distribution of the least saline water. In the Gulf of Maine the flow of the Nova Scotian current past Cape Sable also tends to freshen the surface wherever its influence reaches.

Our first summer's cruise (in 1912) was enough to show what subsequent cruises have corroborated, that the freshest water is not localized off the mouths of the several large rivers, as would be the case if the discharges from these simply fanned out, but that it takes the form of a continuous and comparatively narrow belt skirting the coast line. The region where this freshest water does spread farthest out to sea (off Cape Ann and Massachusetts Bay) is some distance southward from the mouth of the Merrimac, the nearest of the large rivers. No fan of low salinity has ever been demonstrated off the mouth of the Kennebec.

The absence of such a fan off the mouth of any given river may or may not prove the failure of its discharge to drift out to sea, depending on the balance between the activity with which the tides mix the deep with the surface strata there and the volume of fresh water discharged. The river water that runs into the northern side of the gulf, and especially into the Bay of Fundy, is rapidly consumed in this way. Nevertheless, even where mixing is most active, areas of relatively lower salinity off the river mouths might be expected to alternate with areas relatively higher in salinity along the coast sectors between them, unless some dominant drift in one direction or the other disturbed this idealized picture. When we recall how great a volume of fresh water actually pours into the Gulf of Maine every year (p. 837) it is hardly conceivable that it would exert its chief freshening effect on so narrow a coastwise belt, unless the surface water tended to drift parallel to the land in the one direction or the other.

The summer salinities of 1912 (p. 770) pointed very clearly to a longshore movement of this sort around the northern and western margins of the gulf, setting westward along the coast of Maine, southward to Cape Ann, and spreading eastward off the cape in a rather definite tongue, outlined (at the surface) by the isohaline for 31.8 per mille (Bigelow, 1914, pl. 2). It was the presence of this tongue which established the direction of flow beyond dispute, because considerably higher salinities in Massachusetts Bay to the south of it, as well as offshore, left the coastal belt to the northward as its only possible source.

On the other hand, the salinity of the surface then afforded little evidence of river water in the northeastern corner of the gulf, in spite of the proximity of the St. John River. This, however, can be explained by the active mixing that takes place there, for while the mean salinity of the upper 50 to 60 meters was slightly higher (about 32.5 per mille) in the Grand Manan Channel and at its western end that August than it had been at the mouth of Massachusetts Bay a month earlier (about 32.2 per mille), the difference is no greater than can be explained as due to the regular seasonal succession (p. 799). A detailed discussion of the salinities for that summer, given in an earlier report (Bigelow, 1914, p. 90), leads to the conclusion that water of high salinity was being drawn into the eastern side of the gulf while the coastwise belt was dominated by a nontidal set alongshore from north and east to south and west, with expansions of water of low salinity off Penobscot Bay and off Cape Ann suggesting two separate anticlockwise eddies.

The subsequent summer cruises have expanded this preliminary concept of a general circling movement around the northern and western shores of the gulf to the domination of the surface over the entire basin by a great anticlockwise eddy, paralleling the land northward along Nova Scotia and swinging westward and then southward toward Cape Cod (Bigelow, 1917, p. 340), this being the only assumption on which the distribution of surface salinity can be rationalized.

This, it will be noted, has since been corroborated by the bottle drifts just described. A comparison between the recurving tongues of low salinity off Cape Ann and off Penobscot Bay, when such phenomena develop there, with the drifts from the Mount Desert, Cape Elizabeth, and Cape Ann lines, is especially instructive, for we find in such tongues a rational explanation for the tendency of the bottles to veer out from the land on successive radii. If, for example, bottles had been put out off Mount Desert in the summers of 1912 or of 1913, salinity suggests that the majority would have turned southward, abreast of Penobscot Bay, and that few, if any, would have stranded along the coast farther west. This actually happened in 1923 (p. 902, fig. 183). The tendency for bottles put out near land on the Cape Elizabeth and Cape Ann lines of that year to veer offshore from the beginning of their drifts would similarly find a reasonable cause in expansions of low salinity out toward the basin from the offing of Cape Ann, such as were actually recorded in July, 1912, and in August, 1914 (p. 763, fig. 136). But the distribution of surface salinity in August and September, 1915, when scattered observations outlined a band of low salinity of comparatively uniform breadth as paralleling the coast line from Nova Scotia to Cape Ann (fig. 137), would be compatible with drifts hugging the shore more closely as far as the cape, or perhaps to Massachusetts Bay, such as were actually followed by bottles set out in the Bay of Fundy during the summer of 1919 (p. 870) and off Cape Neddick (series O) in July, 1926. The locations of the isohalines at the surface are thus entirely reconcilable, both with the drifts assumed for the bottles and with the annual difference indicated by the sets put out in the summers of 1919, 1922, 1923, and 1926.

Mavor (1923), in his discussion of the distribution of salinities and temperatures in the Bay of Fundy for August, 1919, has shown that these are best explained as due to a movement of water into the bay on the Nova Scotian side, recognizable from the surface down to a depth of 100 meters, crossing northward toward New Brunswick about midway up the bay, with a counterbalancing outflow of water of low salinity southward and westward along the northern (New Brunswick) side. Here, again, temperature and salinity corroborate the evidence of drift bottles (p. 870).

The high surface salinities recorded in the northeastern corner of the gulf on the August cruises of 1912 and 1913 suggested a continuous tongue of highly saline water flowing into the eastern side of the gulf at the surface from the Atlantic Basin. However, subsequent discovery that the high surface values encountered in the basin between Maine and Nova Scotia in successive summers actually represent an isolated pool, resulting from local upwelling combined with tidal stirring (p. 768), and surrounded by less saline water on all sides, has lead to the appreciation that the gulf receives its saline water chiefly in the deeper strata (p. 842), not on the surface.

The rather abrupt west-east transition in surface salinity registered in the offing of Cape Sable in the summers of 1914 and 1915, added to the retreat of the critical isohalines (32 to 31.5 per mille) from the eastern side of the gulf, eastward, with the advance of the spring (p. 755), argues against any notable current from the east past the cape as characteristic of summer. Here, however, the effect which the active tidal mixing southwest and west of the cape would have in increasing the salinity of the surface, moving westward, must be taken into account.

If the evidence of salinity does not make clear the dominant set, if any, past Cape Sable for the summer months, the tongue of low salinity and low temperature found extending along the southeastern face of Georges Bank from northeast to southwest in July, 1914 (p. 770), is "hard to explain, except as an outflowing current from the gulf" (Bigelow, 1917, p. 241); and though this may not be a regular feature of the summer circulation (p. 608), the fact that several bottles from the Cape Cod and Cape Ann series of 1922 and 1923 seem to have drifted out of the gulf via this same route across the eastern end of Georges Bank (figs. 174 and 176) is certainly suggestive of its permanency. A tendency for water of low salinity to spread from the vicinity of Cape Cod southeastward to the neighboring part of Georges Bank is also indicated by the contrast in salinity between the western and eastern ends of the latter on the summer chart for 1914 (fig. 136, isohaline for 32.2 per mille). Here, again, a close parallel appears from the set, as indicated by the salinity of the surface water and the probable drift tracks of bottles that went in that direction from the Cape Cod series of 1922 (series B, p. 880, fig. 174). Farther south, in the southwestern part of the area, successive isohalines for 32.5 to 33.5 or 34 per mille, closely crowded and roughly paralleling the edge of the continent, prove that the dominant set here is along the outer part of the shelf, not transverse to it, though with some tendency indicated toward an eddying movement northward toward the land to the west of Nantucket Shoals. All this, again, is at once reconcilable with the drifts of bottles set out in this side of the gulf, especially with the tracks eddying westward out of the gulf past Nantucket Shoals, and with the group that went west from the edge of the continent abreast of Cape Cod (series B, outer end, p. 882).

The failure of any evidence, by salinity, of a surface drift from the continental edge out into the ocean basin in the region, in any summer of record, is corroborated by the fact that from the outer end of line B (fig. 174) only four bottles are known to have reached the general North Atlantic drift, and so to have gone across, one to England, one to Ireland, the other to the Canary Islands and the Azores.

The distribution of salinity at a depth of 40 meters has proved extremely diagnostic of the dominant circulation of the gulf, even more so than at the surface, the chart for July and August, 1914 (fig. 145), being the most instructive because covering the area as a whole. Its most noticeable feature—a continuous tongue of water of high salinity (33 to 33.4 per mille), extending from the Eastern Channel and Browns Bank inward to the north along the eastern side of the basin as far as the mouth of the Bay of Fundy—obviously reflects an unmistakable set of water into the gulf from the edge of the continent. The surface charts, the reader will recall, show nothing of this sort, evidence that the inward current (the existence of which is proven by several lines of evidence) did not involve the superficial stratum. Neither does it draw direct from the oceanic water (which would swing the isohalines for 34 to 35 per mille into the Eastern Channel), but from the mixture that takes place between tropic water and the water of the banks along the edge of the continent abreast of the gulf (p. 842). So far as the contour of the bottom is concerned, the whole southern aspect of the gulf, from Nantucket Shoals to the vicinity of Cape Sable, is open to overflows from this same source down to a depth of 40 meters.[82] Actually, however, we have found no evidence, in salinity, of any indraft of this sort anywhere to the westward of the Eastern Channel.

The expansion of the isohalines for 33 and 32.9 per mille to the westward along the coast of Maine, and the course of the isohaline for 32.5 per mille on the 40-meter chart just mentioned (fig. 145), combined with the location of the saltest tongue close against the eastern slope of the basin, are most readily reconcilable with a dominant set northward in the eastern side of the gulf (complicated by the evidences of upwelling in the offing of the Bay of Fundy already mentioned on p. 768), veering westward along the coast of Maine, and so southward around the periphery of the gulf, finally to turn southeastward as it is directed toward Georges Bank by the slopes of Nantucket Shoals.

This essentially reproduces the anticlockwise eddy indicated by the distribution of salinity at the surface (p. 911) as well as by the bottle drifts (p. 906), but the fact that the highest salinities at 40 meters lie 10 to 20 miles out from the 40-meter contour line in the eastern side of the gulf, not close in against the latter, is evidence that the eastern side of the eddy lay farther and farther out from the Nova Scotian

---

[82] Except for the shoals on Georges Bank.

coast at increasing depths in 1914, as was also the case in August, 1913 (fig. 146). The comparative uniformity of salinity recorded over a wide area in the western side of the gulf at the 40-meter level in August, 1914, contrasted with the definitely outlined tongue of high salinity in the eastern side, points to the north-flowing side of the eddy as much more definite than the south-flowing side. In August, 1913, however, the distribution of salinity at 40 meters pointed to a closer approach to equality between the two sides of the eddy. The drift is not as clearly shown by the 40-meter salinities taken in August and September, 1915 (p. 990), except that the differential between higher salinities in the eastern side and lower ones in the western side of the gulf calls for some movement of the same anticlockwise sort, not being wholly explicable on the basis of upwelling, though assisted by that process (p. 768).

In none of these years (1913, 1914, and 1915) did the 40-meter level show the expansion of water of low salinity off Cape Ann that involved the upper 40 meters in July, 1912 (Bigelow, 1914, pl. 2; isohaline for 32.6 per mille at 25 fathoms), in a definite easterly drift. Thus, the distribution of salinity reflects much more variation, from summer to summer, at the 40-meter level in the western side of the gulf than in the eastern side, as well as at the surface (p. 770).

Unfortunately, the 40-meter chart for 1914 (fig. 145) does not so clearly show the dominant movement of water in the southwestern part of the area. However, isohalines closely crowded outside the 100-meter contour and the fact that they run parallel to the latter make it certain that no general drift was taking place transverse to the edge of the continent at the time, but that any dominant set that was then active roughly paralleled the latter. Consequently, the broad zone of 33 to 34 per mille between it and Nantucket Shoals (much more saline than any part of the Gulf of Maine at this level, but less so than the tropic water outside the continental edge) did not reflect a direct encroachment of the latter at the time or even any such movement earlier in the season, but merely reflected (by its precise salinity) the proportionate amounts in which water of higher and lower values had mingled there. However this may be, the presence of water of this comparatively high salinity to the south and southwest of Nantucket Shoals, added to rather an abrupt transition to considerably lower values (about 32.8 per mille) on the neighboring parts of Georges Bank, is good evidence that the surface drift, which has carried so many bottles out of the gulf westward across or around the shoals (p. 881), was not then operative to as great a depth as 40 meters, but that it is deflected more to the eastward, as the depth increases, by the contour of the bottom. This suggestion is corroborated to some extent by the fact that the isohalines for 33 per mille or lower include the whole eastern end of Georges Bank on the 40-meter chart in question, with an abrupt transition to much higher salinities (34.5 to 35 per mille) off its southeastern slope.

At first sight the presence of a tongue of water warmer than 10° running obliquely across Georges Bank from southwest to northeast at the 40-meter level, with lower temperatures within the gulf to the north as well as along the southeastern face of the bank (fig. 53), might seem to contradict this, but in this case salinity is the more reliable index to circulation, because the high 40-meter temperature at the station in question (10224), associated as it was with correspondingly low temperature (11.1°) at the surface, simply reflected active vertical mixing by tidal currents. Any tendency for the water to move from west to east over Georges Bank would necessarily be diverted by the considerable area shallower than 40 meters in which the bank culminates.[83] According to the rule general in the Northern Hemisphere, this shoal might be expected to act as the vortex for a clockwise circulatory movement, and the fact that the 40-meter salinity was somewhat lower on the eastern side of the bank than on the western side at the time, with the transition from values lower than 32 per mille to higher than 34.5 per mille most abrupt off its southeastern slope, is evidence of such a drift eddying eastward and southward around the shoal area.

The dominant circulation of the gulf is most clearly reflected in salinity at the time of year (spring and summer) when the regional variations in this respect are widest.

The progressive equalization of salinity that takes place during the autumn (p. 799) makes it increasingly difficult to reconstruct the horizontal circulation, even in its broadest aspects. In the midwinter of 1920–21 salinity yielded no definite evidence of any indraft into the eastern side of the gulf, either at the surface or at 40 meters (p. 804). It is unfortunate that observations could not be taken off Cape Sable during this midwinter cruise, for without such it is impossible to state whether the low values (31.2 to 31.3 per mille) recorded near Yarmouth, Nova Scotia, on January 4 (station 10501) reflected any movement of water past the cape from the eastward or were simply the product of local drainage from the land. However, it is certain that still lower salinity at the surface a few miles south of the Merrimac River, across the gulf, a few days earlier (30.02 per mille at station 10492) had the latter origin, and the rather abrupt transition appearing in both sides of the gulf on the surface chart (fig. 163) between water of low salinity (<31.5 per mille) close in to the land and considerably higher values (32.5 per mille) a few miles out at sea is definite proof that this coast belt was (or had been) drifting parallel to the shore line (if at all), not spreading inshore or offshore in either side of the gulf. However, the fact that the surface belt less saline than 32.3 per mille was much broader abreast of Penobscot Bay than in the offing of Casco Bay, on the one side, or off Mount Desert, on the other, points to some slight tendency for the water to drift out from the coast off the former, such as appears more definitely in the summer isohalines for 1912 (p. 770). Some such eddying movement is also indicated by the undulatory course of the isohalines off the mouth of the Bay of Fundy, suggesting a movement of water of low salinity out of its northern side toward the southwest, but no observations were taken close enough to the Nova Scotian side of the bay to develop the inward drift to be expected there.

The data for deeper levels were not distributed generally enough over the gulf during the midwinter cruise for safe interpretation in terms of dominant drift.

In early spring, when the discharges from the rivers increase, the courses of the isohalines become much more instructive with respect to the dominant drift, because they give a trustworthy clue to the lines of dispersal of the fresh water from the land. One of the most interesting phenomena in the hydrographic cycle of the gulf is the

---

[83] Minimum depth about 6 meters.

tendency of this water to hug the coast, not to fan out over the basin. At certain points along the coast local fishermen have long been aware that this results in a considerable southwesterly drift parallel with the coast, so much so that it is locally named the "spring current." The progressive development of a coastwise band of low salinity, which results from this event, is well illustrated by the successive surface charts for March and April, 1920 (figs. 91 and 101). Such distribution as appears on the latter and on the corresponding chart for May (fig. 120) could persist only with the water of the coastwise belt setting parallel to the general trend of the northern and western coast lines of the gulf, as already explained (p. 910). In the same way the expansion of water less saline than 32 per mille southward from the northern margin of the gulf, along its western shore, in a narrow band past Cape Ann to Massachusetts Bay, from March to April, and so out past Cape Cod toward Georges Bank by May (fig. 120), is unmistakable evidence of a general set of the surface water around the coast line along this same route.

The evidence afforded by salinity is therefore clear to the effect that when the outpouring of land water is at its maximum in spring it parallels the land, with a dominant flow alongshore from east and northeast to southwest and south, instead of spreading seaward, as happens off river mouths in many parts of the world. In other words, when the velocity of the left-hand side of the Gulf of Maine eddy is greatest it hugs the shore closest. The abrupt transition from surface salinity lower than 30 per mille to higher than 32 per mille, recorded 15 to 20 miles out from the western sector of the coast line between Cape Elizabeth and Cape Ann in May, 1915, gives a rough indication of the breadth of the zone along which the combined discharges from the Kennebec, Saco, and Merrimac Rivers are carried when the latter are in flood; and some indication that the main axis of this "spring current" is directed southward across the mouth of Massachusetts Bay, with some tendency to veer westward around the coast line of the latter after it passes Cape Ann, is traceable on the surface charts for April and May, 1925 (figs. 102 and 119), as noted above (p. 743). In this respect salinities and the drifts of bottles set out in Ipswich Bay (p. 890) prove mutually corroborative.

The charts of surface salinity for late summer for the several years, combined with the bottle drifts, suggest that the northern and western sides of the dominant eddy may be expected to trend more out from the land as the summer advances; but the isohalines point to considerable differences in this respect in different years, as just described (p. 770).

The chief line of dispersal for the discharge from the St. John River is located as tending toward the southwest past the eastern side of Grand Manan, by the sudden freshening of the surface recorded by Mavor (1923) at *Prince* station 3 from April to May in 1917 (p. 808; fig. 165), agreeing, again, with the routes probably followed by the bottles that drifted out of the bay in 1919 (p. 870); but the increase in salinity that takes place at this location from May to June and July is evidence equally positive that the velocity of this drift is at its maximum for only a few weeks (perhaps only a few days), though some movement of the surface water probably takes place in this direction throughout the year (p. 917).

The most interesting aspect of the seasonal dislocations of the isohalines in the southeastern part of the Gulf of Maine area is the light they throw on the fluctuations and lines of dispersal of the Nova Scotian current while this is flowing into the gulf from the eastward. The source of this cold water of low salinity and the chilling effect it exerts on the gulf are discussed in another chapter (p. 825), leaving for present consideration the rôle it plays in the dominant circulation of the gulf.

No dominant current of any great volume is demonstrable past Cape Sable in either direction from the salinities for August or September (though bottle drifts show the movements of water stated in another chapter—p. 908), nor in March (fig. 91); but when the Nova Scotian current commences to flood westward into the gulf in spring, its freshening effect is unmistakably reflected by a very noticeable dislocation of the critical isohalines (32 and 32.5 per mille). The seasonal schedule of this event varies from year to year, as described on page 832, 1920 being late in this respect, 1919 early, but experience in those years and in 1915 suggests that as the flow of the Nova Scotian current increases to its greatest head, it may be described as sweeping the isohalines westward before it far out into the gulf.

Unfortunately, our May cruise of 1915 did not extend to the southeastern part of the gulf, nor did the Canadian Fisheries Expedition take observations west of Halifax during that month, which leaves a wide gap for which I can not attempt to reconstruct the courses of the isohalines. However, the curves for 32 per mille salinity at the surface and at 40 meters (figs. 120 and 125) both outline the current as spreading westward from the cape toward the center of the gulf and somewhat fanlike toward the north.

This is corroborated by the fact that the *Grampus* encountered a strong set to the westward, upwards of 2 knots in velocity, on her run from the eastern side of the basin (station 10270) toward Seal Island, off Cape Sable (station 10271), on the 7th of that month. In that year, however, which may be taken as representative, the surface isohaline for 32 per mille had again withdrawn a considerable distance eastward toward Cape Sable by the last week in June (fig. 128), evidence that the westerly drift across the basin of the gulf ceased as soon as the flow of the Nova Scotian current slackened. The general distribution of salinity that characterizes the eastern side of the gulf in summer (p. 765) is best explained on the assumption that any water that rounds Cape Sable from the east during the months of July, August, and September veers northward along Nova Scotia toward the bay of Fundy, which is in accord with the drifts of the bottles that have entered the gulf from the east (p. 908).

It is obvious that the western extension of the Nova Scotian current must profoundly affect the nontidal circulation of water in the gulf at the season when it is at its maximum. Comparison of the surface salinity in May (fig. 120) with the currents deduced from bottle drifts in August suggests that this change consists chiefly in shifting the eastern side of the Gulf of Maine eddy westward—how far, can not yet be stated.

It is also obvious that if the the anticlockwise eddy persists through spring (as there is ample evidence, theoretic as well as direct) it must constantly draw into its eastern side (and so carry northward toward the Bay of Fundy and the coast of

Maine) an admixture of the colder and less saline water from the Nova Scotian current; but the details of this process and the extent to which it influences the temperature, salinity, and circulation of the northeastern part of the gulf can not be worked out until more data are gathered for the critical months of May and June.

It is much to be regretted that no records on the eastern part of Georges Bank have been obtained for June, which might throw light on the expansion of Nova Scotian water in that direction; but the fact that we have found the surface salinity considerably higher in the Eastern Channel and in the basin of the gulf near by than from Browns Bank in to Cape Sable, both in June and in July (figs. 128 and 136), shows that any movement that may take place along this zone toward the southwest in spring had ceased by the beginning of the summer both in 1914 and in 1915.

CIRCULATION OF THE SUPERFICIAL STRATUM AS INDICATED BY TEMPERATURE

The distribution of temperature is by no means as clear an index to the nontidal circulation of the surface waters of the gulf as is its salinity, because any given mass of surface water may be warmed rapidly by the sun or cooled by radiation when the overlying air is the colder without suffering any alteration in its identity by mixture with other water masses. In the deep strata, however, which are more or less insulated from these thermal influences from above, regional differences in temperature are more easily interpreted in terms of circulation.

The relationship of temperature to circulation is referred to repeatedly in other connections;[84] only the most salient aspects, then, need be referred to here.

The belt of coldest water, which fringes the shores of the gulf in winter, owes its low temperature to the chilling effects of the icy winds that blow out over it from the land. The fact that this cold band (as illustrated by the surface charts for midwinter (fig. 80) and for February to March—fig. 1) is comparatively uniform in breadth all along the northern and western shore line, is best reconciled with a set paralleling the shore. Any considerable movement of surface water either from the land out to sea or vice versa would give much more undulatory courses to the critical isotherms of 5° in December to January and 2° in February to March.

Surface water equally cold over the Northern Channel and Browns Bank on the February to March chart (fig. 1), giving place, by a rather abrupt transition, to readings 1.5° higher over the Eastern Channel, reflects the westernmost bound of the Nova Scotian current at the time; and an expansion of water colder than 4° out over the channel from the the gulf and across the eastern end of Georges Bank but not across the western end of the bank is evidence of a movement in that direction, which corresponds to the drifts of bottles set out off Cape Cod in summer (p. 886).

The undulatory course of the March isotherm for 3° gives a rather clear indication of an anticlockwise eddying movement in the central part of the gulf, with warmer water moving northward in the eastern arm of the basin and colder water drifting out from the land off Penobscot Bay, illustrating one of the varying forms

---

[84] See the chapter on temperature.

of the Gulf of Maine eddies. This same distribution of temperature, however, reappearing in April, is reminiscent of a past state of circulation, not of a present one, because the corresponding charts of salinity show the dominant set to have assumed a southwesterly course, more nearly parallel to the coast line, from the one month to the next (p. 743). Neither of these early spring charts of temperature suggest any drift of warmer water into the eastern side of the gulf from offshore; but some drift of this sort is indicated on the 40-meter chart for March (p. 525) by a band warmer than 3° entering via the Eastern Channel. This indraft appears more clearly at deeper levels (p. 526).

With the advance of spring the regional inequalities of temperature become increasingly significant, from the standpoint of circulation, as they outline the lines of dispersal followed in the gulf by the cold water of the Nova Scotian current. In general, temperature corroborates salinity to the effect that the current did not begin to flood westward past Cape Sable until after the middle of April in the year 1920, though it had exerted its chilling effect in this direction as far as the eastern side of the basin of the gulf by the last of March the year before (p. 553). The isotherms for May (fig. 27), however, suggest more of a tendency for this Nova Scotian water to spread northward toward Maine and the Bay of Fundy, as well as westward in the gulf, when at its head, than do the isohalines (p. 745).

Rising temperature, like rising salinity, reflected a slackening in the current in 1915 from May to the last half of June, when an abrupt transition in the temperature of the coldest stratum, from the Eastern Channel (about 8.1°) to the vicinity of Cape Sable (about 0.7°), located its southwestern boundary at Browns Bank. This is also indicated by the abrupt transition from colder to warmer water along the western slope of the bank at 40 meters; but the low temperatures recorded over the southwest slope of Georges Bank on the July profile for 1914 (fig. 58, p. 616)[85] is readiest explained as reminiscent of a cool current skirting the bank from northeast to south some time previous. It seems that in the cold year 1916 such a drift of cool water was either in much greater volume or persisted until later in the season, for it is difficult to account otherwise for the band of low temperature which the *Grampus* encountered over the southwestern slope of the bank that July (p. 629).

"The facts that the cold band of 1916 lay almost exactly in the prolongation of that of 1914; that a similar streak of comparatively low temperature (6.4°) was encountered at the same relative position on the shelf some 60 miles farther west in 1913 (station 10062); and that the axis of the coldest water noted on the shelf south of Nantucket in 1889 (Libbey, 1891) merely prolongs this general zone, practically amount to proof that a northeast to southwest flow of cold water takes place there annually in late spring or summer, dovetailing in between the warmer and fresher bank water on the north and the Gulf Stream on the south." (Bigelow, 1922, p. 166.) Its source is discussed elsewhere (p. 848). The July isotherms for 1914 locate its extreme western boundary between longitude 68° and 69°, where the 40-meter chart

---

[85] This also appears on the corresponding chart for the 40-meter level, but is complicated there by active vertical mixing that maintains a higher temperature over the shoal parts of the bank at this depth (lower at the surface) than on its southern side; the alternation of a warm with a cold belt along the bank, outlined in the 40-meter chart (fig. 53), is therefore partly of local origin.

