Date	General locality	Station	Color in percentage of yellow
1912			
July 10	Off Gloucester	10002	20
11	Near Gloucester	10004	20
13	Off Boston Harbor	10006	20
15	Basin off Cape Ann	10007	14
16	Ipswich Bay	10008	20
16	Northeast of Cape Ann	10009	14
16	Off Hampton, New Hampshire	10010	20
17	Near Isles of Shoals	10011	20
24	Off Kennebunkport	10013	27
24	do	10014	27
25	Casco Bay	10015	27
26	Near Seguin Island	10016	27
27	Casco Bay	10017	35
27	Orrs Island	--------	44
29	Off Casco Bay	10019	20
Aug. 2	Off Monhegan Island	10021	27
3	Penobscot Bay	10021a	27
7	Off Cape Elizabeth	10022	27
7	Platts Bank	10023	14
8	Offing of Penobscot Bay	10025	20
8	Off Matinicus Island	10026	20
8	Near Seguin Island	10026a	20
14	Basin South of Mount Desert	10027	20
14	Basin, east side	10028	20
14	German Bank	10029	20
15	Off Lurcher Shoal	10031	24
16	Off Mount Desert Rock	10032	24
16	Off Machias, Me	10033	35
19	West end, Grand Manan Channel	10035	20
20	Offing of Machias, Me	10036	20
21	Near Mount Desert Island	10037	35
21	Off Isle au Haut	10038	20
1913			
July 8	Off Northern Cape Cod	10057	27
8	Southwestern part of basin	10058	9
9	West side of Georges Bank	10059	20
9	Offing of Nantucket Shoals	10060	5
10	Continental edge, off Nantucket Shoals	10061	2
Aug. 4	Off Chatham, Cape Cod	10085	27
5	Off northern Cape Cod	10086	27
9	Off Gloucester	10087	14
10	Center of basin	10090	9
11	Offing of Penobscot Bay	10091	20
11	East side of basin	10092	9
12	do	10094	27
12	German Bank	10095	27
12	Off Lurcher Shoal	10096	20
13	Off Machias, Me	10098	20
13	Near Mount Desert Island	10099	27
13	Near Mount Desert Rock	10100	27
14	Offing of Penobscot Bay	10101	35
14	do	10102	20
15	Near Isles of Shoals	10104	20
15	Offing of Ipswitch Bay	10105	20

SOURCES FROM WHICH THE GULF OF MAINE RECEIVES ITS WATERS

In few parts of the world is the coast water that bathes the continental shelf as sharply demarked from the oceanic water outside the edge of the continent as it is off the east coast of North America, from the Grand Banks on the north to Cape Hatteras on the south. Not only is the former much colder and much less saline than the latter, but the transition from the one type to the other is often remarkably abrupt. To see the warm sapphire blue of the so-called "Gulf Stream" give place to the cold bottle-green water over the banks is a familiar spectacle to mariners sailing in from sea. While it is unusual to meet as abrupt a transition as Smith (1923, pl. 5) describes for one occasion (March 27, 1922) south of the Grand Banks, where the water changed from a temperature of 1.1° to 13.3° C. (34° to 56° F.) within the length of the ship, and where the line of demarkation between the two waters was made plainly visible on the surface by ripplings, the transition zone from the one to the other is usually compressed within a few miles abreast the Gulf of Maine.

The general characteristics of the coast water in boreal latitudes have been well described by Schott (1912) and are matters of common knowledge. I need merely state here that mean annual surface temperatures lower than 15° and mean salinities lower than about 33.5 per mille may be so classed, as distinguished from the much warmer and more saline (35.5 per mille) tropic water, which is commonly (though rather loosely) termed "Gulf Stream" as it skirts the North American plateau.

In discussing the sources of the sector of the coast water included within the Gulf of Maine, it will be convenient to consider the upper and lower strata separately, for it is now proven they they draw chiefly from different sources.