(fig. 53; isotherms for 10° and 12°) suggests an eddying movement, drawing warmer water inward over the bank on the western side; but in other summers the cool drift extends much farther westward. Bottle drifts, for example, place 1922 in this category (p. 883); and Libbey (1891 and 1895) records it in longitude 70° to 71° in the summer and early autumn of 1889.

In another chapter (p. 585) I have tried to make it clear that the areas of low and high surface temperature, which characterize various parts of the Gulf of Maine in summer, are due chiefly to tidal stirring—most active over the shoal banks and in the northeastern part of the area generally, least so in the basin off Massachussetts Bay. Tidal stirring also plays a part in holding the surface temperature somewhat lower along the western margin of the gulf and around the shore of Massachussetts Bay than a few miles out at sea; but the gradation also points to some movement of the surface water eastward, away from the shore, under the impulse of the prevailing southwestern winds, an event with which bathers on our beaches have long been familiar (p. 588), and which takes part in the development of the western side of the Gulf of Maine eddy. The evidence (by bottle drifts) of a westerly set from the Nova Scotian side and from the Bay of Fundy along the coast of Maine is also borne out by the extension of surface water colder than 14° westward past Penobscot Bay in August (figs. 46 and 47) over depths so great that tidal stirring, *in situ,* is not active enough to be responsible, *per se,* for surface values as low as those actually recorded there.

The 40-meter charts for July and August (figs. 52, 53, and 54) also suggest a similar westerly drift by the isotherms for 8° and 9°, though at this depth the water moving in that direction from the Nova Scotian side is warmer than that which it replaces off the coast of Maine—not colder, as it is at the surface. (For discussion of this bathymetric difference, see p. 608).

The mutual relationships of waters warmer and colder than 9° were especially suggestive in August, 1913, as locating the vortex of the anticlockwise eddy about 60 miles south of Mount Desert and Penobscot Bay (fig. 52). The corresponding chart for 1914 (fig. 53) is not so easy to interpret in this respect, the picture being complicated in the western side by a pool of water cooler than 6°, which probably owed its low temperature to vertical stirring or to local upwelling in the mid depths.

None of the summer charts for temperature reveals any dominant movement of warm water into the gulf from offshore at the surface, nor do the 40-meter charts for the summers of 1914 or 1915, but some circulatory indraft of this sort is suggested on the 40-meter chart for 1913 (fig. 52) by temperature, just as it is by salinity (p. 782), by the warm (>10°) tongue in the eastern side of the basin, with lower temperatures on either hand, to which the reader's attention has already been called (p. 608).

At first sight the distribution of temperatures at 40 meters prevailing in July, 1914 (fig. 53), might suggest a drift into the gulf from offshore across the eastern end of Georges Bank, but a closer analysis makes it clear (p. 617) that in this case unity of temperature had a local significance only, being an adventitious result of the fact that vertical mixing was most active on the northern part of the bank.

CIRCULATION IN THE DEEP STRATA AS INDICATED BY TEMPERATURE AND SALINITY

Dawson's (1905) observations made it known that the tidal currents of the eastern side of the gulf run about as strongly down to a depth of 55 meters as they do at the surface, and measurements taken at 5 stations by the *Grampus* in the summer of 1912 showed bottom currents varying in velocity from 0.1 to 0.25 knot per hour in depths of 100 to 265 meters (Bigelow, 1914, p. 86). Evidently, then, the basin of the gulf is constantly in a state of active circulation right down to the bottom, its whole mass of water oscillating to and fro with the tides, though with velocities somewhat lower in the deep water than at the surface.

Up to the present time no attempt has been made to determine the nontidal movement of the bottom water of the gulf with current meters or by the use of deep drift bottles, such as have proved so instructive in the North Sea, but the regional differences in temperature and salinity outline the major movements over the bottom.

At depths greater than 100 meters the gulf of Maine is an inclosed basin with the narrow Eastern and Northern Channels as the only possible entrances or exits through which water can flow in or out of its basin. It follows from this that any deep current into the gulf can enter only in its eastern side. Such entrance might be via either of the two channels or through both, so far as the contour of the bottom is concerned. Actually, however, salinity and temperature show that the indraft of slope water over the bottom is restricted to the Eastern Channel, the abrupt west-east transition in salinity and in temperature, which characterizes the Northern Channel, being incompatible with any large transference of bottom water through the latter in either direction.

The dominant drift in the eastern side of the Eastern Channel is clearly northerly (into the gulf) at all times of year, but a considerable difference between high values of temperature and salinity in the eastern side of the channel and lower values in its western side in March, April, and July (pp. 770, 789) point to an outflowing current via the latter, continuing southward and westward around the slope of Georges Bank.

Slope water is betrayed in the deep strata of the gulf by its high salinity (33.5–34 per mille, p. 849) and moderately high temperature (4.5° to 8°). At the 100-meter level the isotherms and isohalines show the inflowing current hugging the eastern slope of the basin in March as a rather definite tongue of high temperature and salinity (figs. 13 and 94), veering westward around the northern side of the basin, with a countermovement of cooler and less saline water setting southward and eastward around the southern side of the basin. In fact, physical evidence could hardly be clearer that the general Gulf of Maine eddy was effective to a depth of at least 100 meters in this particular month, though complicated by an indraft through the Eastern Channel in the deeper levels, which did not directly affect the surface (p. 704).

An anticlockwise circulation is also indicated on the 100-meter charts for April (figs. 25 and 116), though less clearly, by concentration of the highest salinities and temperatures in the eastern and northern parts of the basin, the lowest in the western and southern parts. In this case, however, the westerly component involved a broader and less definite band off the coast of Maine than in March, and the easterly component of the eddy had shifted southward to skirt the northern slopes of Georges Bank more closely.

Information as to the movement of water along the bottom of the Northern Channel is much to be desired at the season when the Nova Scotian current is flooding in greatest volume into the gulf. Some drift may be assumed to take place into the gulf by this route as deep as 100 meters in 1915, to account for the concentration of the most saline water in the western side of the basin at the 100-meter level in May (fig. 127), instead of in the eastern side, as at other times of year. It is probable, therefore, that when the drift past Cape Sable is at its maximum it causes a westerly shift in the vortex of the general eddy in the mid depths, though not essentially altering the anticlockwise type of circulation, however. Any westerly drift that may have taken place along the bottom of the Northern Channel in 1915 had ceased by June; on this basis, alone, is the abrupt east-west transition that appears there on the 100-meter chart of temperature for that month explicable (fig. 43).

In midsummer the transition from lower salinities and temperatures in the western side of the gulf to higher in the eastern, at the 100-meter level, and the sweep of the successive isohalines and isotherms from east to west along the northern slope of the gulf, again give evidence of a general set northerly past Nova Scotia and westerly along the coast of Maine in the mid depths, paralleling the dominant circulation at the surface. The nontidal movement of water of the southern side of the basin at this level is not so clear, the picture being confused by an area of relatively high salinity and temperature off the northern slope of Georges Bank near the entrance to the Eastern Channel, which is not easy to account for.

In spite of this and of other apparent anomalies the distribution of temperature and salinity in the mid depths, as exemplified by the 100-meter level, are, as a whole, compatible with the domination of the basin by the general Gulf of Maine eddy, anticlockwise in character.

The horizontal circulation of the gulf at greater and greater depths is more and more directed by the contour of the bottom, which gives the basin the outlines of a Y, with two arms uniting and open to the Eastern Channel (p. 784) at 175 meters, but entirely inclosed at 200 meters and deeper.

With temperatures and salinities recorded at one deep station or another for so many months and years, it can be stated confidently that the movement of bottom water inward into the gulf takes place in pulses, the secular fluctuations of which have only been glimpsed as yet (p. 850). On the other hand, dynamics (fig. 204) and the distribution of temperature and salinity point to some outgoing drift via the western (Georges Bank) side of the Eastern Channel between these pulses in summer (pp. 789, 852).

The presence of water of high salinity (34 per mille) in both arms of the trough but never (so far as yet recorded) over the submarine ridge that separates them is good evidence that the latter divides the slope water as it drifts inward in the deepest stratum of the gulf.

Two separate anticlockwise eddying drifts are indicated in the bottoms of the two arms of the trough, at depths of 175 meters and deeper, by salinities and temperatures averaging somewhat higher on the side that would be to the right, for an inflowing current, than on that to the left (p. 785). The circulation in each may therefore be described as "estuarine," subsidiary to the estuarine circulation of the basin of the gulf as a whole, inward along the right-hand (eastern and northern) sides and eddying to the left. The regional difference between the right and left sides being widest in the eastern trough, with the maximum values of salinity and temperature both higher there than in the western, a greater volume of slope water continues northward over the bottom toward the Bay of Fundy (and at a greater velocity) than is diverted to the westward by the ridge that culminates in Cashes Ledge.

CIRCULATION AS INDICATED BY THE PLANKTON

The tracks which immigrant members of the planktonic community follow into the gulf and in their further wanderings within it are discussed in such detail in the preceding number of this volume (Bigelow, 1926, p. 51), to which the reader is referred for details, that the briefest of summaries will suffice here. Immigrants of this category, whether from tropic or from northern sources, enter the gulf in the eastern side; seldom or never across its offshore rim farther west. (Bigelow, 1926, figs. 31 32, 33, 69, 71, and 72.) The relative regional abundance of our northern copepods, *Calanus hyperboreus* and *Metridia longa* (Bigelow, 1926, figs. 71 and 76), clearly pictures the drift westward into the gulf from the offing of Cape Sable and westward along the offshore slope of Georges Bank in the spring; and the records for the more delicate northern visitors—Mertensia, Ptychogena, *Oikopleura vanhöffeni*, and *Limacina helicina*—are chiefly confined to the area on the eastern side, where the water is most chilled by the Nova Scotian current.

Clearest evidence of the drift within the gulf is afforded, of course, by such species as are comparatively short lived there and can not reproduce in its low (or high) temperature. The records for these in the upper 40 meters or so have been constantly confined to a rather definite belt paralleling the coast around from the Nova Scotian side to the offing of Massachusetts Bay, leaving the central and southern parts of the gulf bare (Bigelow, 1926, fig. 31). A distribution of this sort is reconcilable with an eddying drift inward, anticlockwise around the gulf; in fact, it is explicable on no other reasonable assumption, and this corroborates the drift-bottle experiments. A drift of this same sort from the coast of Maine westward and southward toward Cape Cod is also made probable by the relative distribution of buoyant fish eggs and of larval fishes (Bigelow, 1926, figs. 34 and 35). Planktonic animals that enter the gulf in the mid levels via the Eastern Channel (*Eukrohnia hamata*, for example) parallel the surface communities in their general drift northward, westward, and southwestward, except that they are held farther out in the basin by the contour of the bottom; but visitors characteristic of the deepest water of the gulf (e. g., *Sagitta maxima*) follow the two arms of the Y-shaped trough, just as might be expected from the drift of the slope water, as indicated by the salinity (p. 922).

The comparative scarcity of animals of coastwise or shoal-water origin over the deep basin of the gulf (Bigelow, 1926, p. 32), like the distribution of salinity, is evidence of a circulatory system paralleling the coast, not fanning out in the offing of the river mouths.

VERTICAL STABILITY AS AFFECTING THE CIRCULATION OF THE GULF

A clue to the relative strength of vertical currents in different parts of the gulf during the warm months is afforded by the relative degree of vertical stability of the water that opposes them.

The relationship between vertical circulation and stability is simple. Whenever or wherever the water is so nearly homogeneous as to the density that it has little or no vertical stability (as is the case in the coastwise belt of the Gulf of Maine in winter), vertical mixings or upwellings freely follow the tidal circulation and the disturbing effects which the wind exercises on the surface; but if the superficial stratum be made much lighter than the underlying stata by freshening or by solar warming, it requires a considerable expenditure of force to drive the light surface water down or to bring heavy water up from below. It is conceivable, also, that the column might become so stable as to effectually insulate the deeps from any influence from above.

The activity of vertical circulation at any time or place in the gulf, therefore, depends on the momentary balance between the mixing tendency of the tides, etc., and the degree of vertical stability by which this is opposed.

It is important to bear in mind that any given particle of water has no stability *per se*, but only relative to the water above and below it. It is usual, therefore, in hydrodynamic calculations, to state the stability for strata of convenient thickness.[86] Being strictly a function of the density of the water, a simple visual measure of its relative value is afforded by the usual curves for density, plotted against depth, remembering that the more the curves depart from the vertical, the higher the stability, and that it is zero throughout any stratum where the curve is vertical.

Regional variations in this respect may be represented graphically by plotting the differences in density between the surface and some underlying stratum chosen as a base, as in Figure 185. The greater the difference, the the more stable the water.

In the Gulf of Maine the tidal currents are strong enough at all depths to effect an active mixing of the water, were they unhindered; and the consumption of slope water that takes place in the inner part of the basin (p. 941), with its constant replenishment from offshore, is unmistakable evidence of some interchange between surface and bottom. The prevalence of a decided contrast in salinity between the superficial and deep strata throughout the year proves this interchange a slow process, however, wherever the water is more than 100 meters or so deep. The limiting factor here is the stability of the water, for the specific gravity of the slope water in the bottom of the gulf is always considerably higher than that of the superficial stratum, even in winter, when the latter is heaviest and itself has little or no stability.

The gulf as a whole, then, is always in a state of stable equilibrium, whatever may be the state of the water near its surface; and while not sufficiently so to prevent vertical mixing from taking place constantly, we have no record of slope water welling up to the surface from the bottom of the trough, nor is such an event to be expected.

---

[86] The unit of stability usually employed is the number of surfaces of equal specific volume per 10 meters of depth, represented graphically by vertical lines varying in breadth according to the stability of the water in the several strata. (Sandström, 1919, p. 283.)

The vertical stability varies little from season to season in the bottom stratum deeper than 100 meters, indicating comparative uniformity in the activity of vertical circulation there; but wide seasonal fluctuations in the stability of the superficial stratum reflect corresponding differences in the stirring effects of the tides, etc.

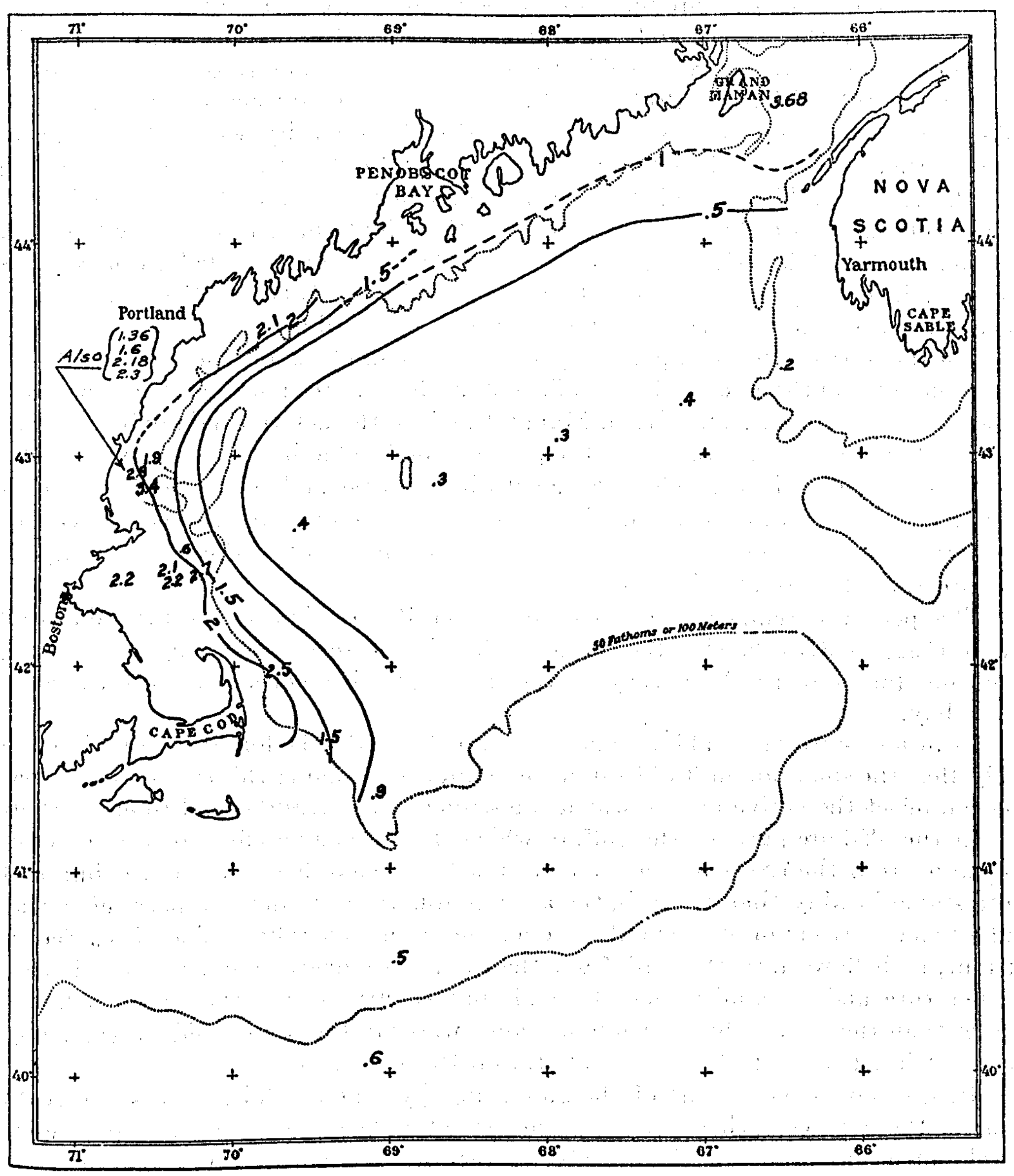

FIG. 185.—Difference in density between the surface and the 40-meter level for May, 1915 and 1920. Corrected for compression

In northern coastal waters generally (the Gulf of Maine is no exception) vertical mixing of the upper 100 meters is most active during the coldest season, when, thanks to low surface temperature, the water has little stability; and it is at this season that the consumption of slope water is most rapid. From March to April, however, vertical currents in the coastal belt between Cape Cod and Cape Ann are suddenly opposed by the increase in stability effected by the combined effect of the freshening of the surface by the river freshets and of the rising surface temperature. Together these processes produce an average difference of about 2 to 3.5 units of density between the surface and the 40-meter level in this zone by May (fig. 185). The most stable state yet recorded in the gulf was off the mouth of the Saco River on April 10, 1915 (Bigelow, 1914a, p. 417), when very low surface salinity (26.74 per mille) was responsible for a vertical range of 4.53 in density within this stratum, showing that vertical mixings had virtually ceased, for the time being. May also sees the rather sudden establishment of a high degree of stability in the Bay of Fundy consequent on the sudden lowering of the salinity of the surface by the freshets from the St. John River (p. 808), Mavor (1923) having recorded a difference of about 3.7 in density in the upper 40 meters on May 4, 1917, at *Prince* station 3, where the water had been virtually homogeneous on April 9.

The Penobscot freshet apparently has much less effect on the stability of the water off its mouth; and without sufficient inrush of fresh water along the coast between Penobscot Bay and Grand Manan to offset the active tidal mixing, we find that in May the upper stratum of the gulf is most stable in its two opposite sides, viz, Massachusetts Bay to Cape Elizabeth in the west and in the train of the St. John River in the Bay of Fundy in the east. Consequently, the active vertical circulation that characterizes the Bay of Fundy during most of the year is temporarily interrupted there at this time.

This period of temporary quiescence for the Bay of Fundy is of brief duration, Mavor (1923, p. 375) showing the 40-meter stability decreasing again by June to only about one-fourth of the May value as the river water is incorporated into the water of the bay.

I can not state the stability along western Nova Scotia for May; but it is not likely that the small amount of fresh water emptying in along this sector of the coast line can offset the active mixing which the strong tidal currents tend to effect there.

In the offshore parts of the gulf, to which the freshening effect of the increased discharge from the rivers has not yet extended, the superficial stratum is but little more stable in May than in April, the average difference in density between surface and 40 meters rising only to about 0.3 over the basin generally. The Nova Scotian current, as it flows into the gulf from the east, is so nearly homogeneous, both in temperature and in salinity, that it, too, is but slightly stable, though considerably lighter than the warmer but much more saline water in the eastern side of the trough over which it floats (cf. the density at station 10270, p. 988).

In the southwestern part of the gulf generally, where tidal currents are weaker than in the northeast, their mixing action is not sufficient to prevent a progressive development of stability in the upper 40 meters through April, May, and June as the surface warms; and as soon as the surface temperature has risen appreciably above that of the underlying water, upwellings are readily recognized by their chilling effect.

As remarked in another chapter (p. 550), water often wells up from below along the western side of the gulf in spring, when offshore gales drive the surface water out to sea. Bathers on New England beaches also are familiar with this same event in summer (p. 588). The fact that the surface averages somewhat cooler along the coast at that season, from Cape Cod to Cape Elizabeth, than a few miles offshore probably reflects the cumulative effect of such upwellings following the prevailing southwesterly winds. No doubt this happens still more frequently there in winter, when northwest gales are frequent, though it is not so easily recognizable then. In the opposite side of the gulf the tendency is the reverse—i. e., the surface water is driven in against the shore and sinks; and with vertical mixing by the tides so active that

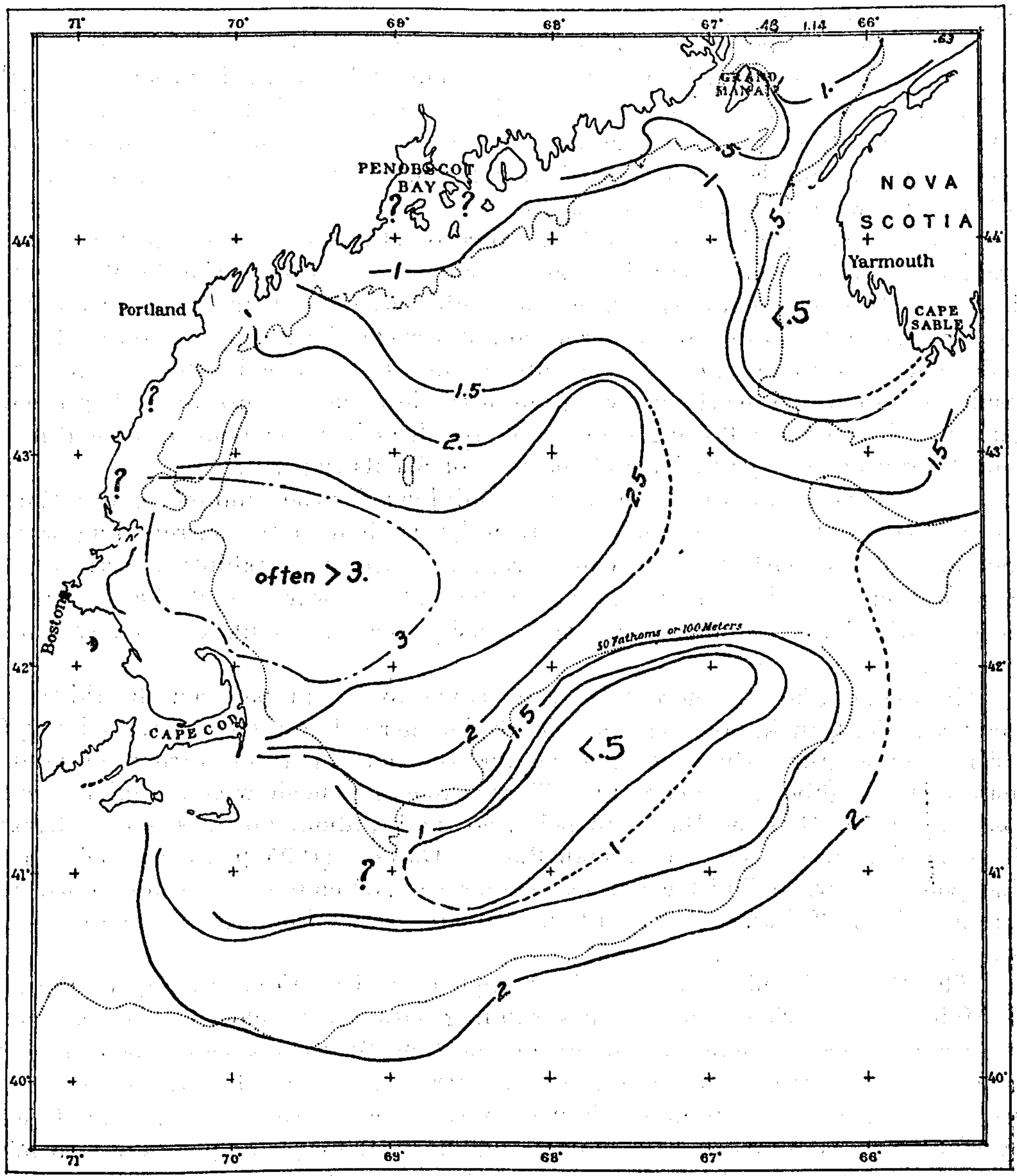

FIG. 186.—Difference in density between the surface and the 40-meter level in July and August for the several years of record, combined. Corrected for compression

but little stability develops there, more or less overturning of this sort probably takes place along the coast of Nova Scotia even at the warmest season. The frequency with which bottles have stranded there after drifting across the gulf may be explained on this assumption.

The upper 40 meters of the southwestern part of the gulf attains its highest stability during the last half of July and first half of August, being then most stable off Massachusetts Bay and out to Cashes Ledge (fig. 186); but the Bay of Fundy as a whole is hardly more stable then than in winter, with a gradation from southwest to northeast around the north shore of the gulf,[87] paralleling the degree of stratification of the water with respect to temperature (p. 596).

These regional differences reflect corresponding differences in the vertical circulation. In the one case this is active enough to prevent the development of the stable state by keeping the water thoroughly stirred, but in the other mixing is not rapid enough to prevent the formation of a warm, light, surface layer, which, as it develops, retards vertical movements of any sort. The insulating effect that results is responsible for the preservation of the low temperature of each preceding winter well into the following summer, in the deep bowl off Gloucester and in the trough between Jeffreys Ledge and the Isles of Shoals (fig. 70).

The following rule, therefore, may be laid down for the summer season: Wherever in the gulf the surface temperature is lower than in the surrounding waters, and the water is nearly homogeneous vertically (with little stability), vertical circulation of some sort is active; but where the water is warmest at the surface and most stratified as to temperature and density vertical circulation of any kind is weakest.

Nantucket Shoals, where tides run strong over and between the ridges and channels, afford an interesting example of the thermal result of active mixing, the surface temperatures there being lower but the bottom water warmer in summer than in the neighborhood generally. These same criteria show active mixing on the eastern side of Georges Bank; likewise, no doubt, about Georges and Cultivator Shoals. This also applies to German Bank. Dawson (1905, p. 15) has pointed out that pools or " wakes" of low surface temperature, extending north and south from Lurcher Shoal off Yarmouth, result in the same way "from the stirring up of the water."

The Bay of Fundy is the classic example of violent tidal stirring for the Gulf of Maine region, where the currents, running with great velocity over the shoals at its entrance and among the islands off the New Brunswick shore, keep the water mixed, top to bottom, throughout the summer, a fact referred to repeatedly in the preceding pages. This peculiar circulatory state of the Bay of Fundy, made clear by Huntsman, is of far-reaching biologic significance; for, as he points out, so low a surface temperature is thereby maintained throughout the summer that "conditions approximating those in the far North are produced in shallow water" (Huntsman, 1924, p. 281).

The rush of the tides between the islands along the coast of Maine, east of Penobscot Bay, is similarly reflected in low stability and slight thermal stratification (p. 599).

---

[87] Only about one-third as stable near Mount Desert and one-tenth as stable near Grand Manan as at the mouth of Massachusetts Bay.

The courses of the curves for 1.5, 2, and 2.5 units of density on the chart (fig. 186) give evidence that the shoal ground off Penobscot Bay and out to Cashes Ledge also is the site of considerable vertical disturbance as the tidal currents are deflected by it.

As summer passes into autumn and the surface waters commence to cool, the parts of the gulf that are most stable in summer become less and less so, with little change in the eastern part, where the whole column of water loses heat more uniformly. The result is that vertical mixing is less and less opposed in the western part of the gulf and regional differences decrease in this respect.

The autumnal decrease in stability is illustrated for the southwestern part of the gulf, generally, by the offing of Cape Ann, where the upper 40 to 50 meters lose stability most rapidly during the early autumn, then more slowly but constantly through the winter. At depths greater than 100 meters no regular seasonal succession appears, all the curves being roughly parallel, their differences attributable to annual fluctuations in temperature and salinity. The seasonal succession is essentially of this same kind in the deep water in the northeastern corner of the gulf, though, thanks to strong tidal currents, the seasonal range of stability in the upper 40 meters (expressed in terms of density) is only about one-third as wide here as it is off Cape Ann.

Stability offers but little opposition to the free vertical circulation of water in any part of the gulf after November; less near the surface than at greater depths, as appears from the following table for October and November of 1916:

Vertical range in density for the superficial stratum and for the mid stratum

Station	0 to 40 meters	40 to 100 meters	Station	0 to 40 meters	40 to 100 meters
10399	0.79	1.00	10402	0.12	1.00
10400	.54	.90	10403	.55	1.30
10401	.51	1.35			

The free mixing that takes place from that time on throughout the winter is illustrated by the uniformity with which the upper 50 to 100 meters cool off during December, January, and the first half of February; evidently, water is constantly being brought up to the surface from below, there to radiate its heat, and water cooled at the surface is as constantly sinking.

It is not necessary to follow in detail the changes in stability that take place in winter in this connection. It is lowest over the gulf as a whole at the end of February or first of March, when the difference in density between the surface and the 40-meter level has been only 0.1 to 0.33 for all our stations on the banks and within the gulf, except at one off the Kennebec River (station 20058).

In fresh-water lakes, in high latitudes, autumnal cooling increases the density of the surface until a dynamic overturning of the water regularly follows. Our first winter's work in Massachusetts Bay (Bigelow, 1914a, p. 387) suggested that this same process was partly responsible for the rapid chilling that takes place there; but subsequent study, and especially the observations made in the bay from the *Fish Hawk* in 1925, proves this earlier interpretation erroneous and make it unlikely that dynamic overturning ever occurs in the open gulf, unless on a small scale and confined to a very thin superficial stratum. This statement is based on the fact that the density has been slightly lowest at the surface at all our winter stations, when compression is allowed for, though without this factor the surface stratum would often appear heaviest. It is true that the stability of the water is virtually *nil* in winter; but tidal stirring and the stirring effect of the wind are everywhere so active during the cold months that they more than keep pace with the chilling of the surface by constantly bringing up new water from below to take the place of the surface layer as the latter chills and before it is heavy enough to sink.

The thermal effect of mechanical mixing is essentially the same as that of dynamic overturning, however—i. e., to bring the whole column of water within the chilling influence of the low air temperatures. It is possible that dynamic overturning does occur locally in the coastal zone, but it has not actually been recorded there.

Vertical dynamic circulation of another sort was observed in Massachusetts Bay in February, 1925, where water, chilled at the surface close to the land, was moving offshore on the bottom, and with surface water from offshore moving in above it to take its place, as described above (p. 659). A more detailed survey of the temperature of the coastal belt in winter may show that circulation of this sort is more widespread than appears from observations taken so far.

DYNAMIC EVIDENCES OF CIRCULATION

CONSTRUCTION OF DYNAMIC CHARTS

Given a difference of pressure between any two stations in the sea, a current will result as surely as water will flow out through a dam when the sluice gate is opened, unless opposed by a stronger counterforce or an unpassable barrier. Even a preliminary examination of the dynamics of the gulf (and no more is attempted here) may be expected greatly to amplify such knowledge of its dominant circulation as has been gained from the more direct lines of evidence discussed in the preceding chapters.

The method of attack chosen here is that of the dynamic-contour chart, widely employed by European oceanographers and recently described by Smith (1926). For the sake of the nontechnical reader, an explanation of the principles involved in its construction and its interpretation are attempted here in the simplest possible language.[88]

In the sea, gravity, acting always directly downward, will set the water in motion if its surface slopes at all; and even if the surface of the water be level, currents will be caused if its specific gravity is greater at one place than at another, because the pressure exerted by the water at a given depth must then vary correspondingly, and the plane at which the pressure is uniform must be oblique to the pull of gravity. All this is embodied in the old adage, "water seeks its own level."

Although the physical principles that govern the gradient currents in the sea are simple, calculation of the drifts that will actually result from any given distribution of specific gravity is so complex that Bjerknes's (1898, 1910, and 1911) illumi-

---

[88] See also Sandström (1919) for a simple explanation of hydrodynamic principles.

nating application of mathematical methods first offered a practical and easy method of solution.

Since that time European, and especially the Scandinavian, oceanographers have devoted much attention to the dynamic calculation of ocean currents, with such success that great advances in our knowledge of oceanic circulation are to be expected. Sandström (1919) has also studied the dynamics of Canadian Atlantic waters; Wüst (1924) of the straits of Florida and neighboring parts of the Atlantic; and Smith (1926, 1927) of the "Labrador" and "Gulf Stream" currents around the Grand Banks.

The simplest and most graphic method of learning the directions followed by the dynamic circulation in any sea area is by a horizontal projection showing (by contour lines) the regional variations in the thickness of the column of water included between the surface of the sea and the level at which some given pressure, equal for the whole area, is reached.

If the specific gravity[89] of the water is regionally uniform over the whole area, the depth of the layer so bounded will equally be uniform, and there will be no dynamic flow from any one part of the picture to any other; but if the weight of an equal thickness of water be greater (i. e., its specific gravity higher) at one locality than at another, a lesser thickness will produce a given pressure at the heavy station rather than at the light, and such a flow will tend to develop.

Consequently, calculation of the height of the column of water necessary to exert a given pressure for any two stations will give the dynamic tendency existing between them in the stratum included in the calculation; and if the survey can be extended to include a number of stations, scattered netlike over any part of the sea, we arrive at the dynamic gradients for the whole area.

This calculation is based on the principal that the pressure exerted by a column of water of unit area is the product of three arguments—its height, its specific gravity, and the acceleration of gravity; and if the first and the last of these be combined into dynamic units of measurements, as explained below (p. 932), pressure may be stated still more simply as equal to the height of the column (in dynamic units), multiplied by its specific gravity. Or, conversely, the height of the column (in dynamic units) will equal the pressure it exerts, multiplied by the reciprocal of the specific gravity of the water, namely, by its specific volume.

For example, if the specific gravity of a given column of water be 1.026, and it be desired to find the height or depth (in dynamic units) necessary to exert 50 units of pressure, we have: Specific volume $0.97466 \times 50 = 48.73300$ dynamic units of depth. If at a neighboring station the specific gravity is only 1.022, 48.92350 units of depth will be requisite to effect this same pressure, so that there will be a dynamic slope between the two stations of 0.2 dynamic units of height (or depth).

---

[89] A brief definition of the much-abused term "density" as employed to express the specific gravity of sea water follows:

In hydrodynamic calculation what is important is the specific gravity that the water in question actually possessed at its temperature at the time and under the pressure to which it was actually subjected—i. e., *in situ;* not that which it might have possessed at any other temperature or depth.

The specific gravity of sea water differs from that of distilled water only in the second and subsequent decimal places. To avoid the use of such long decimal fractions it is usual to subtract 1 and to multiply by 1,000, substituting the term "density" for "specific gravity." For example, the density of sea water of a specific gravity of 1.025 is stated as 25.00.

Specific volume (merely the reciprocal of density) is the more convenient value to use in numerical calculations.

The practical application of this theorem to hydrographic problems thus hinges on the selection of suitable unit values for thickness and for pressure; the selection of such was not the least of Bjerknes's contributions to dynamic oceanography.

The force responsible for dynamic currents in the sea is that of gravity—not the capacity for work inherent in the water itself because of its mass. Consequently, the unit of height (or thickness) used in hydrodynamic calculations must not only stand in a linear relationship to the unit of pressure, but it must also be a direct measure of the potential force of gravity, which accelerates all falling bodies equally, irrespective of their mass. The gravity potential set free when a unit mass of water flows down a sloping surface is the product of two arguments—(1) the vertical difference in height and (2) the accelerating force of gravity. The latter being about 9.8 meters per second, the dynamic value of 1 meter of linear height must (in the meter-ton-second system) be stated as 9.8 units. Thus, gravity performs one unit of work in $\frac{1}{9.8}=0.102$ meters, so that one dynamic decimeter = 0.102 meters, or one dynamic meter = 1.02 common meters. For the reason just stated this relationship between dynamic and common linear measure is constant, no matter what the density of the water under study may be.

It is not practical to make direct instrumental measurement of the pressure below the surface of the sea; this can be deduced only from measurements of the temperature and salinity, and these must be taken at predetermined depths.

To calculate the thickness of a column of water that will exert any given pressure—say 100 units—the first step then is to establish the specific volume. This decreases in the sea with depth; consequently, to learn the mean specific volume it is necessary to determine the value not only for the top but also at the bottom of the column. If we could know before hand how deep it would be necessary to lower our instruments in order to do this—in other words, if the pressure unit of thickness could correspond to the ordinary linear measure—evidently the procedure would be vastly simplified. Strictly speaking, this is impossible because the linear value of this pressure unit *must* vary with the specific volume of the water. In practice, however, as Bjerknes and Sandström and Helland-Hansen (1903) have explained, this objection vanishes because the specific volume of the water varies only so very slightly with depth that the value will be given for the bottom of the chosen pressure column if the readings are taken within a few meters of it, whether shoaler or deeper.

Consequently, if a pressure unit can be found, which shall nearly (even if not quite) correspond to the ordinary linear measure, we can learn the specific volume where the pressure is, say, 100 units, simply by measuring the specific volume at a depth of 100 meters. The selection of such a unit we owe to Bjerknes, who proposed the "bar" to be equal to the pressure exerted by 10 dynamic meters (or 10.2 common meters) of fresh water, not under compression, and at the temperature of its maximum density. By the theorem stated on page 931, that pressure is the product of linear height, specific gravity, and acceleration of gravity, the "bar" will then equal 9.9 meters of salt water 35 per mille in salinity and 0° in temperature, so that a decibar is virtually 1 meter of sea water. For the reasons just stated, if the salinity and temperature be taken at any chosen number of meters below the surface this will give the specific volume where the pressure is that same number of decibars. Thus, if in the example given on page 931 we read dynamic meters instead of units of thickness, the corresponding units of pressure will be 50 decibars.

If the dynamic depth to which it is necessary to descend into the sea to reach a given pressure be greater at one station than at another (as is necessarily the case if the specific gravity of the water varies regionally), only two alternative states are possible: (1) If the surface of the water is level, the given isobaric surface (surface at which the pressure is equal) must slope; or (2), if this isobaric surface is level, the surface of the sea must slope. The resultant circulation will differ accordingly.

If the first alternative actually prevailed, the obliquity of the isobaric surfaces would increase with depth and the dynamic circulation would be most rapid at the bottoms of the deepest oceans. However, as Sandström (1919) and Smith (1926) both have emphasized, this is directly contrary to the truth, for the bottom waters of the ocean show only very slight regional variations in specific gravity and move only with inconceivable slowness. Consequently, when a dynamic gradient exists over any part of the sea it is the surface that slopes. It is of the greatest importance to keep this concept constantly in mind, because the conventional dynamic representations in profile show the surface as level, and hence are likely to prove misleading.

If, then, the isobaric plane chosen as the base for reference.in our calculations lies so deep that it is level, or virtually so, calculation of the thickness of the column of water necessary to effect this pressure for a number of stations shows the actual contour or shape of the surface of the sea. Dynamic-contour charts of the deep oceans, such as have been constructed by Helland-Hansen and Nansen (1926) and by Smith (1926), are cases in point. In shoaler waters, however, where surfaces of equal specific gravity, and consequently the isobaric surfaces, are oblique right down to the bottom, the calculated dynamic slope of the surface of the sea will either exaggerate or minimize the true slope of the latter.

This is the case in the Gulf of Maine. Consequently, the dynamic charts offered here can be taken only as a rough approximation to the state actually prevailing.

The actual charting of the dynamic gradients in horizontal projection is hardly as simple as the foregoing résumé might suggest because of the necessity for intergrating the individual values for specific gravity at the levels of observation to arrive at the mean values for the included intervals; because, also, the specific gravities must be converted into specific volumes, and because the latter must be corrected for compression. The last two steps, however, are robbed of all difficulty by Hesselberg and Sverdrup's (1915) tables, as simplified by Smith (1926, p. 18, Tables 3 and 4). Smith (1926) has so fully explained the construction of the dynamic chart, as well as the principles involved, in a publication universally accessible, that only one aspect of the procedure needs further comment here, namely, the modifications necessary in studying an area so shoal and with stations differing so widely in depth that it is not possible to refer all the calculations to any one isobaric base plane. In this case it is necessary to calculate the gradient between pairs of adjacent stations, afterwards referring all to some one chosen station. Furthermore, if the specific volumes of the water at the two members of each pair of stations are not the same at the greatest depth reached at the shoaler, it is obvious that the intervening mass of bottom water deeper than that level must be in dynamic circulation;

hence, it must be taken into account in some way in calculating the dynamic slope at the surface.

Jacobsen and Jensen (1926) have very fully discussed this question in their dynamic study of the Faroe Channel, finding that in most cases this effect of the bottom water may be sufficiently allowed for by arbitrarily applying to the dynamic gradient between the two stations in question the product of the difference in specific volume between them at the deepest level of the shoaler station multiplied by half the difference in depth. If the station where the calculation shows the surface as highest also has the largest specific volume at the deepest level of the shoaler of the pair, the gradient is to be increased by the amount of this correction—decreased if the reverse obtains. If the difference in depth be greater than, say, 150 meters or so, no arbitrary correction of this sort can be relied upon, consequently the dynamic gradient can be stated only within very wide limits. The only cure is to establish the stations closer together on future cruises.

The dynamic-contour chart[90] closely resembles an ordinary weather map in its general appearance, and it is as easily interpreted in terms of the resultant circulation. Dynamically, the water tends to flow down the slopes from the parts of the picture where the surface stands high to those where it is low, and at right angles to the contour lines. Actually, however, this could happen only at the equator. Everywhere else the effect of the earth's rotation so deflects this motion that the stream lines come nearly to parallel the contour lines, which may then be taken as directly representing the current, just as the direction of the wind is roughly parallel to the isobars on the weather map.

In the open ocean, where tidal currents are weak, the contour lines may even approximate the tracts of the particles of water if approximately constant acceleration has been established. This, however, does not apply in a region such as the Gulf of Maine, where the tidal currents average much stronger than the dynamic tendencies. In this case the latter act only to give to the tidal flow a character more definitely rotary than would otherwise be the case, or to strengthen the one tide at the expense of the other. Here the dynamic-contour lines show only the general advance which the water tends to make good in its tidal oscillations to and fro.

Because in every case the datum plane for the calculation is necessarily the underlying water, not the solid bottom of the sea, the motion indicated by the chart is not absolute, but is only relative to that of the deepest stratum of water included in the picture. If this be motionless, the calculated drift represents the actual motion of the surface (or chosen level) relative to the coast line, but not otherwise.

In the Northern Hemisphere, where moving bodies are deflected to the right, the direction of flow, relative to the plane of reference,[91] is to be identified by the rule that the gradient current will constantly have the lightest water (i. e., the highest surface) on its right hand, the lowest surface on its left, as it veers cyclonically around the latter. If the surface drift be faster than the bottom drift, as is usually the case, this indicated direction of flow will also be the true direction, relative to the bottom; so, too, if bottom and surface drifts be parallel, whichever

---

[90] Dynamic-contour charts may as easily be constructed for any desired depth below the surface of the sea, as described by Smith (1926).

[91] In the Gulf of Maine this is the bottom water between the pairs of adjacent stations.

is the stronger. But if the bottom current be the stronger, and both currents are opposite or diverge by a considerable angle (as may rarely be the case in shoal water, though perhaps never in deep), the method is made unreliable.

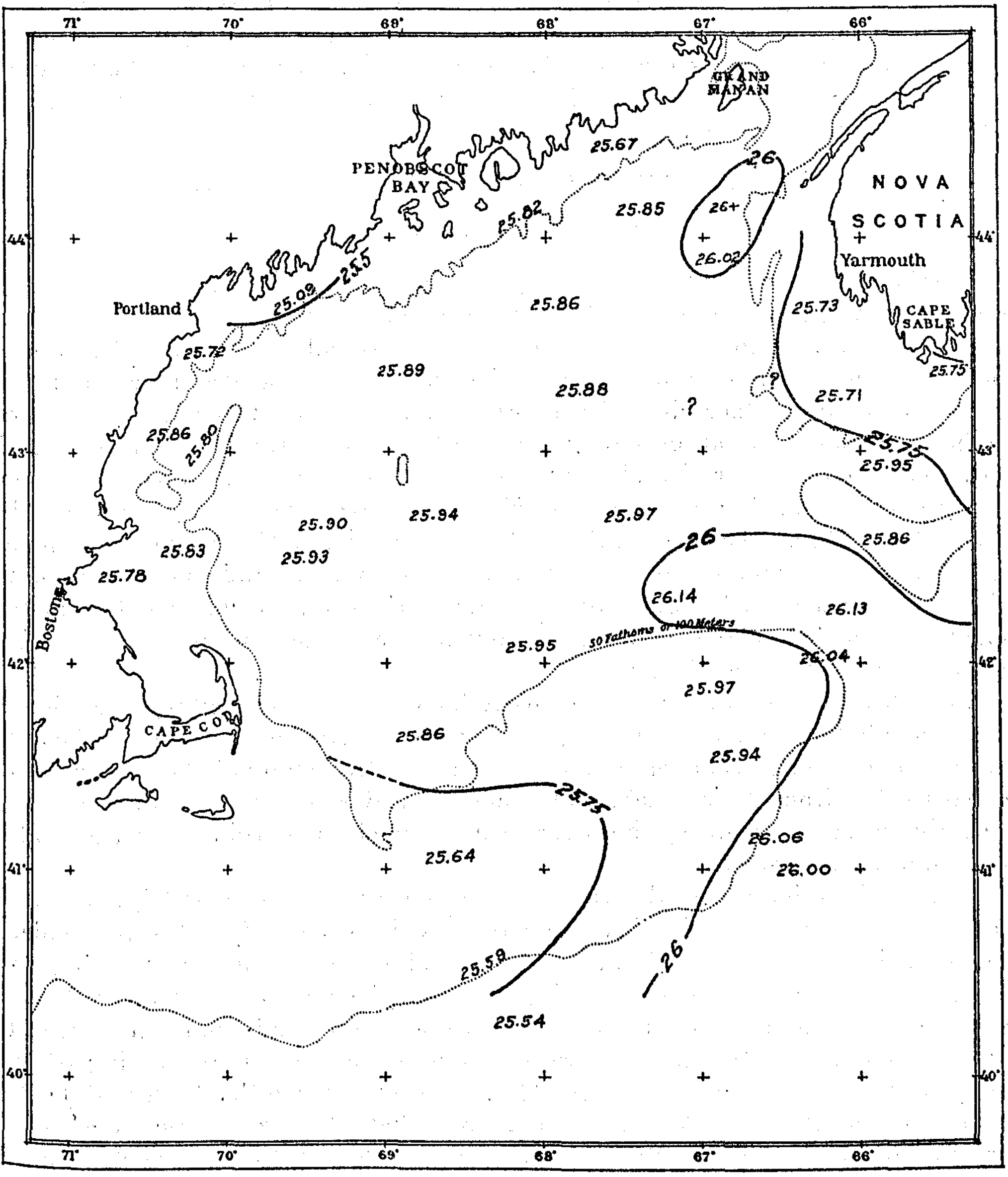

FIG. 187.—Distribution of density at the surface, February to March, 1920

In studying the dynamics of any shoal area it is also essential to appreciate the effect which the contour of the bottom may have in deflecting the gradient currents. This, of course, can not be stated by rule, but usually it is fairly simple of interpretation.

Once the dynamic gradient is established between any two stations, the corresponding velocity of the water at the one, relative to the other, is calculable by a simple formula, described by Smith (1926, p. 31), who also makes clear the correction necessary to learn the true velocity if the profile in question does not cut the current at a right angle. An alternative method of calculating the velocity, often employed, is described fully by Sandström (1919); and the *Fish Hawk* data for Massachusetts Bay (June, 1925) have been treated in this way by R. Parmenter (p. 949; figs. 198 and 199), as an illustration.

DYNAMIC CONTOURS AND GRADIENT CURRENTS

FEBRUARY AND MARCH

At the end of the winter and during the first days of spring, when the general equalization of temperature and of salinity (already discussed) makes the upper 40 meters extremely uniform, regionally as well as vertically (pp. 522, 703), over the whole gulf, the distribution of density at the surface would suggest a very quiescent state. Thus, the surface chart for February and March, 1920 (fig. 187), shows a maximum regional variation of only about 0.4 units over the whole basin, with the central part of the latter virtually uniform (at 25.8 to 25.9) from station to station.

Only the immediate offing of the Kennebec River was then appreciably less dense (about 25) at the surface, the Eastern Channel and the region off its mouth slightly more so (about 26 to 26.1); and the whole western and central part of the gulf, with the coastal belt along Nova Scotia, was then equally uniform at 40 meters, though with slightly higher values (26.3 to 26.5) along the eastern side of the basin and through the Eastern Channel.

It is clear that with the water so nearly homogeneous horizontally there is very little dynamic tendency toward any general system of gradient currents in the upper stratum of the gulf at that season, except that the freshening of the surface by the increasing flow from the Kennebec foreshadows the development of a drift westward along the coast—a tendency, however, still confined to so thin a surface stratum that it did not yet govern.

Neither does the state of the water at the surface suggest a general dynamic tendency at that season toward a drift from the east into the gulf past Cape Sable, or vice versa, in the surface stratum, the density of the upper 40 meters being comparatively uniform (in horizontal projection) from the cape out to Browns Bank for early March. This corroborates the evidence of salinity and temperature that the Nova Scotian current did not flood westward past the cape in the spring of 1920 until later than sometimes happens (p. 832). However, when the density of the deep strata is taken into account it becomes obvious that the hydrostatic forces set in operation by the banking up of the heaviest water against the eastern slope of the gulf (p. 849, fig. 172) must tend to cause a cyclonal or anticlockwise movement of the deeper mid strata, carrying with it, as an overlying blanket, the surface stratum, itself so nearly quiescent.