SUPERFICIAL STRATUM

NOVA SCOTIAN CURRENT

Until detailed study of the physical characters of the coast water off northeastern North America was undertaken by the United States Bureau of Fisheries, the Museum of Comparative Zoology, and the Biological Board of Canada, a northerly source was usually ascribed to the coastal water all along the seaboard of Nova Scotia, New England, and much farther to the south. This, in fact, has been described, time out of mind, as the "Arctic current." As I have remarked in an earlier report (Bigelow, 1915, p. 251), "almost all the ocean atlases show something of this sort; and it has been accepted in one form or another in almost all the textbooks on physical geography and oceanography (for example, Maury, 1855; Reclus, 1873; Attlmayr, 1883; Thoulet, 1904; Krümmel, 1911; Schott, 1912; the German Marine Observatory (Deutche Seewarte, 1882), the current charts of the United States Navy (Soley, 1911), and the British Admiralty (1897) current chart.)"

The low temperature of the surface water near shore, contrasted with the "Gulf Stream" offshore and with the oceans as a whole at the latitude in question, naturally suggests a northern origin until analyzed in relation to other factors (p. 686). Ostensible evidence to the same effect is afforded by the continuity of the cold zone all along the northeastern coasts of North America, with its mean temperature gradually decreasing from the south toward the Newfoundland-Baffins Bay region in the north. The southwesterly drift that has been reported repeatedly along the coasts of the northeastern United States and Nova Scotia argues in the same direction; so, also, the extension of a generally boreal fauna southward and westward as far as Cape Cod, with planktonic communities of this category spreading still farther in this direction in winter.

The observations on the temperature, salinity, and circulation of the gulf, detailed in other chapters, do, in fact, prove beyond reasonable doubt that water from the northeast (low in temperature) does flow past Cape Sable into the Gulf of Maine for a time in spring, sometimes into the summer. Before considering what part this actually plays in the Gulf of Maine complex a few words may well be devoted to its probable source.

Up to 1897 the supposed coldness of the coastal water along North America in general, and any definite evidences or reports of a current from northeast to southwest in particular, were usually classed as southward extensions from the Labrador Current. Without much analysis this Arctic stream was generally thought to flow down from the Grand Banks region, past Nova Scotia, and so southward along the whole eastern seaboard of the United States, carrying to New England the cold resulting from the melting of ice (floe and berg) in Baffins Bay or about the Grand Banks. Some such southerly branch of the Labrador Current is taken for granted in most of the older textbooks, charts, and discussions of North American hydrography. Thus Libbey (1891, 1895), in his studies of temperature south of Marthas Vineyard, definitely identified as such the cool band that he recorded along the continental edge in the offing of southern New England. This view was widely held until recently. Sumner, Osburn, and Cole (1913, p. 35), for example, state, on the authority of the United States Navy Department, that the Labrador Current flows from the Grand Banks past Nova Scotia and so southward as far even as Florida, narrowing from north to south. Krümmel (1911) believes the polar water tends to drift southwestward across the Grand Banks and so to Nova Scotia. Engelhardt (1913, p. 9, chart B) did not doubt that the Labrador Current bathes our coasts at least as far as the Gulf of Maine. Johnston (1923, p. 271) describes it as hugging the coast of North America from Halifax to Cape Cod; and as recently as 1924 Le Danois (1924, p. 14) wrote of the "dernierès eaux du courant du Labrador qui longuent la côte des Etats Unis."

On the other hand, Verrill (1873, p. 106; 1874), in the early days of the United States Fish Commission, had maintained that the actual temperatures of the deep strata of the Gulf of Maine did not suggest the effects of any Arctic current, though he qualified this generalization by adding that the gulf receives accessions of cold water, ultimately coming from the north, by the tides.

It is obvious that for the Labrador Current to follow the track usually ascribed to it implies a dominant cold drift setting southwestward from the Newfoundland-Grand Banks region across the oceanic triangle that separates the Newfoundland from the Scotian Banks, and so in over the latter toward the coast; but although a current of this sort is represented on many charts, its supposed extension westward from the Grand Banks to Nova Scotia seems to have been based more on theoretic grounds (the assumed necessity for connecting the cool coastal water to the southward with the Arctic flow from Baffins Bay) than on direct observation. Schott (1897), who first attempted a detailed study of oceanography of the Grand Banks region, also failed to find any dominant set from northeast to southwest across the banks, in spite of the proximity of the Labrador Current, which has long been known to skirt their eastern edge and sometimes to round the so-called "tail of the bank" for a short distance westward and northwestward. He did, it is true, record sporadic movements of this Arctic water in over the banks, but he believed them too small in volume and too irregular in occurrence to be anything but temporary surface currents caused by the northeast winds, which often blow fresh there. His conclusions were based on so many records of temperature and on measurements of the current taken from fishing vessels lying at anchor on the banks that they form the foundation for more modern knowledge of the characteristics of the Labrador Current in the Grand Banks region.[26]

Schott's chief thesis—that the most southerly bounds of the Labrador Current as a definite stream flow lie not far south or west of the "tail" of the Grand Banks—has been corroborated by the extensive oceanographic observations taken yearly by the International Ice Patrol since 1914 (Johnston, 1915; Fries, 1922 and 1923; E. H. Smith, 1922 to 1927; Zeusler, 1926), both in the region of the banks and in the oceanic triangle between the latter and Nova Scotia; also by the drift-bottle experiments carried out by the Biological Board of Canada (Huntsman, 1924).

The data gathered by the Ice Patrol are especially instructive in connection with the Gulf of Maine, both because of their extent and because especial effort has constantly been made to chart any extensions of the Labrador Current that might carry bergs toward the west or southwest—extensions usually easily traceable by their icy temperature, even if carrying no bergs with them at the time. Furthermore, the operations of the patrol cover the part of the year (March to July) when the Labrador Current is greatest in volume as it flows southward and lowest in temperature—hence, when it would be most likely to reach the coast line of Nova Scotia or the Gulf of Maine, if it ever does so.

So many oceanographic sections have now been run in various directions from the tail of the Grand Banks by the patrol in various years, and between the banks and Halifax, with so careful a record of all bergs since 1911, whether actually sighted by the patrol cutter or reported by other ships (E. H. Smith, 1924a, chart M), that it is hardly conceivable that any considerable or constant flow of icy cold water from the Grand Banks region toward Nova Scotia could have escaped attention during the seasons covered.

Actually, however, not a single phenomenon of this sort has been encountered during all the years of the patrol. Thus, Johnston (1915, p. 41), in his report on the operations of 1914, definitely states that "as a stream, Labrador water never gets west of Grand Bank"; consequently, that the name "Labrador Current," as applied to the cold water along the eastern coast of the United States, is a misnomer. Fries (1922, p. 73), in discussing the oceanographic observations during the patrol of 1921, also failed to find any evidence of the Labrador Current continuing westward from the Grand Banks toward the Gulf of Maine. With the accumulated data of successive years, E. H. Smith (1923) describes the Labrador Current as usually reaching its farthest boundary on the south and west, somewhere between latitude 42° and 43°, longitude 51° and 52°, where it eddies sharply to the eastward. A similar account has recently been given by the Hydrographic Office, United States Navy (1926). As this was the case during the spring and early summer of 1923 (a year that may be classed as normal, both in respect to the number of ice bergs that drifted down to the tail of the Grand Banks and to temperature), and again in the ice-free season of 1924, E. H. Smith (1924a, p. 144) seems fully justified in his conclusion that when the Labrador Current recurves westward around the tail of the banks this is "the extreme

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[26] Schott (1897) described small amounts of polar water as turning westward past Cape Race along the south coast of Newfoundland, to enter the Gulf of St. Lawrence via the northern side of Cabot Strait, where an inflowing current (i. e., setting west) has often been reported. More recent studies, however, have made it seem unlikely that it extends so far.

southern extension of the cold polar water." [27] Observers who have actually studied oceanographic conditions first hand in the Grand Banks region are unanimous to this effect.

The evidence of temperature and salinity on which this general thesis rests is set forth in detail in the successive reports of the patrol (see also Bjerkan, 1919; Le Danois, 1924, p. 40, and 1924a, p. 46) and need not be repeated here. I need only point out that any branch of the Labrador Current that might flow southward from the banks would not only be betrayed by its temperature and salinity (p. 829) but it would doubtless carry bergs with it in greater or less number from time to time. Actually, however, not a single berg (except small ones drifting out from the Gulf of St. Lawrence) was reported west of longitude 55° during the period from 1911 to 1924, very few west of longitude 52°, whereas some hundreds came drifting down along the east slope of the Grand Banks during that period (see E. H. Smith, 1924, chart P, showing distribution of ice bergs from 1911 to 1923).