The dynamic chart for February and March, 1920 (fig. 188), gives an indication of the stream lines to be expected at the surface under the conditions of temperature and salinity then existing, which may be taken as typical of the first two weeks of spring. However, I must here caution the reader that at this time of year, when the propulsive force for gradient currents is derived mostly from the deep strata of

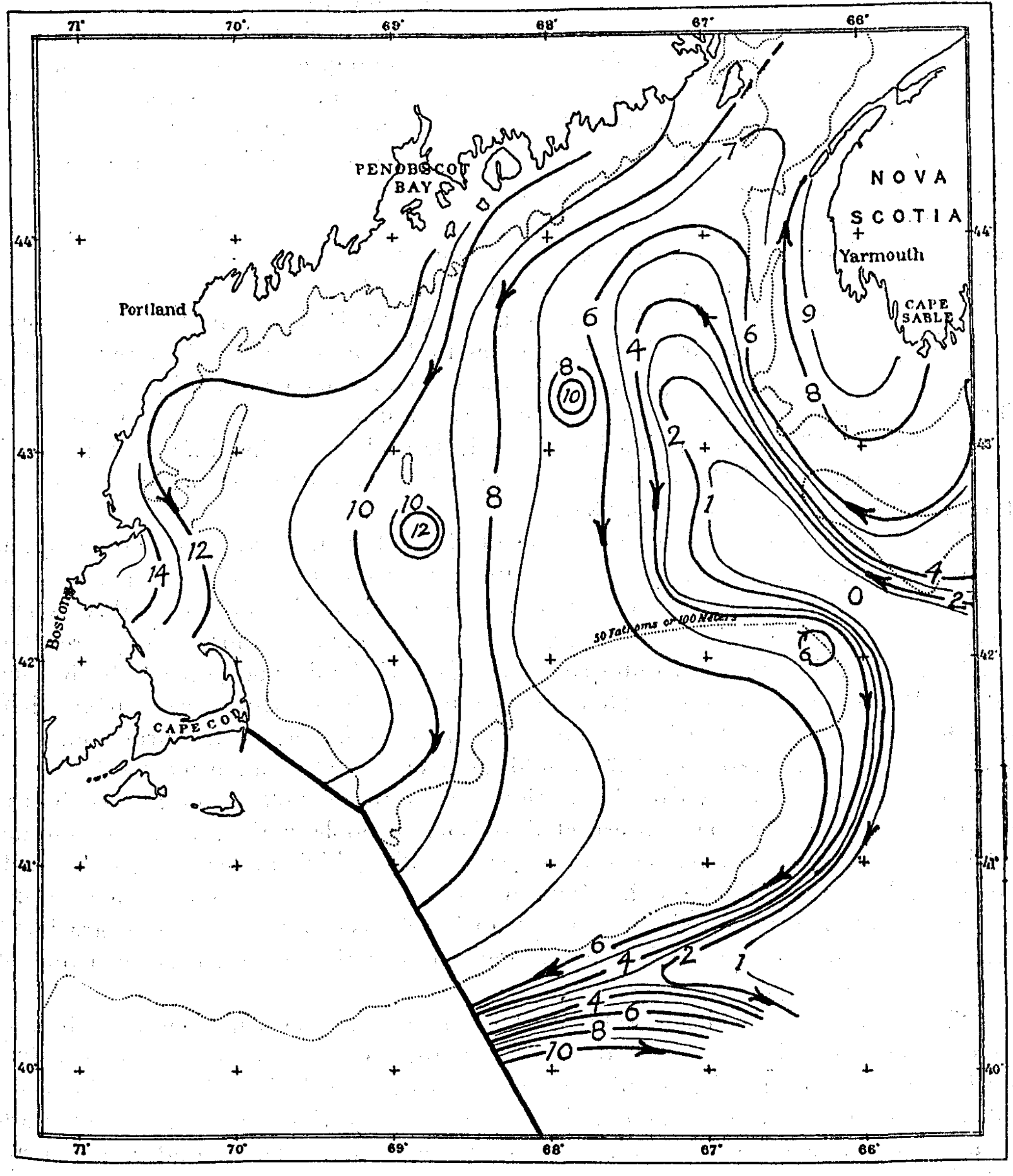

FIG. 188.—Dynamic gradient at the surface of the gulf for February to March, 1920, referred to the Eastern Channel as the base station. The dynamic heights are given for every dynamic centimeter. For further explanation see p. 937

water, the probable error introduced into the calculations by the necessity for assuming an arbitrary correction for the differences in depth between pairs of adjacent stations (p. 934) is relatively greater than for late spring or summer, when the surface stratum is moving more rapidly than the underlying water. Consequently, the contour lines on the early spring chart (fig. 188) and the dynamic gradients which they show can be accepted only as a rough approximation, not in detail. Some smoothing of the curves has proved necessary in the construction of the chart, also.

Even with this reservation these contours show that the basin of the gulf (potentially, at least) was then the site of one major cyclonal (i. e., anticlockwise) eddy, with its center taking the form of a troughlike depression extending from the Eastern Channel northward and inward toward the offing of the Bay of Fundy. It is interesting that this general eddy seems also to have involved the latter, with the surface water drifting inward along the Nova Scotian side, outward next the New Brunswick shore and past Grand Manan.

The highest velocities then indicated were a drift northward into the gulf along the western slope of Browns Bank and a counter movement outward along the Georges Bank side of the Eastern Channel. With the correction used here for the difference in depth this indraft works out at about 13.5 centimeters per second, equivalent to 0.27 knot, or about 6½ miles in 24 hours. The calculated velocity for the outdraft around Georges Bank is lower—0.22 knot, or 5¼ miles in 24 hours. These velocities, however, are on the assumptions, first, that the water in the center of the Eastern Channel was stationary and, second, that the difference in depth between the trough of the channel and the crests of its two slopes was correctly allowed for in the calculation (p. 934).

By contrast, the whole western side of the gulf was "dead," dynamically, as late as the middle of March, in 1920, its upper stratum only tending to drift southward (anticlockwise) very slowly, except at the mouth of Massachusetts Bay, where greater velocity in this direction is suggested by contour lines more closely crowded (fig. 188). It is interesting to find that the effect of the discharge from the Kennebec and Penobscot was most evident in speeding up the southwesterly surface drift some 40 miles out from the land—not close in to the latter, as the surface chart of density for the same date (fig. 187) would have suggested if taken by itself.

Lower densities at two of the stations in the basin (20054 and 20052) than in the general vicinity are best interpreted as isolated pools, which, if correct, implies sudsidiary clockwise eddies; so, too, a corresponding high appearing on the eastern edge of Georges Bank on the dynamic chart (fig. 188). While these seem not to have seriously interrupted the general anticlockwise movement, they are interesting illustrations of the persistence of such pools, which have drifted off from the general zone of low density next the coast.

The comparatively dead state of the water over the whole eastern half of Georges Bank at this season also deserves a word. The chart suggests a slow drift southward and so out of the gulf across the western half of the bank at this time, but the contour of the bottom makes it more likely that the surface water was actually moving eastward around its northern edge, because the underlying strata (which in this case supplied the motive power) are necessarily directed by the submarine slope, against which any southward drift must strike. Thus, we may conclude that the dynamic movement of water around the basin was even more definitely eddylike and anticlockwise in March than the chart (fig. 188) suggests.

Lacking March data for the region of Nantucket Shoals, the chart fails to show whether a definite dynamic outflow is to be expected around the latter to the westward from the gulf at that season.

In the offing of Cape Sable the dynamic gradient for March,1920, calls for a weak drift clockwise but spreading far offshore toward Browns Bank before eddying northward again toward the gulf. Hence, thecold Nova Scotian water that we encountered midway out over the shelf (station 20075, p. 1000) did not then tend to round the cape, but to veer offshore, which agrees with the distribution of temperature and salinity at the time. Dynamic evidence also is strong that whatever water was then entering the eastern side of the gulf in the upper stratum was drawn chiefly from the region of Browns Bank and from the edge of the continent in the offing of Cape Sable—i. e., from the source whence the gulf regularly receives its slope water (p. 848).

The dynamic gradients for March are especially instructive along the continental slope abreast of the gulf because of the light they may throw on the problem of the so-called "Gulf Stream" along this sector. Fortunately, this is made comparatively clear for this region (fig. 188) by the considerable difference in density between the outer stations on the two cross profiles of the bank—western and eastern (stations 20044 and 20069). On the eastern profile the gradient (dipping to a low at the outermost station) shows a strong drift to the westward along the edge of the bank, its calculated velocity being about 0.6 knot, or 14 miles in 24 hours. While this calculation depends on the correct allowance for the difference in depth between stations, one of which was much deeper than the other,[92] the direction of this gradient current is well established. A weak continuation of this westerly drift (indicated by a low in the dynamic contour) extended along the edge of the bank as far as the western profile (run three weeks earlier); but here this gave place to a much steeper counter gradient to high in the next 10 miles offshore, implying a counter drift to the east.

Unfortunately, the difference in depth between the stations on the edge of the bank and outside is again so great on this profile (150 to 200 and 1,000 meters) that the arbitrary correction employed to take account of it becomes only a rough approximation, though the order of this correction (i. e., whether increasing, decreasing, or even tending to reverse the gradient calculated for equal depths) is in every case clear enough (p. 934). When all reasonable allowance is made for this source of error, however, the velocity of the easterly drift may safely be set as at least half a knot. Fortunately, calculation of the dynamic head between the two outermost stations on these two profiles is not subject to this error, both being deep enough (1,000 meters) to reach equal density at the lowest levels. Consequently the general contour, as laid down for this region in Figure 188, is established, as is the fact that the western profile reached out to water of comparatively high temperature and salinity in the upper stratum, while the eastern profile did not, though its outermost station was still farther out from the edge of the continent.

So long as the dynamic gradient continues to be of this sort it is evident that the superficial drift of warm water along the continental slope, commonly spoken of as the "inner edge of the Gulf Stream," is not only to be described as a typical gradient current but is to be expected within 15 to 20 miles of the edge of the bank between longitudes 68° and 69°. Farther east, however, the contour lines on the chart (fig. 188) show it departing farther and farther from the bank, agreeing in this

---

[92] Station 20068, 200 meters; station 20069, 1,000 meters.

with general report. On the other hand, the westerly counterdrift set in motion along the inshore side of the dynamic depression (or cabelling zone) loses in velocity and hugs the bank more closely from east to west.

From the general oceanographic standpoint this demonstration that this sector of the "Gulf Stream" receives a propulsive impulse from the local hydrostatic forces (i. e., is strictly a dynamic drift) is one of the most interesting results of our explorations.

The upper 50 meters or so of the gulf being close to quiescent, dynamically, during February and March, the chart for the surface (fig. 188) will as well represent the gradient currents down to as deep as 100 meters or so for that season, leading to the interesting result that the whole column down to this depth tended to drift inward along the eastern side of the Eastern Channel at the time, outward along its western side, which is also evident in the profile (fig. 189). However, if we descend to as great a depth as 150 meters a rather different dynamic distribution appears, with the center of anticlockwise revolution located as a low close to the northern slope of Georges Bank, with a weak but definite tendency toward a gradient drift crossing the basin from northeast to southwest, shown better graphically by the dynamic contours (fig. 190) than verbally. This drift was then bounded on the west by a considerable dead area covering the whole west-central part of the basin (except as interrupted by a subsidiary high marking a clockwise whirl in the offing of Penobscot Bay), with a very weak southerly tendency along the western slope in the offing of Massachusetts Bay.

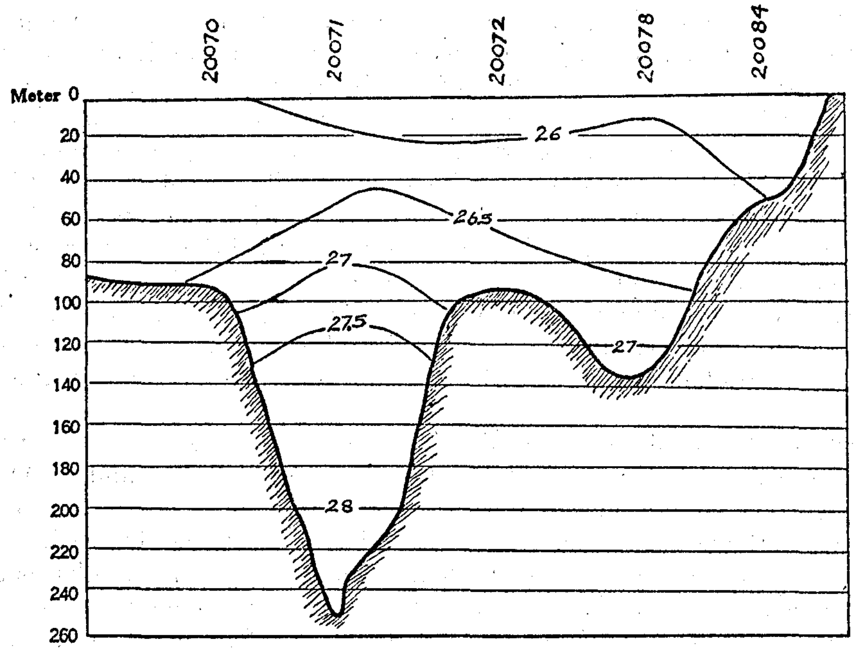

FIG. 189.—Distribution of density on a profile running from the eastern end of Georges Bank across the Eastern Channel, Browns Bank, and the Northern Channel, to the vicinity of Cape Sable, March 13 to 23, 1920. Corrected for compression.

In the eastern side of the area this deep projection points to a slow creep inward through the Eastern Channel; but with only one station in the latter it is impossible to state whether this creep involved the whole breadth at this depth or (which seems more likely) hugged its Browns Bank slope, as in the shoaler strata.

In interpreting the dynamic contours in terms of potential drift at a depth at which the basin of the gulf is entirely inclosed except for one narrow channel, it is obvious that prime consideration must be given to the contour of the bottom, as this controls the possible movement of the water. When this is taken into account, the March chart (fig. 190) affords the best clue yet available to the movement of the slope water over the floor of the gulf at a season when this is entering in large volume via the trough of the Eastern Channel (p. 850). Dynamic contours for the 150-decibar level, like the distribution of temperature and of salinity, show this indraft following the eastern side of the basin inward, to eddy westward and so southward; but instead of completing a circuit around the cyclonic center ("low" on the chart—fig. 190), the drift will obviously be deflected by the slope of Georges Bank. The angle at which the contour (or stream) lines strike the latter suggests an overflow into the dead western side of the basin. It is here, then, as well as along the northern slopes of the gulf, that the consumption of this slope water chiefly takes place during the early spring, as tides and wind currents constantly mix it with the less saline but colder stratum above.

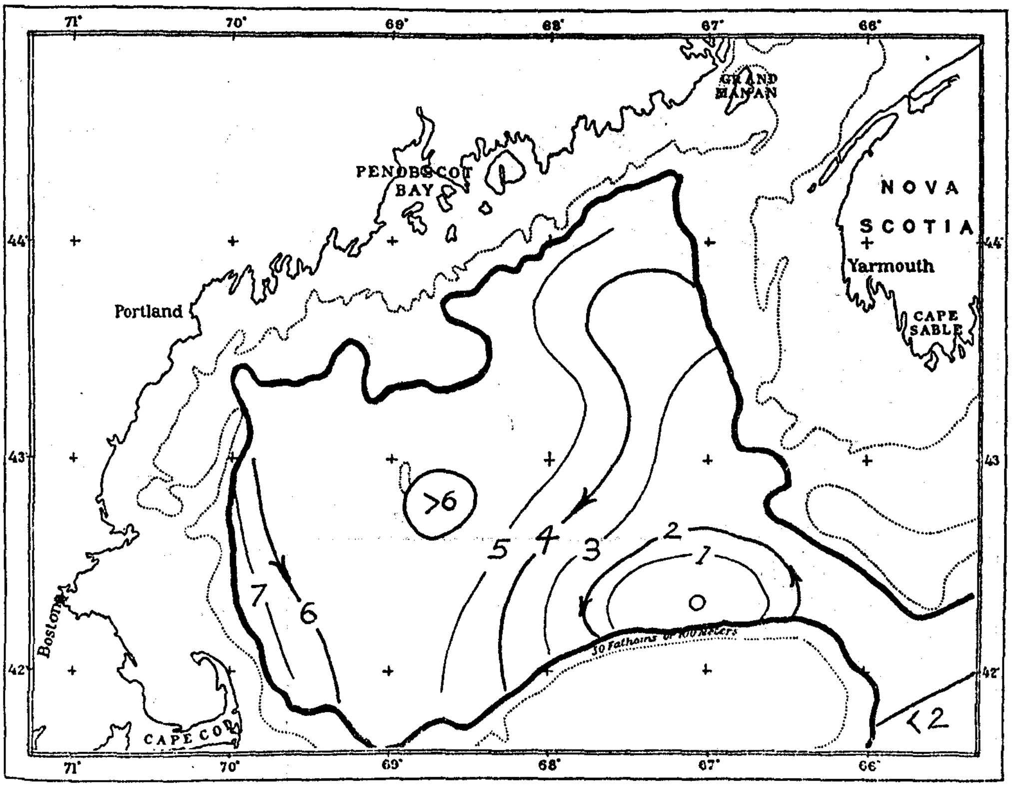

FIG. 190.—Dynamic gradient, bottom to 150 decibars, referred to the southeastern side of the gulf as base station, for February and March, 1920. Contour lines for every dynamic centimeter

The implication of a dynamic contour of this sort in the deeps of the gulf, combined with the effect of the confining slopes and with this consumption in the inner part, is obvious; it provides a propulsive force to pump into the gulf the slope water with which the offing of the Eastern Channel is kept supplied—also dynamically—from the source of manufacture to the eastward (p. 847).

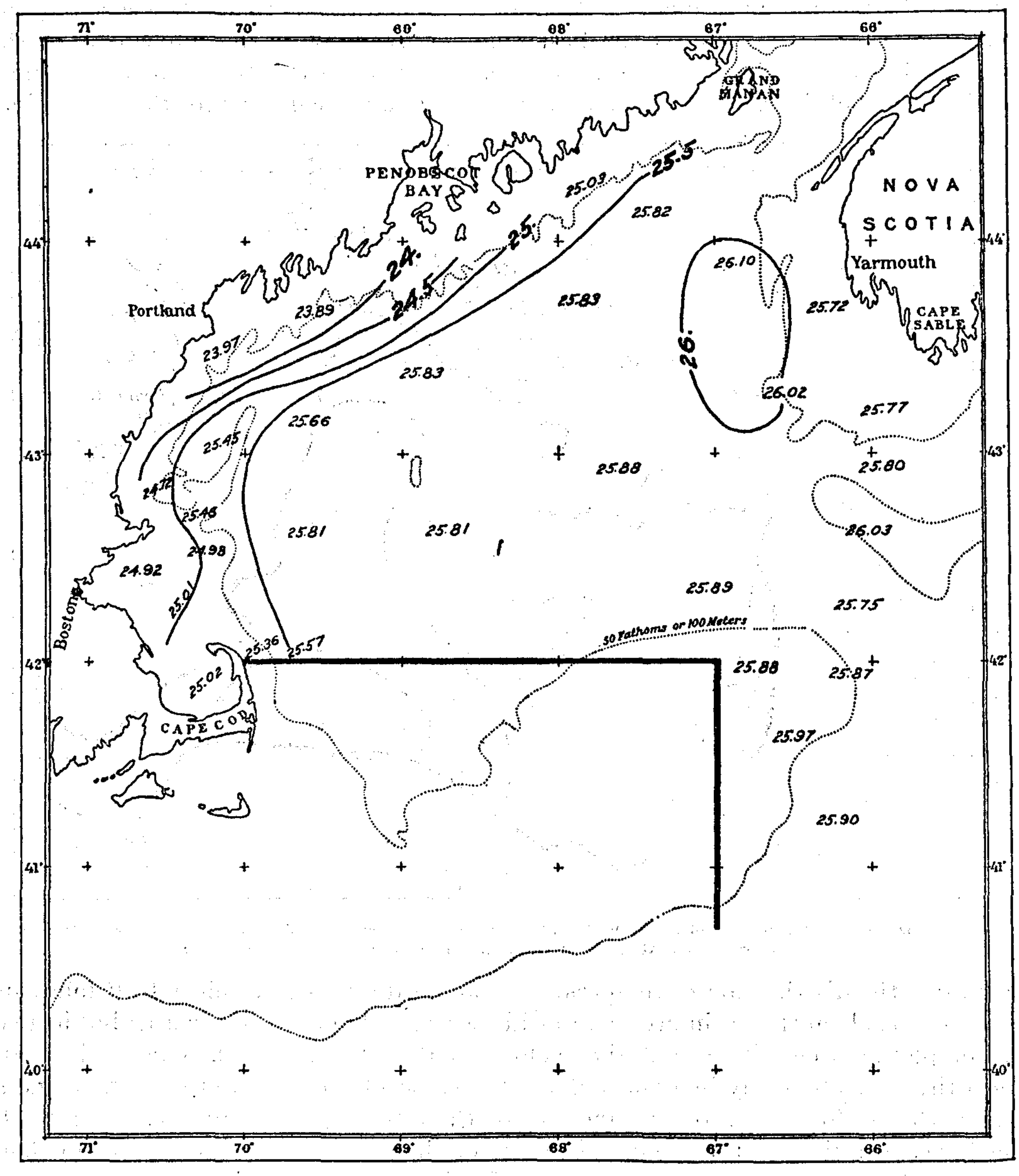

FIG. 191.—Distribution of density at the surface of the gulf, April 6 to 20, 1920

APRIL

The progressive freshening of the surface, which takes place along the northern and western shores of the gulf with the advance of spring, results in the development of a corresponding coastwise belt of low-surface density by April, grading abruptly to considerably higher values a few miles out in the basin (fig. 191). This development adds both velocity and volume to the longshore drift west and south, which was foreshadowed on the March chart (fig. 188).

In 1920, according to the dynamic contours at the surface (fig. 192), this spring current had come to dominate the entire coastal belt of the gulf from the neighborhood of Mount Desert Island (probably from the Grand Manan Channel) to Cape Cod by the middle of April, and probably it does so every year by this date—earlier in years when vernal progression in the sea is more forward. During the period covered by this April cruise the average calculated rate of this current, referred to the "low" in the offing of the Bay of Fundy (assumed stationary), was about 0.3 knot abreast of Mount Desert, about 0.18 knot abreast of Cape Cod, or an average drift of about 5¾ miles per 24 hours along this coast sector as a whole. In spite of the sources of unavoidable error this calculation falls at least within the order of magnitudes suggested by other lines of evidence.

In Massachusetts Bay, also, a continuation of this longshore drift is indicated by the dynamic contours from the north shore around toward Cape Cod. This, again, agrees with the drifts of bottles that were set out a few miles north of Cape Ann in April, 1925 (p. 890; fig. 177); and evidently this is the characteristic state during that month, for salinities and temperatures taken in the bay by the *Fish Hawk* on April 21 to 23, 1925, show a drift of low density (fig. 193) southward past Cape Ann and across the mouth of the bay to Cape Cod as the water from the Merrimac and other rivers to the north floods southward.

Surface projection (fig. 191) and dynamic contours (fig. 192) for April unite in locating the low in the offing of the Bay of Fundy some 60 miles off Mount Desert Island for that month, the whole east-central part of the basin out through the Eastern Channel being virtually dead dynamically, contrasting with a weak northerly set along the western shores of Nova Scotia. In the southern side of the area the dynamic contours point to a persistence of the drift out of the gulf to the south around the eastern end of Georges Bank, just described for March (p. 938; fig. 188), though at a lower velocity; but as a result of the equalization of temperature and salinity from the Eastern Channel in across Browns Bank (p. 553) only a very slow movement into the gulf along this side of the channel is suggested by the April chart (fig. 192).

The general result of the lightening of the northern and western margins of the gulf, combined with the shift of the cyclonal low northward across the basin, which follows a slackening in the indraft of slope water, is to give the anticlockwise circulation more definitely the character of a great eddy in April than in March, centering off the Bay of Fundy and with its western side traveling southward with greater velocity than its eastern side drifts north.

It is probable that in April the gradient currents are given an easterly direction along the northern slopes of Georges Bank, just as in March (p. 938), by the contour of the bottom, with a separation off Cape Cod between this easterly drift and a southerly drift past the cape and past Nantucket Shoals. This suggestion is corroborated by the fact that bottles followed both these routes from Massachusetts and Ipswich Bays in April, 1925.

MAY

Progressive incorporation of river water into the northern and western sides of the gulf, coupled with vernal warming, constantly favors the anticlockwise movement of the so-called "spring current" (fig. 194); and with the resultant changes in salinity and temperature affecting chiefly the surface, the site of the chief dynamic impulse toward circulation shifts from the deep strata to the superficial. In May, 1915, for example, a difference of about 1.5 units of density was recorded at the surface between the vicinity of the mouth of Massachusetts Bay and the basin in its offing (fig. 194) in a distance of 30-odd miles, but only about one-seventh as wide a difference at the 50 or 100 meter levels (stations 10266 and 10267).

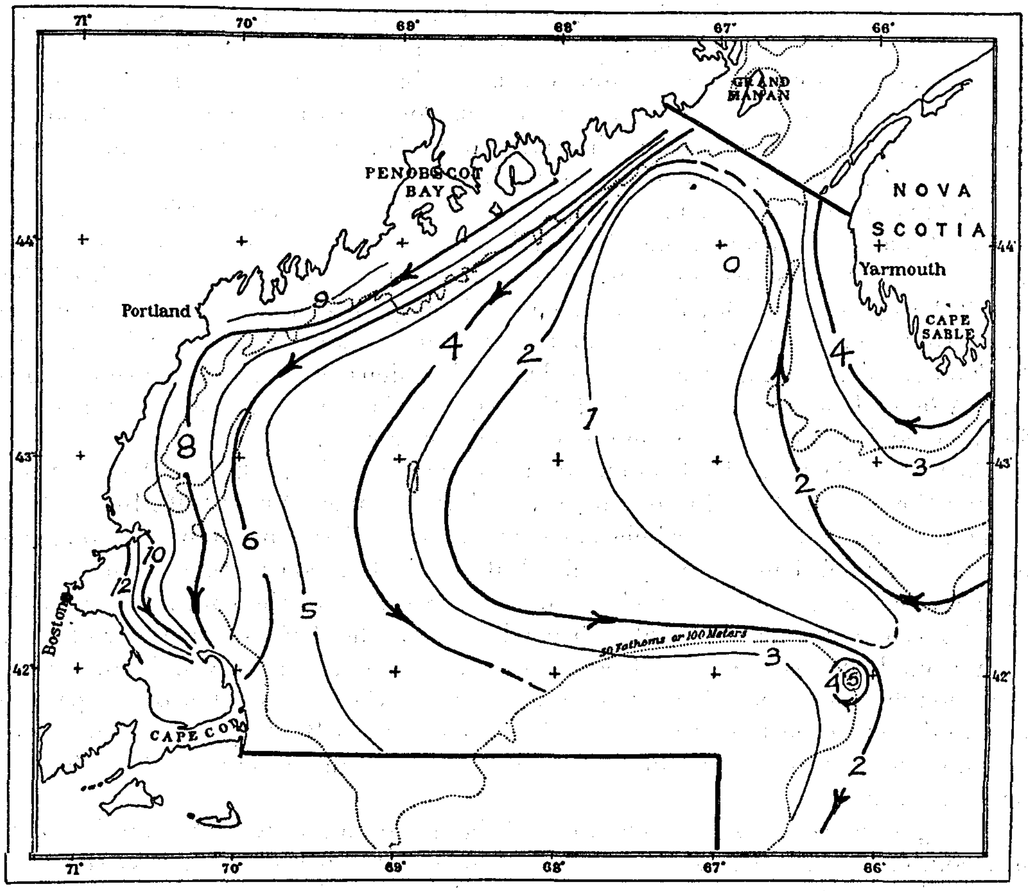

FIG. 192.—Dynamic gradient at the surface of the gulf, April 6 to 20, 1920, referred to the offing of the Bay of Fundy as base station. Contours for every dynamic centimeter

As a result, the dynamic chart for May (fig. 195) corresponds closely to the distribution of density at the surface, except for the relationship between the shallows of German Bank and the deep water immediately to the west of the latter. In this region the surface projection, taken by itself, would give a false picture, being confused by the strong tides that keep the water thoroughly stirred over the bank, thus

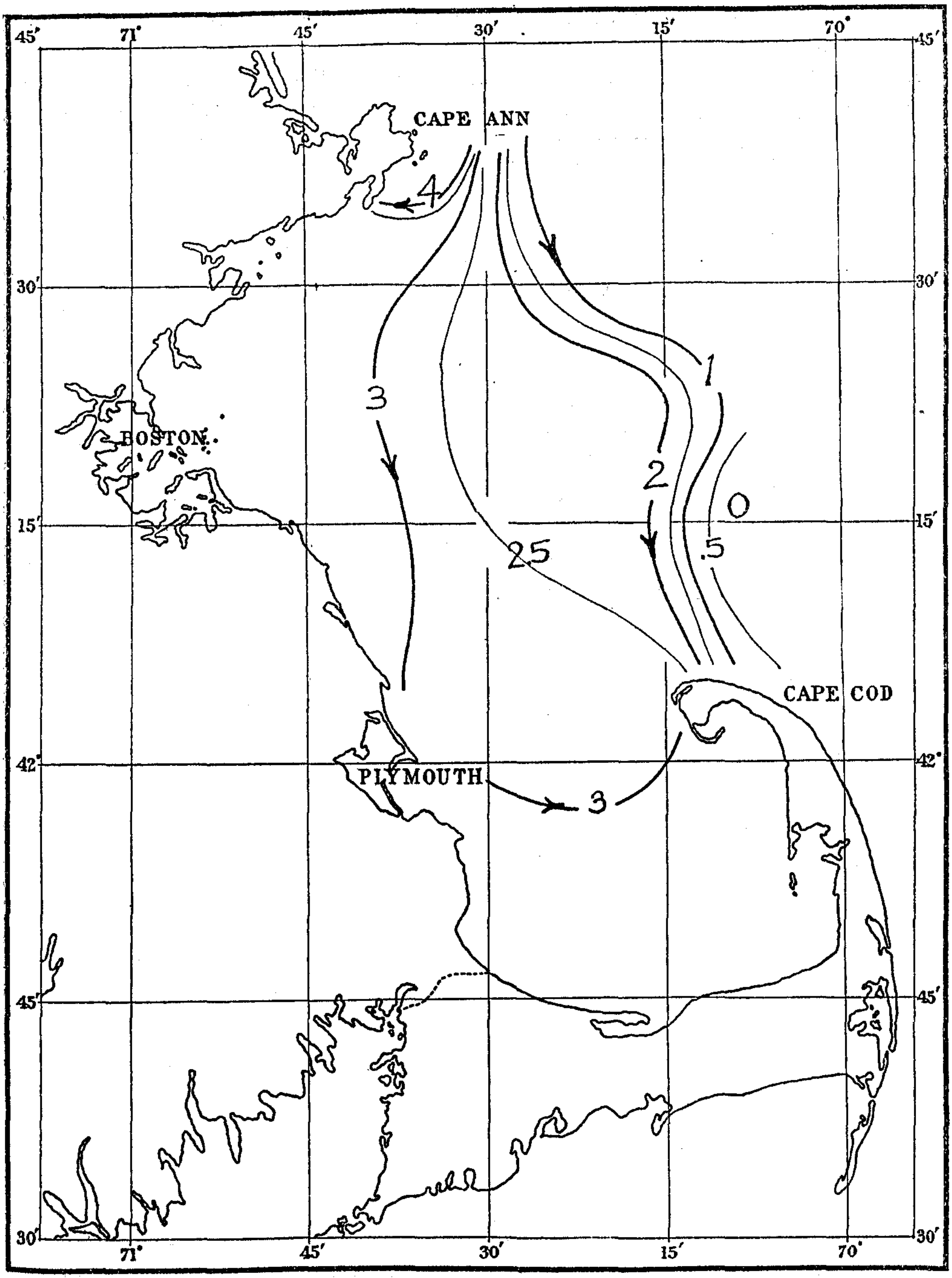

FIG. 193.—Dynamic gradient at the surface of Massachusetts Bay, April 21 to 23, 1925. Contours are for every one-half dynamic centimeter. Based on hydrometer readings

locally increasing the density at the surface but correspondingly decreasing that of the underlying strata.

At some time between the last of March and the first of May—the exact date varying from year to year (p. 832)—the Nova Scotian current, flooding westward past Cape Sable into the gulf, is reflected by the development of a corresponding tongue of low surface density extending westward from the offing of the cape. Thus, in 1919 the eastern half of the Cape Sable-Cape Cod profile proved less dense than the western in the upper 50 meters at the end of March and again at the end

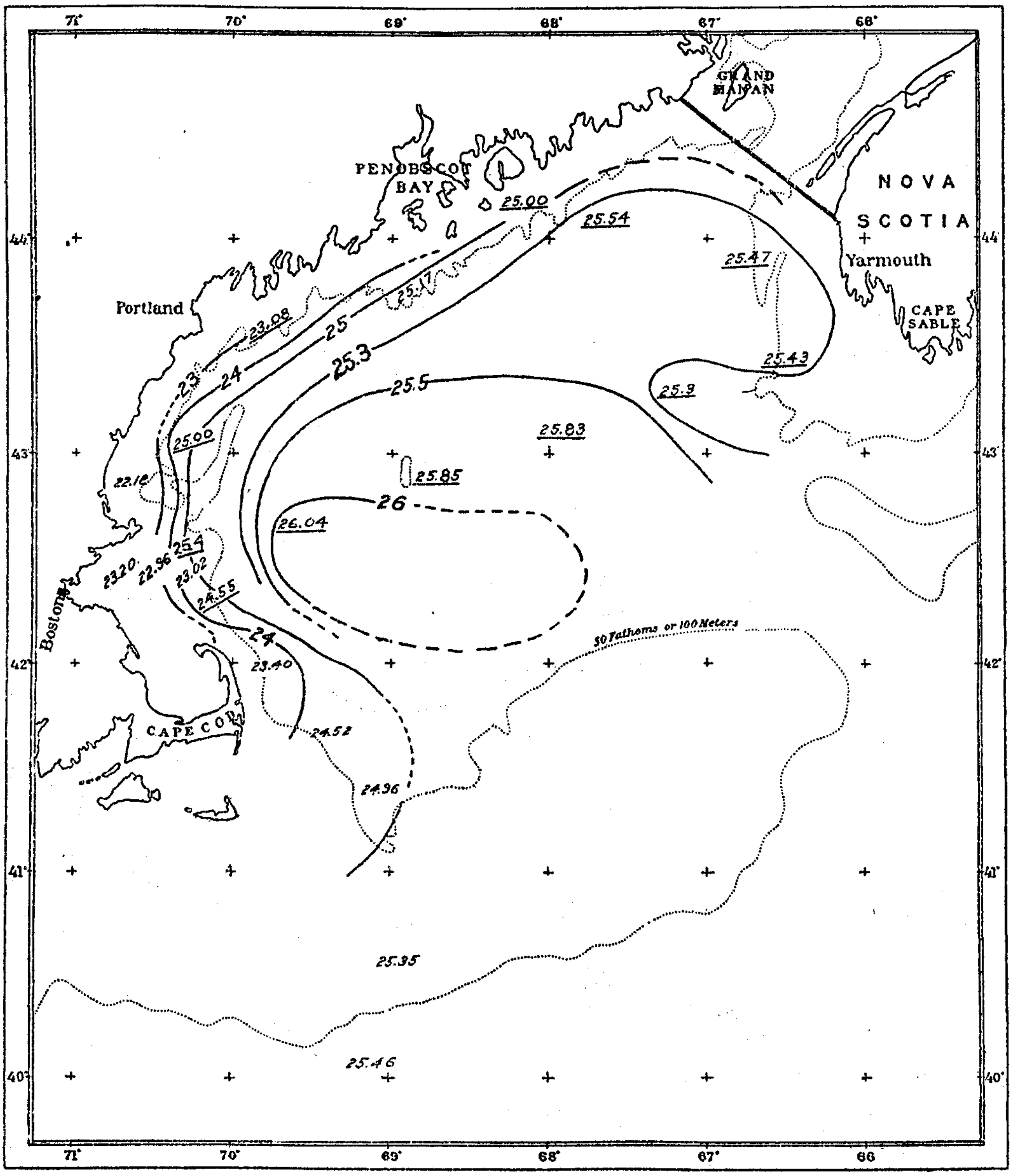

FIG. 194.—Distribution of density at the surface of the gulf for May, 1915 (underlined), and May, 1920, combined

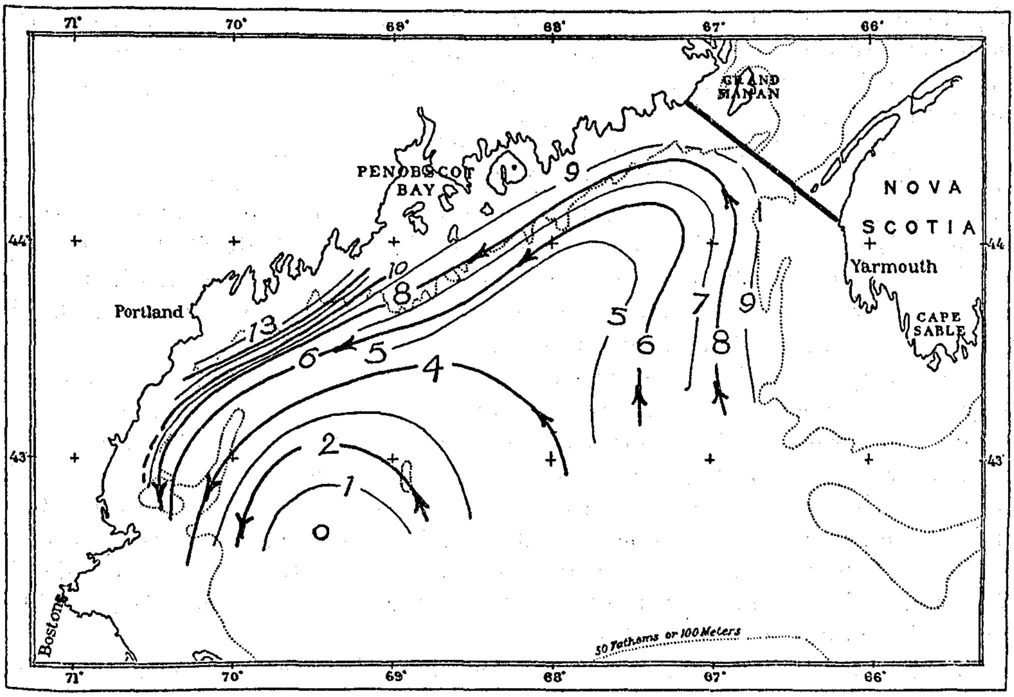

FIG. 195.—Dynamic gradient at the surface, for the northern part of the gulf, May 4 to 14, 1915, referred to the offing of Cape Ann as base station. Contour lines are for every dynamic centimeter

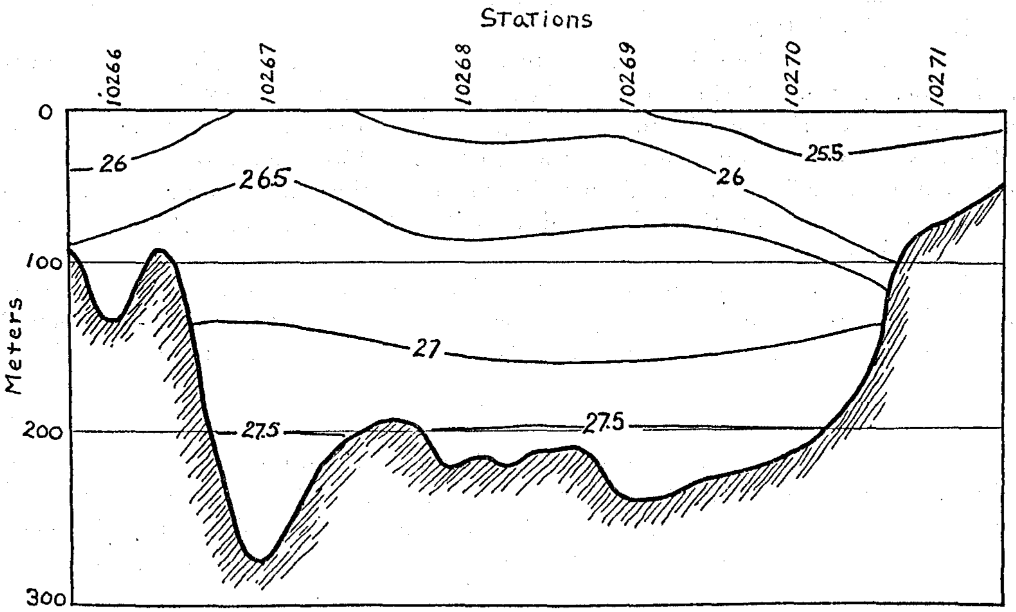

FIG. 196.—Density on a profile crossing the gulf from Massachusetts Bay toward Cape Sable, May 4 to 14, 1915. Corrected for compression

of April (Ice Patrol stations 2 to 3 and 21 to 23, p. 997). The regional distribution was essentially the same on this profile for May 4 to 7, 1915 (fig. 196), and it is because this Nova Scotian water is relatively so light that it so little affects the temperature of the deep strata of the gulf.

This overflow of water of low salinity shifts the potential depression, or low (representing the center of high density), from east to west across the gulf to the offing of Massachusetts Bay (figs. 194 and 195)—i. e., to the situation where the surface is high in summer (p. 956). So long as the regional distribution of density is of this sort (from early May in some years; probably as early as April in others) the anticlockwise vortex centers over the western arm of the basin 30 to 50 miles out from the mouth of Massachusetts Bay.

Under these conditions the surface water may be expected to drift with considerably greater velocity from northeast to southwest around the western margin of the gulf than from south to north along its eastern trough (fig. 195), though the current may be equally strong next the west coast of Nova Scotia, where data for May are lacking. To what extent this anticlockwise circulation involves the Bay of Fundy in that month is yet to be learned, though the sudden freshening of the surface there by the freshets from the St. John River (p. 808) suggests a considerable differential in density between the two sides of the bay as characteristic of May, pointing to an outflow in its northern half.

The data for 1915 fail to outline the longshore drift farther south than Cape Ann, lacking observations close in to the cape or in Massachusetts Bay, but the very low densities recorded at the mouth of the bay in May, 1920 (fig. 194), show it continuing down past Cape Cod, consistent with the drifts of bottles set out in Massachusetts Bay in April, 1926 (p. 893).

The dynamic gradient is so much steeper at the surface than in the deeps of the gulf in May that calculations of the relative velocity would approximate the truth more closely then than earlier in the spring. In 1915 the calculated velocity relative to the low off Cape Ann (assumed stationary, fig. 195) was about 0.23 knot per hour near Cape Elizabeth, or about 5½ nautical miles in 24 hours. Abreast of Mount Desert, however, the calculated velocity was only about 0.14 knot toward the west at the time.

Unfortunately no dynamic data are available for the southeastern part of the area for May, so that nothing can yet be said about the effect that the Nova Scotian current may exert on the gradient currents of the Eastern Channel and vicinity.

JUNE

No one of our cruises affords a general dynamic picture of the gulf as a whole in June, but the state of its eastern side shows that in 1915, at least (fig. 197), the slackening of the Nova Scotian current from the east, coupled with the vernal warming and progressive incorporation of land water in the west, caused the low center of anticyclonic circulation to shift from the offing of Cape Ann to the Eastern Channel by the last week of June. This seasonal return to the location it occupies in March (judging from 1920) probably represents the normal progression, the physical changes on which it depends being yearly events.

With this gradient a considerable indraft is indicated into the eastern side of the gulf; not, however, from the coastal belt to the eastward of Cape Sable, but from the region of Browns Bank and of its offing. Probably this indraft had as a counter current an outdraft from the gulf around the eastern end of Georges Bank, though, lacking a station on the bank, this can not be asserted definitely. It is certain, also, that the dynamic impulse for a northeast-southwest current around the northern and western margins of the gulf had slackened by the middle of that June.

Unfortunately, no observations were taken in the western side of the gulf that June, but a survey of Massachusetts Bay carried out by the *Fish Hawk* on June 16 and 17, 1925 (cruise 14), has enabled Mr. Parmenter to calculate the relative velocities and directions of the gradient current on various profiles by the method elaborated by Sandström (1919), and his results are offered here to illustrate this alternative procedure.

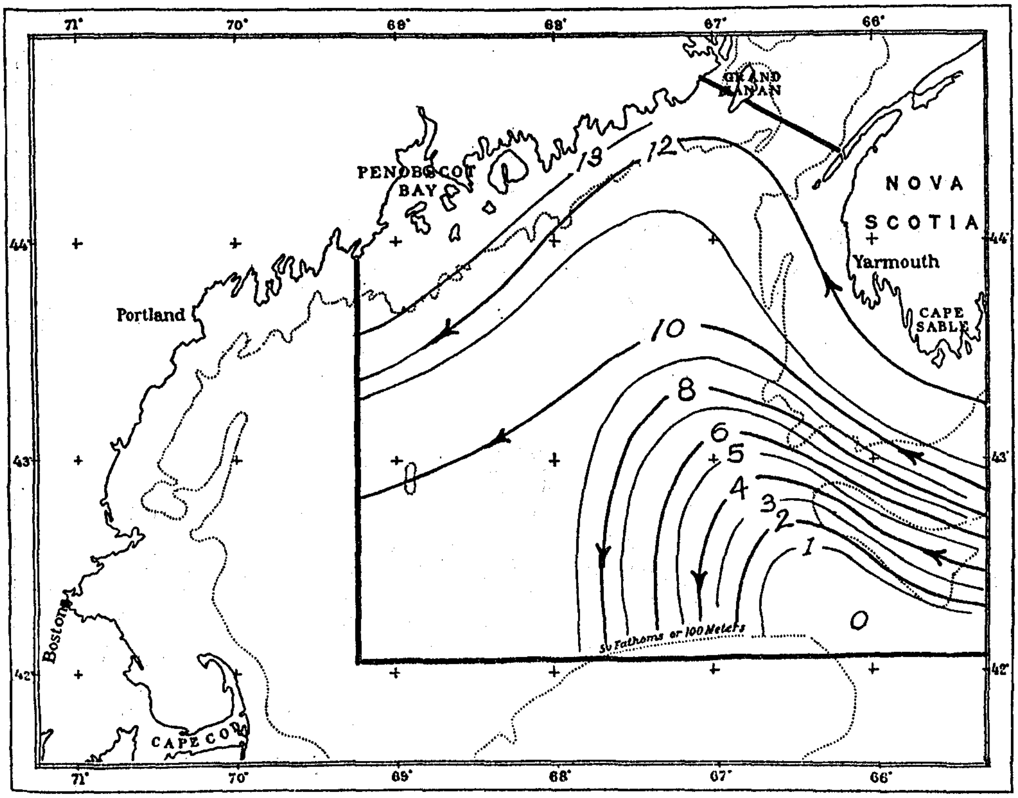

FIG. 197.—Dynamic gradient at the surface of the eastern side of the gulf, from June 10 to 26, 1915, referred to the Eastern Channel as base station. Curves are for every dynamic centimeter.

These calculations (tabulated below) rest on two assumptions—first, that the water was stationary at the greatest depth of the shoaler of each pair of stations, and, second, that the profiles selected (typical examples are shown in fig. 198) are at right angles to the existing current. In the present instance neither of these requirements is exactly fulfilled, but the close agreement between the calculation and the general distribution of density in the upper 20 meters (fig. 199) makes it probable that the calculated directions are a close approximation to the actual dynamic tendency toward circulation at the time.

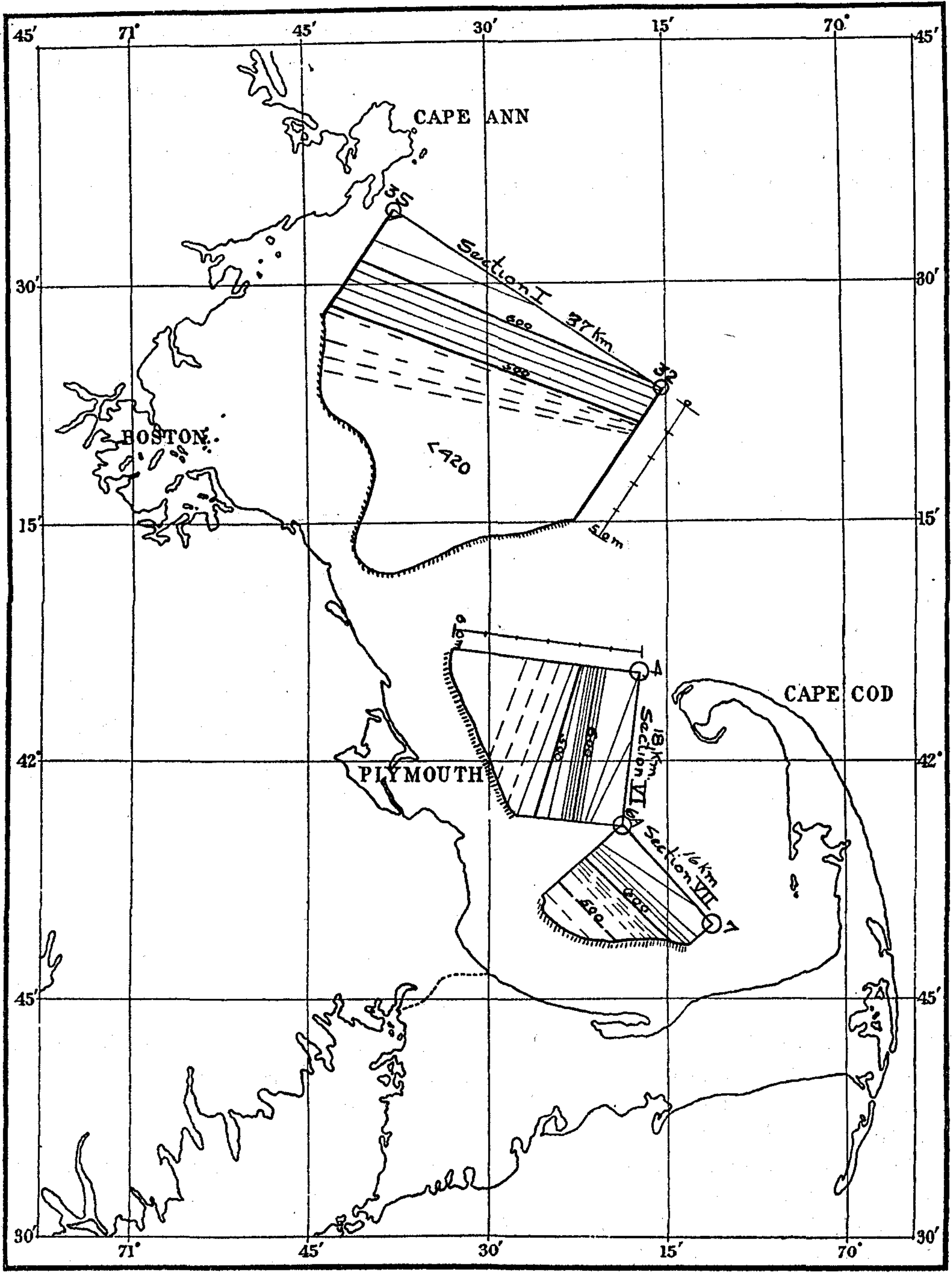

FIG. 198.—Specific volumes on three profiles in Massachusetts Bay, June 16 and 17, 1925. Calculated by R. Parmenter

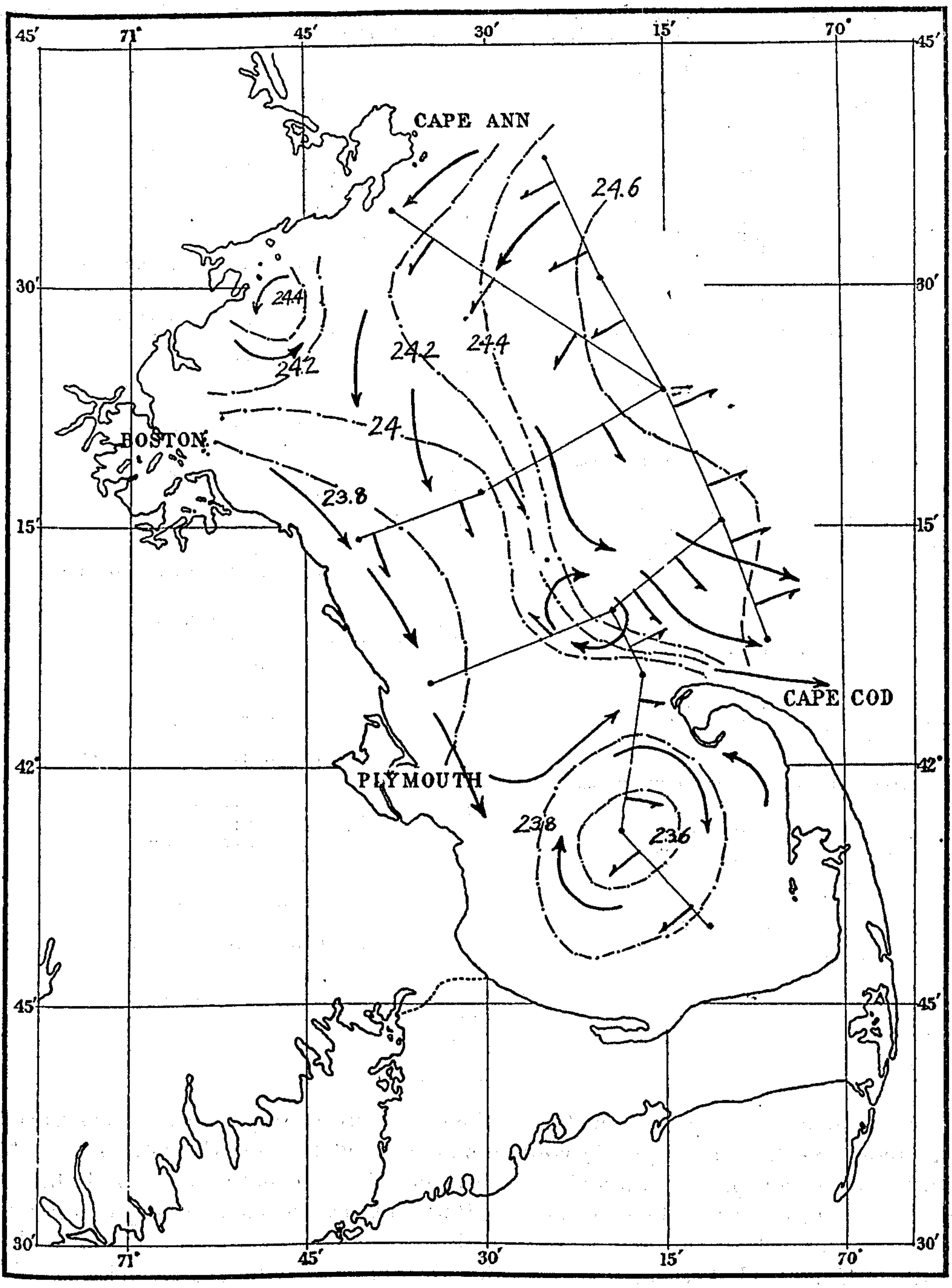

FIG. 199.—The single-barbed arrows show the direction of the gradient current, as calculated for Massachusetts Bay by R. Parmenter, June 16 and 17, 1925. The double-barbed arrows outline the nontidal circulation as it probably existed at the time. The broken curves give the density at the surface. For further explanation see p. 952.

Relative velocities and directions of the currents in Massachusetts Bay, "Fish Hawk" stations, June 16 and 17, 1925, calculated by R. Parmenter

SECTION I

STATIONS 35 TO 32. DISTANCE, 37 KILOMETERS

Depth, meters	Velocity (cm. sec.)	Direction
0	5.16	Southwest.
10	3.43	Do.
20	(1)	

SECTION II

STATIONS 16 TO 18A. DISTANCE, 15 KILOMETERS

0	5.67	Southeast.
10	4.24	Do.
26	(1)	

STATIONS 18A TO 32. DISTANCE, 24 KILOMETERS

0	7.74	Southeast.
10	3.91	Do.
20	.63	Do.
40	.76	Northwest.
50	(1)	

SECTION III

STATIONS 14 TO 3. DISTANCE, 24 KILOMETERS

0	0.08[2]	Northwest.
10	1.40	Do
22	(1)	

STATIONS 3 TO 33. DISTANCE, 16 KILOMETERS

0	8.22	Southeast.
10	8.03	Do.
20	4.28	Do.
30	(1)	

SECTION IV

STATIONS 3 TO 4. DISTANCE, 8 KILOMETERS

0	1.92	Northeast.
10	4.98	Southwest.
20	4.47	Do
30	(1)	

SECTION V

STATIONS 30 to 31. DISTANCE, 15 KILOMETERS

0	6.94	Southwest.
10	4.18	Do.
20	1.62	Do.
40	.13	Do.
75	(1)	

STATIONS 31 to 32. DISTANCE, 15 KILOMETERS

0	2.09	Southwest.
10	2.79	Do.
20	2.29	Do.
40	0.00	
50	(1)	

STATIONS 32 to 33. DISTANCE, 16 KILOMETERS

0	6.33	Northeast.
10	4.69	Do.
20	2.41	Do.
50	(1)	

STATIONS 33 to 34. DISTANCE, 15 KILOMETERS

0	1.63	Northeast.
10	2.51	Do.
20	2.31	Do.
50	(1)	

SECTION VI

STATIONS 4 to 6A. DISTANCE, 18 KILOMETERS

0	7.77	East.
10	5.74	Do.
20	3.52	Do.
34	(1)	

SECTION VII

STATIONS 6A to 7. DISTANCE, 16 KILOMETERS

0	1.47	Southwest
10	(1)	

[1] Assumed stationary.
[2] Negligible.

With the entire column of water on the whole lightest (specific volume greatest) along shore and heaviest (specific volume smallest) off the mouth of the bay at the time, the direction of the gradient drift was clearly anticlockwise around the bay and outward past the tip of Cape Cod (fig. 199), but also with a southerly component crossing the mouth of the bay more directly from north to south. A pool of low density in Cape Cod Bay must have tended to produce a subsidiary clockwise eddy occupying most of the area between the Plymouth shore and Cape Cod.

The calculated directions and velocities also show a second but smaller eddy of the same sort centering over the southwestern edge of Stellwagen Bank, though this would not appear from the distribution of density at the surface.

Dynamic evidence thus suggests the persistence of the general southerly drift past this sector of the coast line through June, involving Massachusetts Bay, which is corroborated by the drifts of a considerable number of bottles that were put out in the bay by the *Fish Hawk* a month earlier.

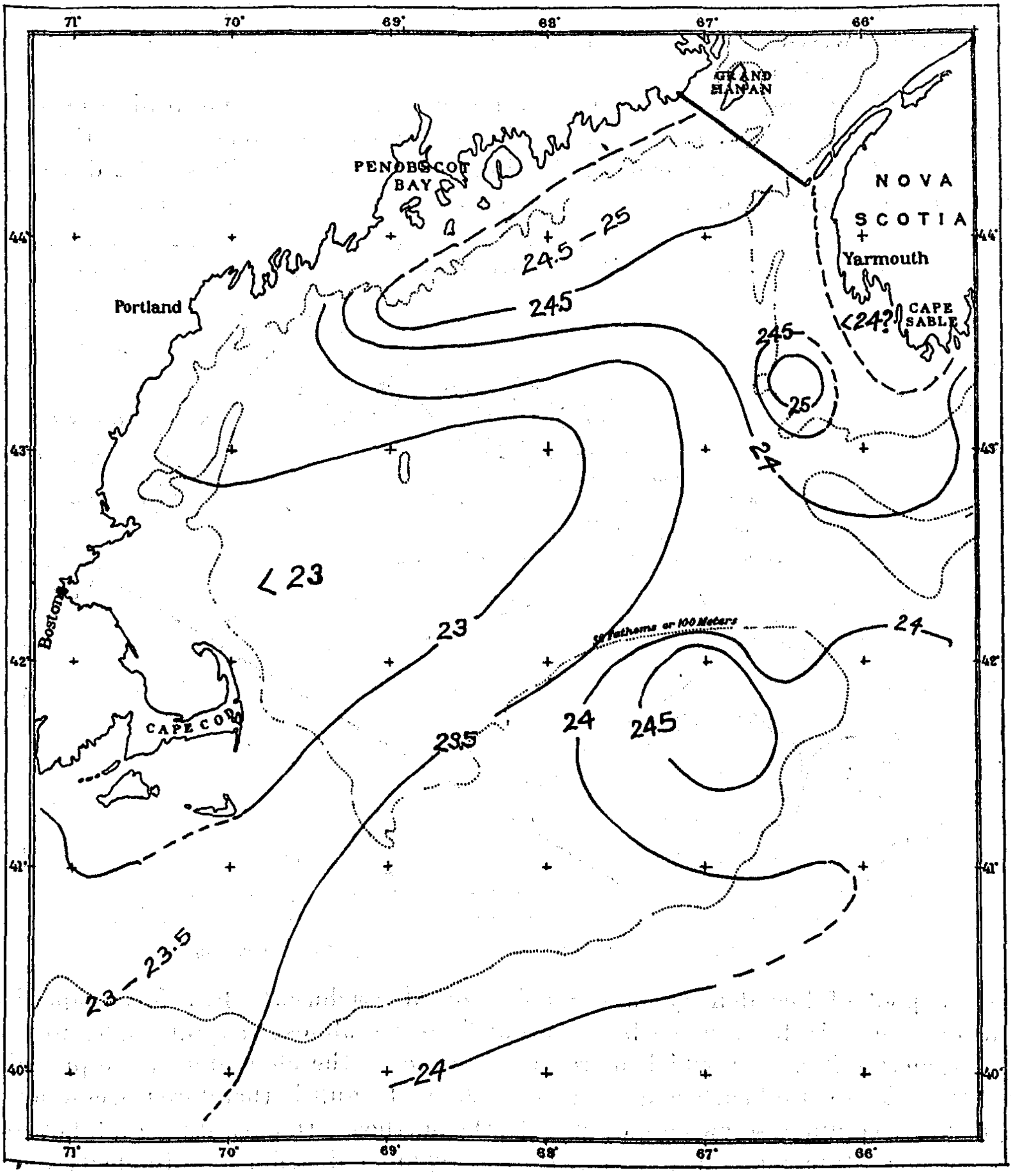

FIG. 200.—Distribution of density at the surface of the gulf, July and August, 1914

JULY AND AUGUST

The rapid solar warming of the surface over the western arm of the basin leads to the development of a pool of low density in the offing of Cape Ann by July and August (figs. 200 and 201). The eastern part of the gulf, on the other hand, continues high in surface density throughout the summer, because of the strong tidal currents that constantly mix the surface stratum, as it warms, with colder and more saline water from below (p. 928), and because the indraft of slope water of high salinity is directed into this side of the gulf. Consequently, the regional variation in the density of the upper 40 meters is wider in summer than at any other season, with the fundamental west-east gradation reappearing from year to year in essentially the same spacial relationship.

In April, and especially in May, the reader will recall, simple projection of the density contours at the surface mirrors the general dynamic tendency for the whole body of water in the gulf, regional distribution being essentially similar downward through the whole column. This, however, is not the case in summer, because the surface pool of low density in the offing of Massachusetts Bay is a superficial phenomenon. In fact, the surface contour lines run almost at right angles to those at 100 meters (fig. 202), which more nearly preserve the character of the preceding months. The actual surface drift in this side of the gulf is therefore the component of a rather complex screwing motion. In the northeastern part of the gulf, however, the surface state more nearly mirrors the regional distribution of density for the whole column.

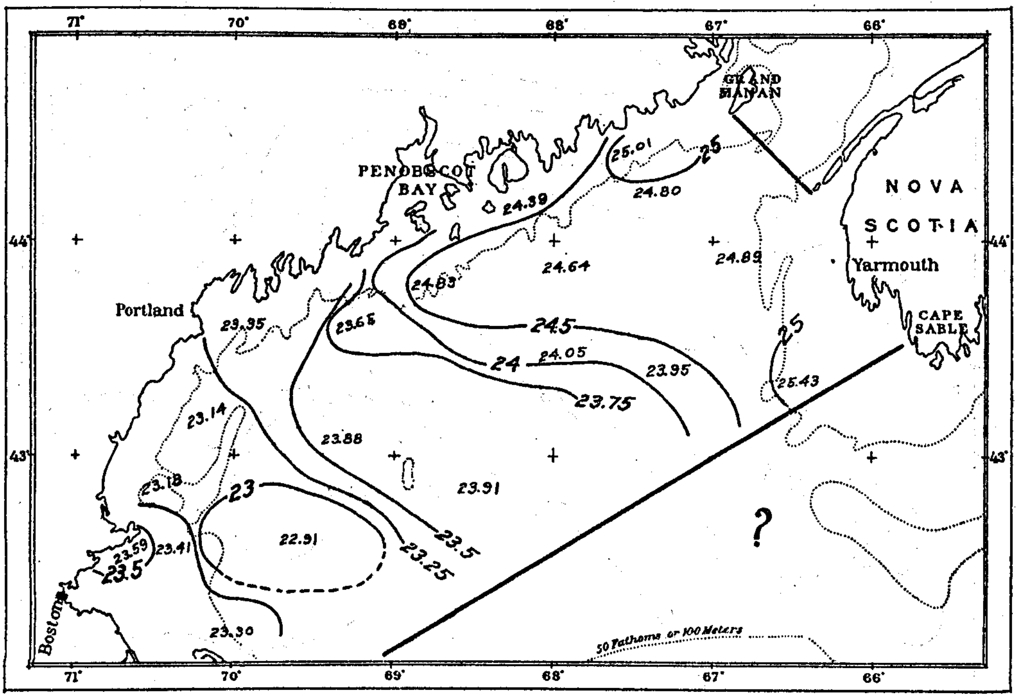

FIG. 201.—Distribution of density at the surface, for the inner part of the gulf, August, 1913

Unfortunately no one of our summer cruises has afforded the data needed for a satisfactory mapping of density for the whole area. In the only summer (1914) when the southeastern part of the area was surveyed, the coastal belt (more important dynamically) was neglected. In every case, too, allowance must be made for possible errors caused by the considerable period of time over which each survey extended. The rapidity with which the density of the upper stratum may be increased, if the surface be chilled by vertical circulation of any kind, makes it unsafe ever to lay any stress on small regional differences where tidal currents cause as much overturning of the water as they do in parts of the Gulf of Maine.

The accompanying dynamic chart for the summer of 1914 (fig. 203) shows the dynamic tendency toward circulation at the surface of the inner parts of the gulf and of the waters off Marthas Vineyard for August and of the Georges Bank-Browns Bank region for that July. Unfortunately, these two divisions of the picture are not strictly comparable because solar warming had been responsible for some slight decrease in the density of the surface stratum from the one month to the next, and for a very considerable decrease close to Cape Sable, where stations situated close together but occupied 17 days apart differed by 0.4 in density. Nevertheless, the general dynamic gradient proved so consistent for the gulf as a whole for the two months that it has seemed justifiable to neglect the time interval in drawing the contour lines; the more so since the heaviest centers for July and August proved almost exactly equal in dynamic height.

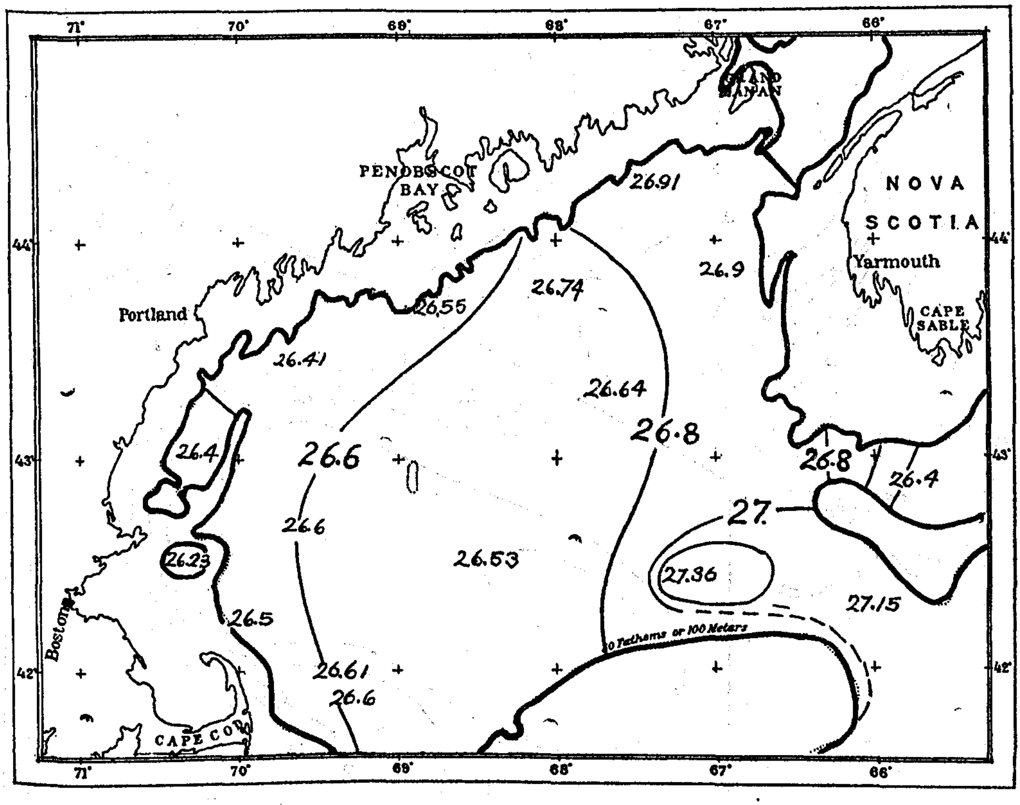

FIG. 202.—Density at 100 meters, July to August, 1914. Corrected for compression

If the chart, so combined, be indeed typical of the season (as seems likely from general knowledge of the temperature and salinity of the region), two centers of high density (indicated as "low" on the dynamic chart) are now to be expected—the one overlying Browns Bank, the Eastern Channel, and the water off the mouth of the latter; the other situated over the northeastern part of the basin; the two separated by a slight potential elevation of the surface. Contrasting with these "lows," which are obviously the vortices of anticlockwise circulation, is the high in the offing of Massachusetts Bay. A slight gradient, west to east, is also shown from the northern low toward Nova Scotia in August; a steeper gradient of the same order northward toward the coast of Maine. There is every reason to suppose that the water

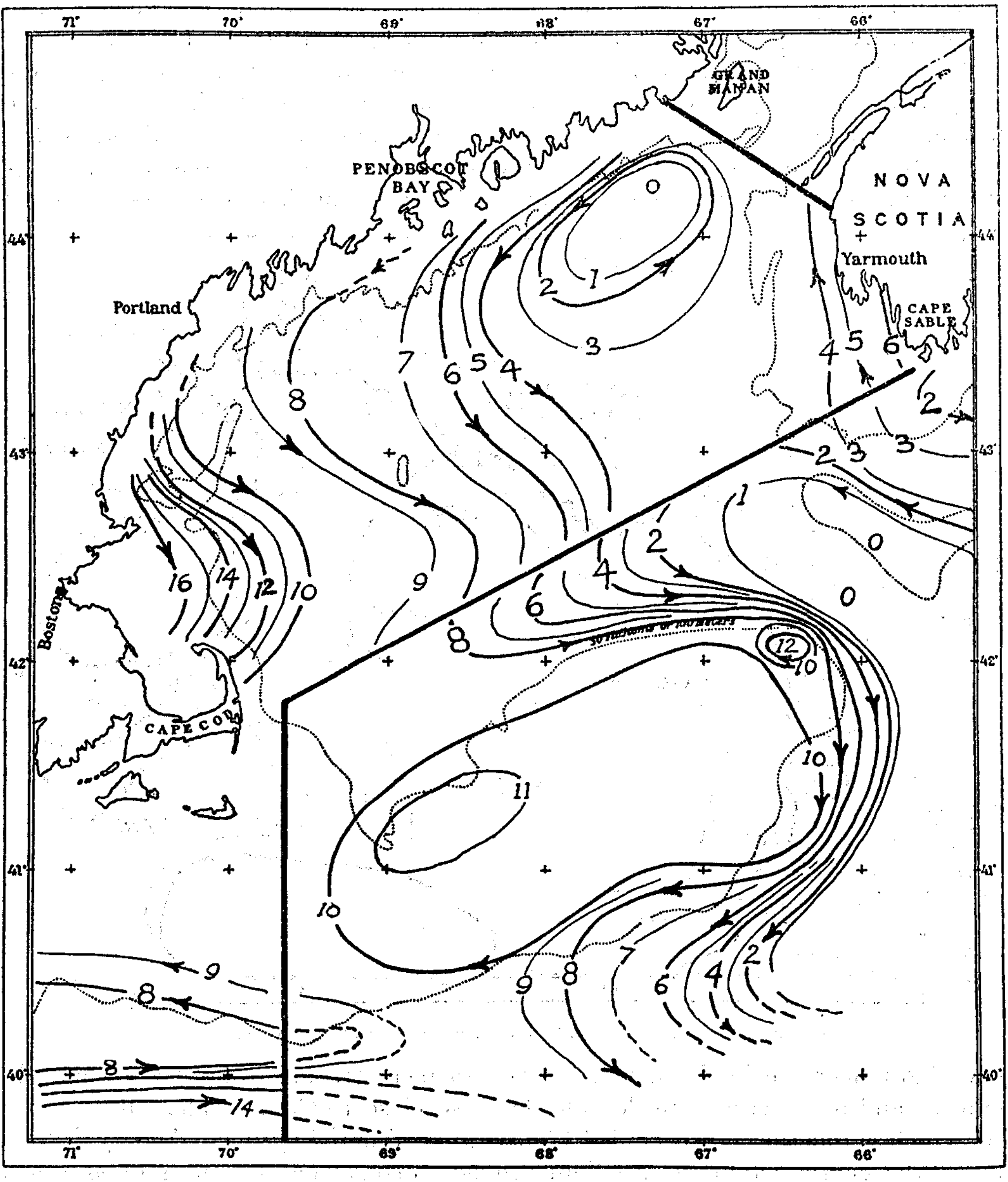

FIG. 203.—Dynamic gradient at the surface, July to August, 1914, referred to a base station in the Eastern Channel. The curves are for every dynamic centimeter. The picture south and east of the heavy dividing line is for July; north and west of it for August

was then lighter still (i. e., the surface potentially still higher) all along the coast westward from Mount Desert, where no observations were taken that summer.

Only in one small region did the dynamic contours for that July prove nonconformable to those of August—namely, in the immediate offing of Cape Sable. Here a slope rising from Browns Bank across the Northern Channel gave place to a potential dip next the cape in July, reflecting the high density of the cold water next the Nova Scotian coast reminiscent of the Nova Scotian current of a month or two earlier. Consequently, while the surface water over the Northern Channel was then drifting toward the gulf, that next the cape was drifting away from it; but the rising temperature of the next three weeks (combined with considerable freshening) so decreased the density of this relict water that by mid August a rising slope was recorded from German Bank in toward the cape, corresponding to the northerly drift toward the Bay of Fundy with which so many drift bottles have journeyed. Observations taken near Yarmouth, Nova Scotia, by Vachon (1918) in September, 1916, make it probable that in summer this sector of the coast line is normally fringed by water relatively lighter than is shown on the chart for 1914 (fig. 200).

The distribution of density in the Bay of Fundy in summer has been studied by Mavor (1923). Here the lightest water lies along the northern side in the upper 60 to 80 meters, the heaviest bottom water banking up in the central part of the basin in depths greater than about 100 meters. This type of distribution, as Mavor (1923, p. 364) makes clear, must tend to develop a surface drift from east to west toward the mouth of the bay along the New Brunswick shore. The "rising of the cold (below 7°) and salt (above 33 per mille) water in the middle of the section" indicates, as he remarks, an anticlockwise rotation of the bottom water guided by the contour of the slopes, which is consistent with the bottle drifts (p. 868).

So long as the dynamic contour of the surface of the gulf is of the general type shown on Figure 203, a generally anticlockwise type of circulation will tend to dominate the whole basin, centering some 40 to 60 miles offshore in the offing of Mount Desert Island, with a subsidiary eddy, likewise anticlockwise, involving the Bay of Fundy. The contour lines show that a southwesterly drift is then to be expected off Mount Desert Island and past Penobscot Bay, but one constantly tending offshore, veering rather abruptly southward and southeastward in the offing of Casco Bay and so out across the basin.

Off Cape Ann, too, the dynamic drift tended to the southeast in August, 1914; but a division was indicated there, with the coastal water recurving toward Cape Cod.

Comparison with the bottle tracks makes it evident that dynamic circulation of this type corresponds very closely to the drifts of the bottles set out off Mount Desert, as these have veered from southwest through south and east and so northward along the Nova Scotian coast (figs. 183 and 184). The center of this eddy movement, however, seems to have been situated a few miles farther south and west in 1923 than the dynamic chart (fig. 203) shows it for 1914.

These dynamic contours also correspond to the southeasterly component of the tracks of bottles set out off Cape Elizabeth (figs. 180 to 182) and with the fact that most of these turned offshore from the beginning and did not parallel the coast line southward toward Cape Ann, as happens earlier in the season.

It is not so easy to reconcile the continued drifts of these Cape Elizabeth bottles toward Nova Scotia and the Bay of Fundy with the dynamic contours, for the latter suggest that any driftage from the northern coast of the gulf that reached the central part of the basin would rather be drawn into the circulation around the heavy center in the Eastern Channel, and so be carried outward around the eastern end of Georges Bank. This, in fact, seems to have been the fate of some of the bottles set out off Cape Ann and of most of those set out off northern Cape Cod in 1923 (fig. 176). It seems reasonable, therefore, to conclude that by the end of July or first of August of most years the zone of demarcation between the eastward drift around the southern side of the northern heavy pool and the counter drift around the northern side of the southern pool is located somewhat farther south than it was in August, 1914—not far, in fact, from the line of monthly separation laid down on the chart for that year (fig. 203).

The distribution of density around the eastern slopes of Georges Bank affords a striking illustration of the necessity for taking account of the difference in depth between pairs of adjacent stations in the dynamic calculations, arbitrary though this correction be (p. 934). Without the inclusion of this factor (p. 934), the dynamic head between the low over the Eastern Channel and the high surface over the neighboring part of Georges Bank would have been only about 1 to 2 dynamic centimeters in July, 1914 (except for one station at the extreme edge of the bank—station 10226—where an isolated pool of low density was recorded). Inclusion of the difference in depth increases this gradient to about 10 dynamic centimeters, working out at a relative velocity of about 0.5 knot out of the gulf around the eastern end of the bank (except as interrupted by a subsidiary clockwise circulation around the light center, just mentioned), which is probably a closer approximation to the truth.

The dynamic gradient along the southern edge of Georges Bank for July, 1914 (fig. 203), offers an explanation for the fact that none of the bottles from the lines set out off Cape Ann and off northern Cape Cod, which have gone out of the gulf around the eastern end of Georges Bank, have been reported from west of the longitude of Cape Cod, when so many set out to the south of the cape have gone in that direction (p. 881; figs. 174 and 176). With the dynamic contours turning southward to sea from the eastern end of the bank, and with the surface gradient rising from longitude 67° to longitude 68°, the March state (fig. 188) is recalled.

The reasonable expectation with this dynamic distribution is that driftage leaving the gulf by this route would circle offshore somewhere abreast the eastern part of Georges Bank, to be carried toward the northeast, finally, with the so-called "Gulf Stream drift." It is probable, also, that at least three bottles that went to England and to Ireland from the Cape Ann and northern Cape Cod lines of 1923 (fig. 176) followed this route.

The whole area of Georges Bank was comparatively dead water in July, 1914, just as in March; consequently no dominant movement is indicated across it either into or out of the gulf, which is corroborated by the evidence of temperature and of salinity. The bank as a whole is therefore made the center of a clockwise type of dynamic circulation in July, just as the inner part of the gulf is of an anticlockwise type.

The dynamic state is not so clear for the southwestern part of the banks area in summer, where the rise in temperature during the time interval between the two cruises of 1914 (July 20 to 21; August 25 to 26) may have been more than counterbalanced by some encroachment of water of high salinity inward over the shelf. Consequently, the dynamic values for the offing of Marthas Vineyard for that August are not directly comparable with those taken farther east during the month preceding. However, no gradient is suggested sufficient to account for the repeated drifts of bottles westward around Nantucket Shoals from the vicinity of Cape Cod.

The dynamic relationship along the continental slope in the offing of Marthas Vineyard and eastward about to longitude 68° for July and August, 1914 (fig. 203), recalls the March state (p. 939; fig. 188) so closely that a low or dynamic trough, with the gradient rising to seaward as well as shoreward, may be taken as typical of this belt. Its circulatory implication has already been discussed (p. 939). At the date of our August profile for 1914 the calculated velocity of the easterly or "Gulf Stream" drift along the offshore edge of this low, and relative to the latter, was at least half a knot off Marthas Vineyard, or about the same as in March, 1920 (p. 939),[93] which corresponds very well with the average velocities reported in this sector of the so-called "inner edge of the Gulf Stream" by passing ships in summer.

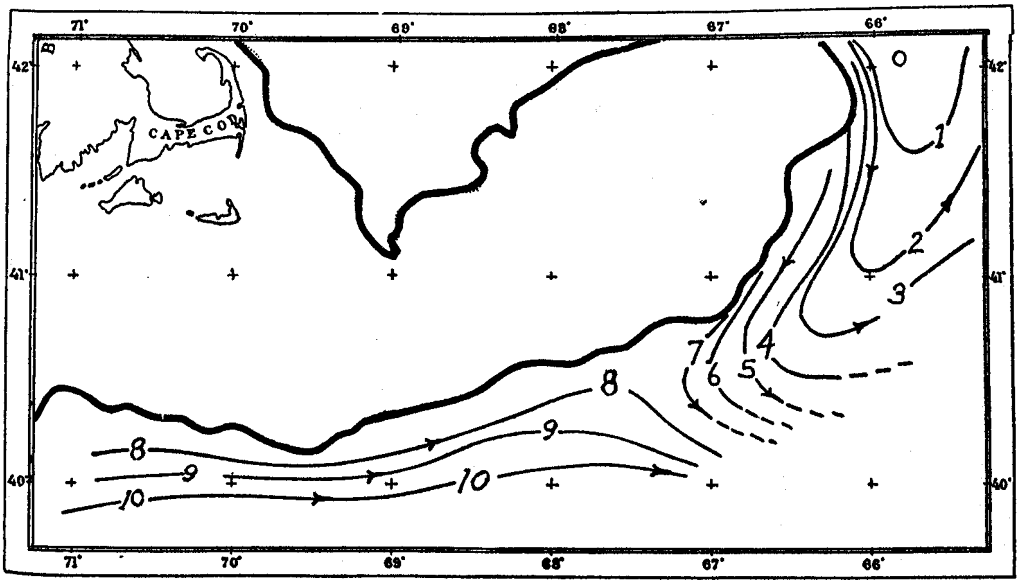

FIG. 204.—Dynamic gradient along the continental slope, bottom to 100 decibars, July to August, 1914. Contours for every dynamic centimeter

The dynamic contours at 100 decibars for that July and August (fig. 204) show the easterly set actually washing the continental slope to the west of longitude 68° then swinging offshore. We have here a ready explanation for the fact that water of high temperature and high salinity—the "warm zone"—usually bathes the slope along this western section but is separated from the slope farther eastward by the colder counter drift out of the Eastern Channel.

---

[93] For the reasons stated above (p. 939), the calculation of velocity in this region can be taken only as a rough approximation.

In August, 1914, the bottom water of the gulf, as represented by the dynamic contours at 150 decibars (fig. 205), tended dynamically to drift across the basin from northeast to southwest—i. e., from the Nova Scotian slope and the offing of the Bay of Fundy toward the southwestern side of the basin, closely paralleling the March state (p. 941; fig. 190). The mechanism by which the deeps in the offing of Cape Ann are kept supplied with slope water that has previously entered the gulf is thus made clear. However, no direct dynamic drift seems to have been operative through the Eastern Channel in either direction at depths as great as this that July or August, contrasting with the strong outflow along its western side at the surface at the time (fig.203; p. 958).

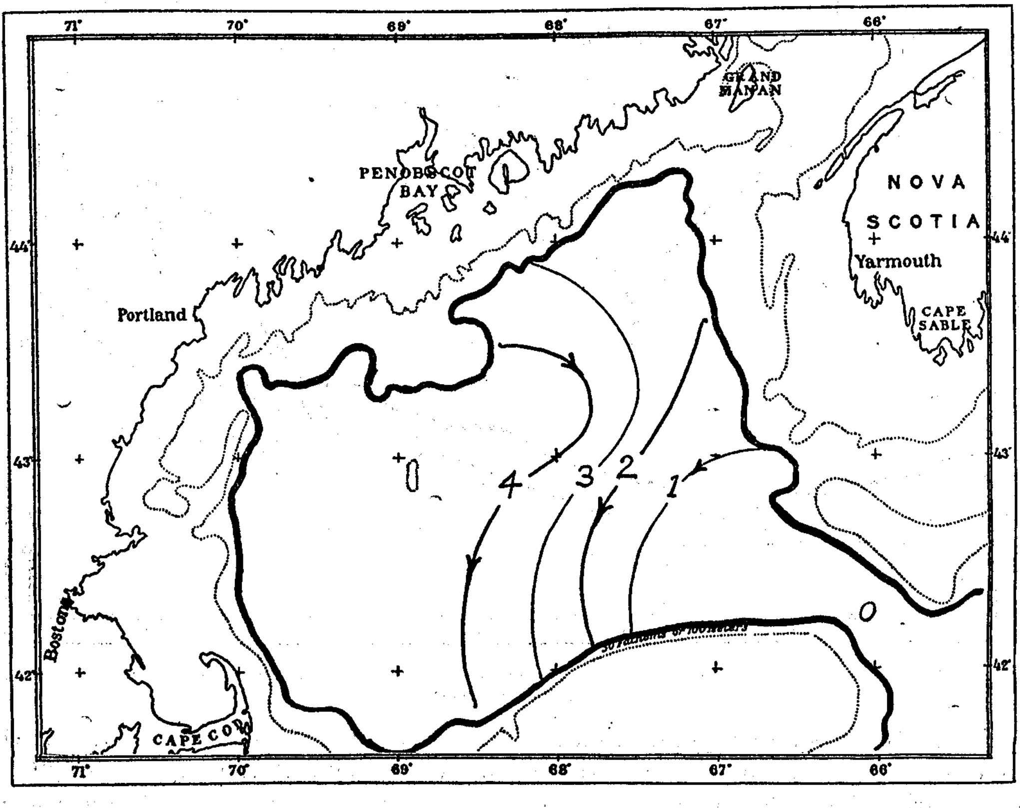

FIG. 205.—Dynamic gradient, bottom to 150 decibars, July to August, 1914. Contours for every dynamic centimeter

To test the constancy of the dynamic state of the gulf from summer to summer, a dynamic chart of the surface is also offered for August, 1913 (fig. 206, stations 10086 to 10106). Unfortunately this is not as trustworthy as the chart for 1914, because considerable interpolation of values, both for temperature and for salinity, was necessary in its construction. It is probable, also, that there was some error in the one or in the other, as recorded for two stations in the eastern side of the basin (stations 10092 and 10093), accounting in part for the contrast between the two. Nevertheless, the general gradient that results is so consistent, from station to station, that it may safely be taken as an approximation to the actual state of the northern and western parts of the gulf at the time.

Obviously, the center for the general anticlockwise gulf eddy lay considerably farther offshore in that summer than in 1914—according to the chart approximately 50 miles south of Mount Desert Island. The general drift in the northwestern and western sides of the gulf, then, more nearly paralleled the coast line from northeast to southwest, and so southward past Cape Elizabeth toward Cape Cod. Under these circumstances drifts might be expected more closely to approximate the tracks of the bottles that went from the Bay of Fundy to Cape Cod in 1919 (p. 870), rather than to show the offshore trend characteristic of the series set out off Mount Desert and off Cape Elizabeth in the summers of 1922 and 1923 (p. 895).

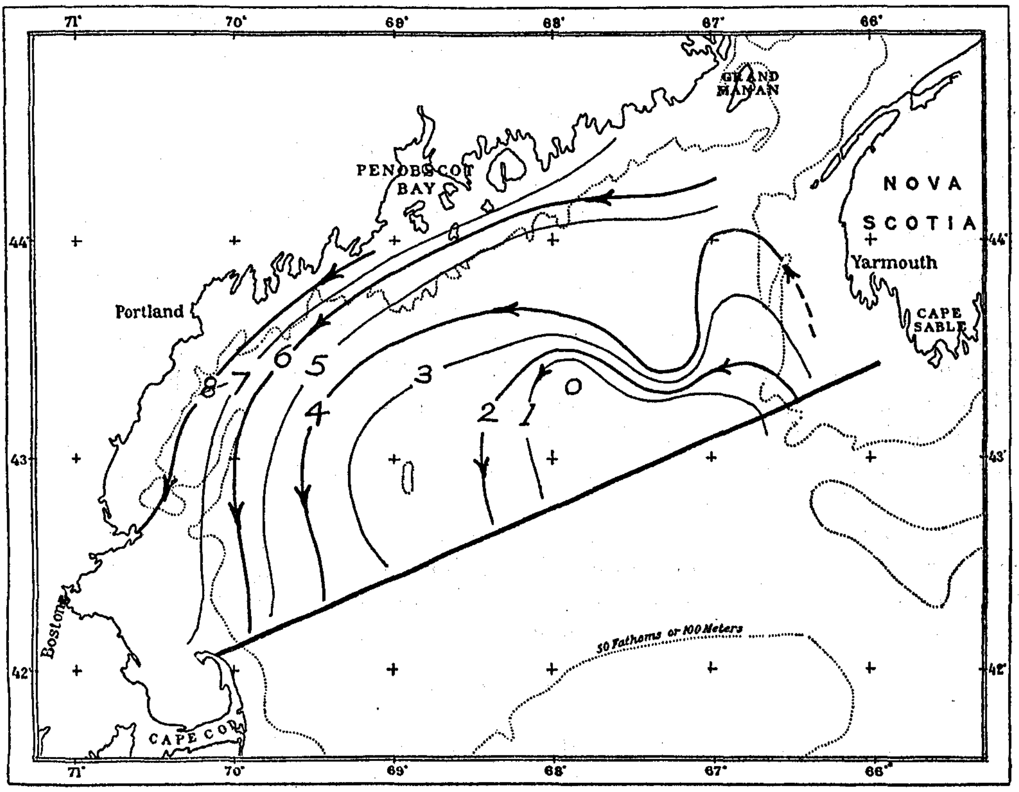

FIG. 206.—Dynamic gradient at the surface, August 4 to 20, 1913. Contours for every dynamic centimeter

In August, 1913, no data were obtained closer to the Nova Scotian coast than German Bank; but a higher surface in over the latter than over the basin suggests the northward drift to be expected on this side of the gulf. As it happens, this general scheme is obscured by a rather complex interaction between light and heavy water over the eastern side of the basin, which may, perhaps, mirror nothing more than some observational error at one or other of the two stations concerned (10092 and 10093).

Unfortunately, no observations were taken in the southern or southeastern parts of the area in August, 1913. However, the distribution of salinity (p. 767) makes it probable that the heavy water in the offing of Mount Desert was then entirely surrounded by lower densities to the south, and so separated from equally heavy water to be expected near the Eastern Channel and through the trough of the latter, just as was the case in July and August, 1914. The available data thus suggest that the dynamic tendency toward circulation continues regularly anticlockwise from summer to summer in the northern and northwestern parts of the gulf, though differences in the location of its center of revolution and in the regional distribution of density off the western shore are correspondingly reflected in the stream lines.

AUTUMN AND WINTER

Progressive equalization of temperature taking place in the shoaler strata of the gulf during the autumn obliterates the pool of low density that characterizes the offing of Massachusetts Bay in summer. As a result, the distribution of density comes to conform more and more closely to that of salinity. In the midwinter of 1920–1921 (apparently a representative season), the upper 100 meters were less dense around the coast than in the basin offshore, with the transition more abrupt in the western side than in the eastern, and the values highest in the offing of Cape Ann (station 10490).

A regional inequality of this sort must cause a dynamic tendency for the coastal belt to drift parallel with the land anticlockwise around the gulf, much as in spring (p. 942), producing a northerly set along Nova Scotia, westerly along the coast of Maine, and southerly from the offing of Cape Elizabeth past Cape Ann to Massachusetts Bay, relative to the underlying water mass. This latter (as represented by the 150-meter level) then proved nearly uniform in density horizontally (i. e., was nearly stationary). Unfortunately, no data are available for the southern or southeastern parts of the area for midwinter.

The progressive mixing of the water that takes place as winter advances makes the upper stratum more and more uniform, both horizontally and vertically, with respect to density as well as in temperature and salinity, until by February it becomes nearly homogeneous, as described above (p. 522), and the annual cycle is complete.

WIND CURRENTS

Seafarers have known, from the dawn of history, that the wind sets up surface currents often so strong that they must be taken seriously into account in navigation; and many a good ship has been wrecked from ignorance of the wind current.

In the Gulf of Maine the motive effect of the wind is made most apparent to the oceanographer by the upwellings of colder and salter water from below, which take place along its western margin when the surface water is driven offshore (p. 550). Every fisherman along our coasts knows from first-hand experience that strong winds, blowing from one quarter or another, strengthen the ebb at the expense of flood—or vice versa, as the case may be.

The dynamic principle according to which wind currents are produced is extremely simple: The wind drives the surface water before it, the motion of the latter being propagated to underlying strata by the internal friction of the water. Once in motion, the water, as Nansen (1902) and Ekman (1902) have pointed out, must be deflected by the effect of the earth's rotation. Nansen's (1902) observations on the drift of

Arctic ice, with subsequent studies of currents at lightships and analyses of wind and drift at localities widely separated in the Baltic, North Atlantic, Mediterranean, North Pacific, and Adriatic unite in proving that the wind drift does, in fact, average to the right of the wind in the northern hemisphere, to the left of it in the southern, as theory demands.

According to Ekman's (1905) more recent mathematical analysis, the surface drift in a free ocean of unlimited depth will be deflected 45° to the right of the direction of the wind in the Northern Hemisphere, more and more to the right with increasing depth, but decreasing correspondingly in velocity until a level (the so-called "frictional depth" is reached where the drift is opposite the wind but at only about one twenty-third the strength of the surface current. The depth of this level depends on the strength of the wind and on the latitude; theoretic calculation for homogeneous water of a specific gravity (1.025) approximating that of the shoaler water of the Gulf of Maine (Smith, 1926, p. 47, Table 14) locates it at 45 to 90 meters for the latitude of the Gulf of Maine, with winds ranging in strength from 15 to 20 nautical miles per hour (Beaufort scale, 3 to 4).

The Gulf of Maine lies within the belt of variable winds, frequently reversing in direction. The length of time required for the full development of a wind current is therefore important. This is affected by many factors; but Ekman's mathematical study with the measurements of wind and currents, which have been made at lightships in various seas, makes it almost certain that only a few days are required at the latitude of the Gulf of Maine. It is therefore reasonable to assume that winds prevailing from a given quadrant of the compass for 50 to 70 per cent of the time, such as actually blow over our gulf, are sufficiently constant in direction to play a major rôle in governing the circulation of at least the upper stratum of water, if not of the deeper levels.

If, then, the water of the gulf were homogeneous, free to move in any direction, and considerably deeper than the "frictional depth," moderate winds, blowing comparatively steadily from one general direction for a few days, should set the whole upper 45–90 meters in spiral. Actually, however, the vertical stability and generally stratified state of the water of the gulf tend greatly to limit the depth to which wind currents may be expected to penetrate downward.

The angular deviation of the wind current from the direction of the wind may also differ widely at sea from the theoretic expectation. If the depth of water be less than the frictional depth, the angle will be less; and while this limitation does not affect the development of wind currents in the basin of the gulf, it does affect the coastal belt out, say, to the 40 to 50 meter contour. The vicinity of the coast line, with the contour of the bottom, also governs the directions which surface drifts, set in motion by the wind, must actually follow. The effects of these influences have also been attacked mathematically by Ekman (1905); but, as Krümmel (1911, p. 469) has emphasized, so many variables, which can not be exactly measured, enter in that the surface currents which the wind has actually been found to set up in other coastwise localities, in comparable latitudes, still afford the best available indication of what is to be expected in the Gulf of Maine.

Long series of measurements of the currents at various lightships in the Baltic[94] have shown the nontidal surface drift averaging about 30° to the right of the wind, and much more often to the right than to the left. Analysis by Forch (1909) of the relationship between the wind in the eastern Mediterranean, and the drifts there, as reported in ships' logs for the Arabian Gulf by Gallé (1910), have brought out a corresponding tendency for the current to set about 40 to 60° to the right of the wind.[95] According to the current tables published by the United States Coast and Geodetic Survey (1923), local winds off the eastern coast of the United States likewise produce currents setting about 20° to the right of the wind direction at a velocity about 1½ per cent of that of the wind.[96]

The Baltic measurements just mentioned had already proved that the current sometimes sets to the left of the wind, due, no doubt, to the effect of the coast line. This relationship between coast line and wind current has been brought out very clearly by a recent investigation of the currents at five lightships along the Pacific coast of the United States by the Coast and Geodetic Survey. For a detailed account of these observations the reader is referred to Marmer (1926 and 1926a). In summary they are as follows: Offshore winds and winds parallel to the shore, if having the latter to the left, produce surface currents averaging 20 to 25° to the right of the wind; but if the wind blows against a coast line lying to the right of its track, at an angle of 45° or less (i. e., a southwest wind against a north and south shore line), the current is deflected to the left as it strikes the coast, as might naturally be expected from ordinary observation on the behavior of the tides.

The observations tabulated below (p. 964) for Portland lightship also show the nontidal current drifting to the right of the wind during months when winds blowing toward the southern half of the compass favor the dominant southerly set. When the wind blows toward the north or northeast against the current, the latter may or may not be reversed. If it is, the resultant set may be either to the right of the wind or slightly to the left of it, depending on the complex interaction between direction and strength of wind, nontidal set, and the trend of the coast line.

Dominant surface set and prevailing wind at Portland lightship

Month	Current [a]	Wind [a]	Current to right	Current to left
1913				
October	S. 67° W	S. 2° E	69°	
November	S. 31° E	N. 84° E	65°	
December	S. 11° W	S. 50° E	61°	
1919				
June	S. 36° W	N. 3° E		147°
July	N. 62° E	N. 28° E	34°	
August	S. 74° W	N. 33° E		139°
September	N. 47° E	N. 27° E	20°	
October	N. 58° E	N. 73° E		15°

[a] The directions are those toward which winds and currents set. For full data see pp. 861 and 862.

---

[94] Dinklage (1888), Witting (1909), summarized by Krümmel, 1911, p. 451.

[95] For theoretic discussion and explanation of modern mathematical methods of calculating wind currents see Ekman (1905), Krümmel (1911), Sandström (1919), and Smith (1926).

[96] This statement has as its basis current measurements taken at a large number of localities, some of which are discussed above (p. 963).

The following tables, supplied by the United States and Canadian weather bureaus, show the prevailing winds, by months, for several stations around the coast of the gulf and over the latter.

Average percentage of winds from each direction (10 years, 1911 to 1920)

BOSTON, MASS.

Month	North	North-east	East	South-east	South	South-west	West	North-west
January	10	5	2	6	3	23	28	23
February	11	5	4	3	5	17	31	24
March	12	7	6	6	8	17	24	20
April	9	11	12	7	6	16	18	21
May	8	9	13	8	8	21	18	15
June	10	9	15	6	6	23	18	13
July	5	6	10	5	8	33	21	12
August	7	8	10	7	11	25	18	14
September	11	7	6	8	9	22	19	18
October	9	7	7	7	10	23	20	17
November	10	4	4	4	7	20	32	19
December	10	4	3	3	5	16	32	27
Average for 3 winter months	10	5	3	4	4	19	30	25
Average for 3 summer months	7	8	12	6	8	27	19	13
Average for year	9	7	8	6	7	21	23	19

PORTLAND, ME.

January [1]	21	6	1	3	6	19	19	24
February [1]	22	4	1	4	8	17	19	24
March	17	6	3	5	13	15	18	23
April	18	12	6	4	13	13	14	20
May	12	10	9	7	21	14	12	15
June	10	11	10	8	18	14	13	16
July	11	7	7	6	25	19	15	10
August [1]	9	7	9	8	23	18	11	14
September [1]	14	7	4	5	18	19	12	20
October	15	4	4	6	15	22	15	19
November	18	4	2	4	8	24	19	21
December	21	4	1	3	5	21	19	26
Average for 3 winter months	22	5	1	3	6	19	19	25
Average for 3 summer months	10	8	9	7	22	17	13	13
Average for year	16	7	5	5	14	18	15	19

EASTPORT, ME.

January	11	7	5	4	8	17	27	21
February	11	9	4	4	6	16	28	22
March	10	8	5	5	13	17	20	22
April	12	14	8	3	17	16	13	17
May [1]	10	11	6	3	30	16	9	14
June	6	12	7	4	31	15	11	14
July [2]	6	9	3	2	40	21	8	9
August [1]	4	9	4	3	38	18	10	13
September [1]	9	6	5	3	22	21	12	21
October	10	6	5	2	22	20	14	21
November	10	9	4	3	9	24	21	20
December	14	7	6	4	6	13	27	23
Average for 3 winter months	12	8	5	4	7	15	27	22
Average for 3 summer months	5	10	5	3	37	18	10	12
Average for year	9	9	5	3	20	18	17	18

[1] One per cent calm.

[2] Two per cent calm.

Average percentage of winds from each direction (10 years, 1911 to 1920)—Continued

YARMOUTH, NOVA SCOTIA

Month	North	North-east	East	South-east	South	South-west	West	North-west	Calm
January	15	12	10	9	6	10	6	30	2
February	16	13	9	8	7	7	7	29	4
March	17	9	7	7	9	11	10	26	4
April	13	10	10	8	9	12	13	20	5
May	11	6	6	10	16	18	15	16	2
June	8	3	6	8	20	20	15	14	6
July	5	3	4	6	20	31	14	8	8
August	6	2	5	6	20	23	11	14	13
September	13	7	6	7	14	15	11	15	12
October	15	8	9	7	14	18	10	13	6
November	15	12	10	5	6	14	11	23	4
December	16	14	10	8	5	10	5	30	2
Average for 3 winter months	16	13	10	8	6	9	6	30	--------
Average for 3 summer months	6	3	5	7	20	25	12	12	--------
Average for year	13	8	8	7	12	16	11	20	--------

Five-degree square, including Gulf of Maine, from pilot charts

Month	Percentage of winds from the most frequent quadrant	Month	Percentage of winds from the most frequent quadrant
January	North to west, 63.	July	West to south, 68.
February	North to west, 73.	August	West to south, 50.
March	North to west, 57.	September	Northeast to northwest, 49.
April	North to west, 58.	October	North to west, 58.
May	West to south, 50.	November	North to west, 64.
June	West to south, 45.	December	North to west, 63.

These tables may be briefly summarized as follows:

Along the western and northern shores of the gulf the wind blows most often between southwest and north in winter, averaging about northwest. In summer southwesterly and southerly winds prevail. On the eastern side of the gulf the wind averages more westerly (south to northwest) in summer, northerly (between northwest and northeast) in winter. Over the offshore waters of the gulf, where the direction of the wind is not so much influenced by the diurnal warming and cooling of the land, the prevailing winds are between west and north (though with frequent reversals) from November to April; between west and south from June to August; more variable in late spring and again in early autumn.

In summer, by theoretic expectation, winds of this character would tend to produce a general drift of the surface water about 20° to 45° to the right of the octant, north to northeast—i. e., toward the northeast and east. Thus, the prevailing winds favor the general drift out from the western side of the gulf and eastward across the southern part of the basin toward Nova Scotia, which prevails at that season (p. 974). Striking Nova Scotia, this wind current would tend to bank up against the coast, raising the level of the sea slightly. Thereupon hydrostatic forces are brought into play, dynamically, against the wind; but any resultant movement of the water out from the land being in turn deflected to the right by the earth's rotation, a northerly drift might be expected to result along Nova Scotia, and in this instance theoretic expectation agrees so well with the drifts of bottles actually recorded that the prevailing southwesterly winds of summer certainly assist the surface drift from south to north, which characterizes the eastern side of the gulf at that season, though as certainly not the only motive force for it.

Thus, the wind then tends to act as a motive force for the southern and eastern sides of the Gulf of Maine eddy.

It is obvious, however, that no matter how steadily the wind blew from the southwest it could not drive the entire surface of the gulf eastward unless the water were nearly enough homogeneous to allow a sinking current to develop in the eastern side, with the deeper stratum so fed flowing back from east to west, to well up again, in turn, in the western side. Circulation of this sort probably does take place to some extent along the Nova Scotian side of the gulf, in the Bay of Fundy, and along the coast of Maine east of Mount Desert, where active tidal currents keep the water so thoroughly stirred that it has little stability at most times of year. It is certain, also, that offshore winds do cause more or less upwelling along the western shore line, but the basin of the gulf as a whole, with its western and northwestern margins, is so stable vertically that hydrostatic forces very strongly oppose any such "jibing," as Sandström (1919) terms it. Consequently, any constant movement of the surface water northward toward the Bay of Fundy would tend to cause an "overflow" in the shape of a westerly drift along the coast of Maine—i. e., *against* the winds prevailing in summer.

It is obvious that if the water be in stable equilibrium, southwesterly winds might or might not set a closed circulation of this type in motion, depending on their relative strengths and constancy in various parts of the gulf; depending, too, on the balance in various parts of the gulf between the hydrostatic forces opposing jibing and the tendency of the wind to cause that process, as just explained. To value these several factors will require a knowledge of the gulf and of its winds much more intimate than can yet be claimed. It is certain that with winds reversed as often as they are over the gulf the balance varies constantly. However, the preceding analysis does make it clear, I think, that any eddying circulation which the southwesterly winds of summer might set up in the surface stratum of the gulf would shortly assume the anticlockwise character that, by evidence of more direct sorts, does actually dominate its basin. Consequently, the summer winds parallel the hydrostatic forces set in operation by regional inequalities of density in their general effects to this extent. On the other hand, the current flowing southward and out of the gulf past Nantucket Shoals, which forms part of the overflow from the gulf, is at right angles to the potential wind drift, hence holds its dominant set in spite of the prevailing wind. Neither can the wind be held responsible for the westerly drift of slope water along the continental edge in summer, because this current sets directly against the drift which the prevailing southwesterly winds would tend to produce there.

The wind current, as it extends its effects deeper and deeper below the surface, will turn more and more to the right of the wind (losing, also, in velocity by geometric progression); also, with increasing depth the gulf becomes more and more nearly inclosed, so that any currents, however set in motion, are more and more directed by the contour of the bottom.

The depth to which currents of wind origin do actually penetrate in the Gulf of Maine is therefore of immediate interest. Unfortunately, no mathematical method yet suggested can measure this, even approximately. However, it is certain that the stable state of the water of most parts of the gulf ordinarily confines wind currents to a stratum much shoaler than the theoretic "frictional depth" as calculated by Smith for homogeneous water at corresponding latitudes (p. 963).

With an average wind strength of 3 to 4, by the Beaufort scale (a fair average from the gulf in summer), this depth is set by him as about 43 to 70 meters at latitudes 40° to 50°. It is not likely, however, that the wind ever sets water as stable as that of the western side of the gulf in motion half so deep as this during the brief periods when it blows steadily from any given direction at a strength as great as 4, on the Beaufort scale (about 20 nautical miles per hour), during the summer months. With the more usual summer breezes no stronger than 10 to 15 miles per hour (2 to 3 on Beaufort scale), the frictional depth must be even smaller. Frequent reversals of the wind direction, with periods of calm, also further hinder the propagation of wind currents downward into the underlying water. On the whole, then, it is unlikely that wind currents are effective deeper than 10 to 20 meters in the gulf in summer, except perhaps during brief periods of windy weather. Even if this limitation be too small it leads to the important conclusion that whatever currents may be set up in the gulf in summer by the wind are confined to a very thin superficial stratum, and that the dominant anticlockwise and estuarine circulation of the deep water below the 40 to 50 meter level is caused by hydrostatic forces and by the tidal oscillations (p. 970).

The pulses of slope water into the gulf via the trough of the Eastern Channel are equally independent of the wind.

In winter the winds of the gulf of Maine area blow stronger (average about 3 to 5 on the Beaufort scale), and the prevailing quarter is northwest (p. 966). Winds of this character tend, theoretically, to drive the surface water of the whole gulf out to the southward, toward the open sea. Probably it is this prevalence of strong offshore winds all along the North American seaboard, from Chesapeake Bay to the Gulf of Maine, during the cold season, which is primarily responsible for the recession of the tropical water from the edge of the continent during autumn and winter, their cessation allowing its inshore movement in summer. The prevailing northwest winds of winter tend, therefore, to strengthen the dominant southerly drift along the western side of the gulf. With the coast line trending north and south, the deflective effect of the earth's rotation gives a long-shore character to currents caused by winds from this quarter, except so close in to the land that the whole depth of water is less than the frictional depth. Under these last conditions (by Ekman's calculation) the wind current will set more nearly with the wind than in deeper water offshore.[97]

Consequently, the prevailing winter winds from the northwest quadrant do not tend to cause any general or constant upwelling along the coast sector from Cape Ann to Cape Elizabeth except within 2 to 3 miles or so of the land, where the water is shoaler than one-fourth the assumed frictional depth of 50 meters. This is corroborated by our station data, but upwellings, such as are actually recorded (p. 588), necessarily tend to follow these same west to north winds along the north shore of Massachusetts Bay. This same tendency for water to well up from below must operate spasmodically throughout the winter all along the coast of Maine, where

---

[97] Theoretically, 21.5° to the right of the wind, if the depth of water be one-fourth the frictional depth.

prevailing winds (and the strongest winds), between west and north, drive the surface water offshore to the southward.

By this reasoning wind currents go far to explain the very interesting fact that in April the freshening effect of the spring freshets is so much more evident (in lowered salinity at the surface) along the coast sector west and south of the Kennebec than it is off Penobscot Bay (fig. 101). The discharges from the former, from the Saco, and from the Merrimac, driven southward by the prevailing northwesterly winds of March and April, parallel the trend of the coast and so preserve the identity of the coastwise belt of low salinity. Off Penobscot Bay, however, the more or less active upwelling that must follow this same southerly drift off this west-east coast line, combined with tidal stirring, tends to prevent the development of so fresh a band next the land, but at the same time to carry the least saline water farther out from the land. The distribution of salinity at the surface for March and April, 1920 (figs. 91 and 101), is of this sort.

It is probable that the development of a tail of very low salinity from the St. John River southward across the Bay of Fundy in April (p. 808) similarly reflects a southerly set caused by the northwest winds, which often blow strong there during the first month of spring, though their average direction veers through west to southwest during April.

The pool of low-surface salinity spreading out to the southwest from Nova Scotia, which appears on the surface chart for March, 1920 (p. 703; fig. 91), likewise finds plausible explanation as a wind-driven drift out from the bays south of Yarmouth, where northerly winds prevail in February (p. 966).

The effects of the winter winds are more puzzling in the eastern side of the basin of the gulf, where prevailing west-north winds tend to produce a southeasterly or southerly drift at the surface, but where the evidence of salinity and temperature points to a movement in just the opposite direction—i. e., northerly toward the Bay of Fundy in winter as well as in summer (p. 910).

It is evident here that although strong northerly winds may and no doubt do temporarily drive the surface water southward, the general dominant drift is caused not by the wind but by other forces (p. 976) strong enough to overcome the wind effect in the long run. Consideration of the depth to which wind currents may be set in motion corroborates this conclusion, because the frictional depth of the average winter wind of about 4, on the Beaufort scale, is theoretically only about 67 meters. Actually, the water of the eastern side of the gulf not being homogeneous, the depth of the wind current will be something less than this—perhaps 50 meters with the state of stability prevailing in winter. The thickness of the stratum which the wind can set in motion at an appreciable rate is still less.

According to the long series of observations on wind and current that have been carried out by the United States Coast and Geodetic Survey, the velocity of the wind current is 1.5 to 2 per cent that of the wind—say, about 0.4 knot, with a wind of 4 (Beaufort scale, 20 nautical miles per hour). Smith's table of theoretic velocities (Smith, 1926, p. 46, Table 8), applied to a current of this strength with assumed frictional depth of 50 meters, gives a residual current of only 0.2 knot at a depth of 10 meters, about 0.15 knot at 20 meters, and 0.07 knot at 30 meters. Theoretically (in a free ocean), in the example just stated the current at 10 meters should set 36°

to the right of the surface current, the water at 20 to 30 meters 72° and 108° to the right of it, respectively.

This calculation shows that even in winter wind currents are virtually negligible in the Gulf of Maine at depths greater than, say, 20 meters, and so weak at 10 to 15 meters that they can oppose but little resistance to hydrostatic forces or to tidal oscillations (as deflected by the earth's rotation), which may tend to drive the water in the opposite direction.

The general effect of the wind on the circulation of the gulf may be summarized as follows: In summer the prevailing southerly-southwesterly winds tend to maintain the anticlockwise circulation of the surface water, so far as they are effective at all in producing a constant circulation. It is probable, also, that the easterly set caused by the wind is chiefly responsible for the accumulation of the surface pool of high temperature, though low salinity, in the offing of Massachusetts Bay, which is characteristic of July and August. The outflow that takes place southward past Cape Cod and over the eastern end of Georges Bank, however, is against the prevailing wind. In winter the prevalent northwesterly winds assist the southerly drift in the western side of the gulf and are the chief cause for the wider dispersal of water of low salinity off its northern shore than off the western, but the general movement of water inward (northward) along the eastern branch of the basin is contrary to the wind.

Winter as well as summer wind currents are confined to the upper 10 to 20 meters. Consequently the dominant circulation of the deeper strata does not receive its motive power from this source.

HORIZONTAL TIDAL OSCILLATIONS AS DEFLECTED BY THE EARTH'S ROTATION

Huntsman (1923, 1923a, and 1924) recently has suggested that the tidal oscillations deflected by the effect of the earth's rotation are the chief motive force for the great eddies, anticlockwise and clockwise, that occupy the basins and circle about the islands and submarine banks in high latitudes. In his own words (Huntsman, 1924, p. 278), "the rotation of the earth" acts "as an imperfect valve in diverting the ebb and flood toward opposite sides of the channels and basins," thus causing a balance of inflow on the one side, of outflow on the other.

That the earth's rotation must exert a deflective effect on the tidal currents is beyond dispute. It is equally clear that if the oscillatory (back and forth) movement of the tides of any partially inclosed basin be altered by any agency into a progressive forward movement, the current, like any other, will be held against the right-hand bank in the northern hemisphere by the deflective force of the earth's rotation, and thus circulate anticlockwise, as Huntsman states. Furthermore, the deflective effect of the earth's rotation as it affects the tidal oscillation, if effective at all in this respect, must be most definitely so in regions where tidal currents attain considerable velocities at the strength of flood and ebb, as they do in the Gulf of Maine.

Beyond stating this proposition and certain applications of it to definite regions, Huntsman has not yet published any discussion of the dynamic principles involved, nor am I able to give it the physical analysis necessary for its proof or disproof.

However, there are certain grounds for concluding that Huntsman's theorem is probably effective in basins sufficiently inclosed, and that if so, the tides and earth rotation combined must have an unceasing pumping effect, working season in and season out on the following principle:

In the open sea, with no barrier to the free movement of the water, the rotation of the earth will merely change the track of ebb and flood (if flowing back and forth with equal velocity) from a right line to a closed ellipse; but in an inclosed basin, open to the tides only at one side, the case becomes altered by the fact that when the tide is flowing in the water is confined and prevented by the right-hand shore from eddying to the right. Consequently, the band of water closest the land on that side must either flow farther in, parallel to the coast, than it would if unconfined, or it must rise higher against the bank. No doubt both results actually follow. When the water next the land is so diverted from its normal path water farther out toward the center of the basin is correspondingly prevented from eddying to the right. Consequently, the effect of the shore line, in turning the flood tide to the left from the track it would follow if free to flow in any direction, extends far out to sea from the confining bank against which it presses. Under such circumstances the deflective effect of the earth's rotation tends to transform what is fundamentally an inshore current into a drift flowing into the basin in question, paralleling the shore line.

In the opposite side of the basin, which lies to the left of the flood tide, setting inward, this deflective force tends to turn the inflowing current away from the shore; consequently, it is reasonable to assume that the flood will not flow as far inward as it would otherwise. When the tide begins to ebb out of the basin conditions naturally are reversed, the ebb being driven against the coast, which is to the right of it (but to the left for the flood), and so carried farther out, but turned away from the side against which the flood was pressed as it flowed in.

The mobility of the water makes the picture exceedingly difficult to visualize or to represent by any diagram, and very likely complicated by vertical movements screwing forward, which I can not attempt to reconstruct; but as a net result it is reasonable to expect the flood to flow in farther than the ebb makes out in that side of the basin which is to the right of an inflowing current, and for the ebb to flow out farther than the flood makes in, in the opposite side. With a differential of this sort established an eddying movement would necessarily follow, forced to assume anticlockwise form by the confining shore line, in place of the clockwise character which the rotation of the earth would give it if not so opposed by the coast line or by the contour of the bottom. Translated into terms of the Gulf of Maine this would call for a dominance of flood over ebb (hence a northerly component) in the eastern side and a dominance of ebb over flood (i. e., a southerly component) in the western, such as has actually been demonstrated by drift bottles and by measurements with current meters.

Tidal currents in the gulf of Maine, the reader will recall, run nearly as strong right down to the bottom of the trough as they do at the surface. Consequently, Georges Bank, confining the basin on the south, should act as a coast line toward the deep tidal circulation, producing a west-east drift paralleling its northern slopes, if the foregoing analysis be correct. Here, again, the theoretic expectation is actually reproduced by the drifts of bottles that have crossed the southern side of the gulf from west to east (p. 886), corroborating Huntsman's (1923a, p. 18) conclusion that the dominant circulation in basins of this sort is kept in motion by the deep currents, not by the movements of the surface water. The clockwise drifts, which have been found to circle (or partly circle) several of the submerged banks (Georges, for instance (p. 974), and Nantucket Shoals), are also equally good evidence of dominance of the general circulatory scheme by the current flowing over the bottom, which the banks deflect just as islands would.

SUMMARY OF THE HORIZONTAL, NONTIDAL CIRCULATION OF THE GULF OF MAINE

The nontidal circulation of the Gulf of Maine (fig. 207) is essentially estuarine in type, as might have been expected from the contour of its bottom as well as from the trend of its coastline and from the large volume of fresh water discharged from the rivers tributary to it. The very considerable outflow from the gulf takes place at and near the surface—southward and westward past Nantucket Island and Shoals, in part, but in part as a clockwise movement circling around the eastern part of Georges Bank.

The evidence marshaled in the preceding pages—measurements with current meters, drifts of bottles, temperatures, salinities, distribution of the plankton in the superficial waters, and dynamics—can be harmonized with one type of dominant circulation only—a general anticlockwise eddy around the basin of the gulf. The demonstration of this, named by Huntsman (1924) and by me the "Maine" or "Gulf of Maine" eddy, with all it implies in its biological bearing, is perhaps the most interesting result of the joint explorations of the gulf.

The circulatory features most clearly established within the gulf are as follows:

The eddying drift is operative throughout the year but differs in velocity, and generally in detail, from season to season. It is also complicated by subsidiary eddying movements in the Bay of Fundy, Massachusetts Bay, Vineyard Sound, around Nantucket and Nantucket Shoals, and around and over Georges Bank, which are clockwise around these shoals but anticlockwise in the bays and basins, as Huntsman has shown to be the rule in northeastern American waters.

In the late summer and early autumn, when our information is the most extensive (fig. 207), the surface stratum of the inner part of the gulf eddies anticlockwise around an area of high density, the precise location of which shifts, from summer to summer, from the offing of the Bay of Fundy to a center in latitude about 43° to 43° 30′, 60 to 70 miles southerly from Mount Desert Island.

The eastern side of the circling movement follows so definite a track northeastward and then northward, paralleling the coast of Nova Scotia, that at least 8 per cent of all the bottles yet put out in the gulf off Cape Ann and to the northward are known to have followed this route, no doubt with others not reported for one reason or another. The large number of bottles that have stranded on that coast shows a strong tendency inshore. This Nova Scotian side of the Gulf of Maine eddy also receives water in some volume from the dead zone off Cape Sable in summer, and in some years a westerly drift past Cape Sable into the gulf of Maine persists from spring through summer.

A definite indraft into the southern side of the Bay of Fundy along its Nova Scotian shore is sufficiently demonstrated. However, this involves only the outermost edge of the Gulf of Maine eddy, the inner part of which continues northward across the mouth of the bay, a route followed by some of the bottles.

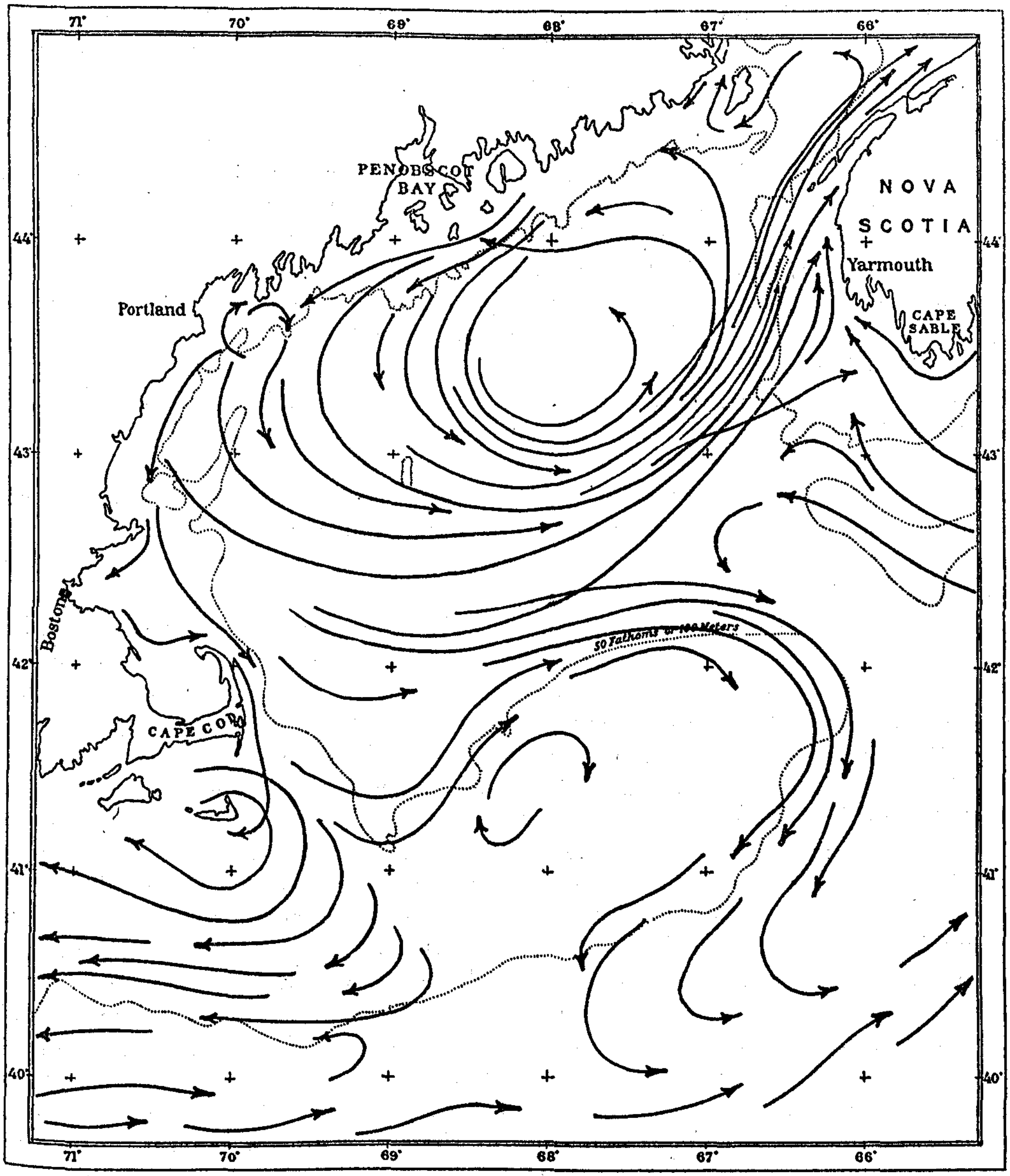

FIG. 207.—Schematic representation of the dominant nontidal circulation of the gulf, July to August

Within the Bay of Fundy the water eddies inward along the Nova Scotian side, outward along the New Brunswick side and to the southward of Grand Manan Island. However, there is some evidence that the latter forms the vortex of a second eddy of the opposite sort (clockwise) carrying water inward to the Bay of

Fundy along the Grand Manan shore of the Grand Manan Channel, with still another counter movement outward (westward) along the northern shore of the channel.

Bottle drifts identify the coastal belt between the west end of the channel and Petit Manan, some 35 miles to the westward, as to some extent a dead zone (p. 907) intervening between the coast line and the inshore edge of the gulf of Maine eddy; but the latter approaches close to the outer islands off Mount Desert.

In most summers the belt of surface water involved in the Gulf of Maine eddy is much broader in the western side of the gulf than in the eastern, with the general set more variable and its velocity smaller. As a rule a general tendency prevails for the surface water to move out from the shore all along the coast from Penobscot Bay to Cape Ann during July and August. Under these conditions a second dead area develops off the mouth of Casco Bay, with the water generally setting in the opposite direction (easterly or northeasterly) across it. A few miles farther out, however, bottle drifts and dynamic contours unite to show a decidedly definite continuation of the eddy southeastward and eastward across the basin, and so around again to Nova Scotia, dominating this side of the gulf north of an imaginary line, Cape Cod–Cape Sable.

This state is illustrated by the bottle drifts for 1922 and 1923 and by the dynamic gradients for the summer of 1914. In other summers (typified by 1913 and 1919) the westerly and southerly component of the Gulf of Maine eddy parallels the general trend of the coast line more closely as far as Cape Ann, even involving Massachusetts Bay.[98]

Somewhere in the offing of Cape Cod a division takes place between the outflow out of the gulf to the south and an easterly drift along the northern side of Georges Bank, the latter, as a whole, being the center of a clockwise system of circulation. As far as longitude 68°, or thereabouts, this easterly drift parallels the neighboring side of the Gulf of Maine eddy; but to the east of this there is a definite separation, with the water next the bank drifting around the eastern edge of the latter and so out of the gulf at considerable velocity, a fact made evident by bottle drifts as well as by dynamic evidence. Some clockwise movement is also to be expected around the shoal part of the bank; otherwise the latter is comparatively dead.

The bottle drifts, combined with current measurements, show the southerly outflow from the western side of the gulf continuing around or across Nantucket Shoals and so westward along the southern shores of New England and New York.

An easterly set has been found dominant in the entrance to Nantucket Sound, between Nantucket and Monomoy, in the only summers of record, contributing to the circling movement around Nantucket but not to the Gulf of Maine eddy. If this condition prevails as constantly as now seems probable, the local circulation of the water offers a reasonable explanation for the rather abrupt general division between the waters west and east of Cape Cod, biologic as well as hydrographic.

Bottle drifts suggest that this easterly outflow from Nantucket Sound is given off from the southern side of an anticlockwise type of circulation that involves the sound as a whole; but the tidal currents run so strongly there that more information is needed before this can be stated positively.

---

[98] *Vide* the drifts of bottles from the Bay of Fundy to Cape Cod in 1919.

In some summers, if not in all, the westerly drift just mentioned involves the surface water across the whole breadth of the continental shelf in the offing of Marthas Vineyard and Nantucket. This, however, can not be regarded as a direct continuation of the outdraft from the gulf around the eastern end of Georges Bank On the contrary, the latter probably swings offshore to join in the easterly movement of the so-called "inner edge of the Gulf Stream."

The evidences of temperature, salinity, and of dynamic gradient unite to show this "Gulf Stream" current departing from the edge of the continent as it crosses the mouth of the gulf from west to east, so that while it may be encountered within 15 miles of the 200-meter contour line at longitude 69° to 70°, it is usually at least 40 to 50 miles out at longitude 66°. Farther east, however, it again approaches the slope, at least in some summers.

Our recent cruises have afforded no evidence of any movement across Georges Bank from south to north, though the surface water not infrequently drifts northward from the edge of the continent to the west of Nantucket Shoals during the late summer.

The chief seasonal variations from the circulatory scheme just outlined result during the autumn and winter from a shift in the heavy ("low") center of anticlockwise circulation to the Eastern Channel, from a speeding up of the coastwise drift around the northern and western shores in spring, and from the brief overflow of the Nova Scotian current into the eastern side of the gulf at that same season.

As a result we find the circulation centering chiefly around the Eastern Channel in March with velocities greatest as it drifts inward along the eastern side and outward along the western side of the latter. From March to April, however, the center of circulation shifts northward across the basin; the movement slackens in the southeastern part of the area, and the coastwise drift gathers strength. Shortly thereafter, when the water of the Nova Scotian current floods into the gulf from the east, the heavy center is shifted southwestward right across the gulf. At the same time (in May) the northeast–southwest drift around the northern and western coasts attains its highest velocity and its most definitely long-shore character, and is most definitely continued southward past Cape Cod. It also involves Massachusetts Bay, not only crossing the mouth of the latter, but also skirting its coastline from north to south, and so out again past Cape Cod. Under these circumstances flotsam of any kind (buoyant fish eggs, for instance, or the larvæ hatched therefrom) that may drift from the north into the northern side of Massachusetts Bay, or that may be produced there, tends to drift out of its southern side.

This long-shore movement (involving Massachusetts Bay) may continue, little altered, into the summer; but some time between May and July the heavy center again shifts eastward, and in some years, at least, this center becomes divided into the two lows recorded for the summer of 1914—the one in the offing of the Bay of Fundy, the other in the region of the Eastern Channel. This completes the yearly cycle.

On the bottom the water moves inward along the eastern side of the Eastern Channel during the early spring, and at other times of year in pulses not yet understood, usually outward along the western side. At depths of 150 meters, or deeper, the general tendency within the basin is northward along the eastern (Nova Scotian) slope the year round, veering through west to southwest across the basin toward the offing of Massachusetts Bay; and though variations in salinity and temperature prove this drift intermittent, its stream track seems comparatively constant from season to season during its periods of activity.

The correspondence between the dominant circulation of the gulf, as established by direct evidence, and the dynamic gradient is close enough to show that the former is essentially dynamic, set in motion by the regional inequalities in density, but given its eddylike character by the confining effect of the bottom contour of Georges Bank to the south.

Deflection of the horizontal tidal oscillations by the rotation of the earth similarly tends to produce an anticlockwise movement around the basin of the gulf, and with the effect of the wind consistent with this, the several motive forces are parallel in effect.

The westerly drift of slope water along the slope of the continent is also dynamic in source, and available evidence suggests the same motive power for the "Gulf Stream" drift abreast of the gulf.

TABLES OF TEMPERATURE, SALINITY, AND DENSITY

Temperature is in degrees Centigrade, salinity in parts per mille, and density is at the temperature *in situ* but without correction for compression. The tables on page 977, summarized from Ekman's (1910) tables 2, 4, and 5, give a close enough approximation to the latter for general purposes in depths as small as those of the Gulf of Maine. For computations involving the specific volume, Smith's (1926, p. 19) simplification of Hesselberg and Sverdrup's (1915) tables are to be preferred.

STANDARDS OF ACCURACY

The old type reversing thermometers used in 1912 and 1913 were accurate only to within about ±0.15° C., but with the instruments used subsequently for the subsurface readings the probable error in temperature determination is less than 0.05° C. As the surface readings have often been taken under difficulties and by various persons, accuracy is not claimed for them beyond about ±0.3° C.

All the determinations of salinity, except some for the winter of 1925 (noted below under the respective stations), have been by titration. So far as personal and instrumental errors are concerned, the results are reliable considerably within the requirements of the International Committee for the Exploration of the Sea—probably to ±0.03 per mille of salinity. However, as Giral (1926) has recently emphasized, regional or seasonal variations in the relative proportions of the various solutes in sea water, such as are known to occur, introduce another source of error, which makes it unsafe to claim accuracy closer than about 0.05 per mille even for waters as nearly uniform in their saline content as the Gulf of Maine probably is.

The accuracy of the calculated densities depends, of course, on that of the determinations of temperature and salinity on which they are based; and while errors in these two may partially offset each other, they may, on the contrary, be cumulative. Allowing as the probable range of error 0.05° and ±0.3 per mille, the probable error