The results of the drift-bottle experiments carried out in eastern Canadian waters within the past few years by the Biological Board of Canada have not yet been published in detail. However, Dr. A. G. Huntsman kindly supplies the information that they give no more suggestion of a definite stream from the Grand Banks toward Nova Scotia than do the temperatures or ice drifts just discussed.[28]

In short, no actual evidence of such a current is forthcoming from recent investigations, but the reverse. I have no hesitation, therefore, in definitely asserting that the Labrador Current does not reach, much less skirt, the coast of North America, from Nova Scotia southward, as a regular event, corroborating Jenkins's (1921, p. 166) statement that it does not reach the coast of the United States. Consequently this is not the direct source of the cold current that reaches the Gulf of Maine from the east. If overflows of the Labrador Current do take place in this direction they are of such rare occurrence that no event of this sort has yet come under direct scientific observation.

As Huntsman (1924, p. 278) points out, a certain amount of the water flowing down from the Arctic may move westward and southwestward along the slope of the continent as a constituent of the slope water (p. 842), so much warmed, however, en route, by mixture with tropic water that if it reaches the Gulf of Maine at all it does so as a warming and not as a cooling agent, and on bottom, not at the surface. Labrador Current water in small amount may also reach the gulf indirectly via the Gulf of St. Lawrence route, shortly to be discussed; but if so, its distinguishing characters as an Arctic current are lost, and it becomes one of the constituents of a coastal current.

The physical characters of the cold band of water that hugs the outer coast of Nova Scotia also forbid the idea that it draws direct from the Labrador Current. According to the observations by the *Scotia* (Matthews, 1914), the records of the Canadian Fisheries Expedition of 1915 (Bjerkan, 1919), and the much more extensive data that have been accumulated during the years of the Ice Patrol, the

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[27] The reader is referred to Smith's chart (1924a, sketch 10, p. 150) for the normal distribution of the Arctic water around the banks in the spring and early summer; also to his general scheme of circulation in the vicinity of the tail (Smith, 1924a, p. 135).

[28] Huntsman's chart (1924, fig. 32) showing the complexity of the circulation between Nova Scotia and Newfoundland includes the most outstanding results of these experiments.

unmixed Labrador Current (temperature below −1°) is colder than the coldest outflow from Cabot Strait, or than the coldest water over the Scotian shelf, which have never been found to fall below −0.5° in temperature. The evidence of salinity, of like import, is even more instructive in this respect, for the undiluted Labrador Current off the Grand Banks is considerably more saline than the cold water next the Nova Scotian coast, being characterized by a salinity of at least 32.5 per mille, while its surface salinity hardly falls below 32 per mille even along its inner edge, where most influenced by drainage from the land (minimum so far recorded about 31.9 per mille; Matthews, 1914).

"From this," as I have stated elsewhere (Bigelow, 1917, p. 236), "it appears that did any considerable amount of unadulterated Labrador water join the Nova Scotia coast current, the temperature of the latter would be lower, its salinity higher, than in Cabot Straits"; whereas both the temperature and the salinity of the cold band skirting the Nova Scotian coast have proved remarkably uniform, from the straits westward to its farthest extension. It is true that an infusion of Labrador Current water (spreading westward from the Grand Banks region) might join the Nova Scotian coast water without lowering the temperature of the latter did it mix sufficiently with the warmer water, which it must needs displace en route, to raise its own temperature by 1° or more. Such a mixture, however, would necessarily raise its salinity as well as its temperature, because the water that normally fills the deep oceanic triangle between the Scotian and Newfoundland Banks is considerably more saline than the Labrador Current, a fact amply demonstrated by repeated profiles run by the Ice Patrol and by the Canadian Fisheries Expedition (Bjerkan, 1919). Hence, if any large amount of such mixed water joined the cold Nova Scotian coast current, the salinity of the latter would be made considerably higher than it actually is, so that salinity would betray the event even if temperature did not. Actually nothing of the sort has been recorded, observations taken by the *Grampus*, the Canadian Fisheries Expedition, and the Ice Patrol uniting to demonstrate that low salinity is as characteristic of the cold band next Nova Scotia as low temperature is. However, the temperatures and salinities taken by the *Acadia* in July, 1915 (Bjerkan, 1919), make it at least highly probable that isolated offshoots, pinched off as it were from the Labrador Current, do occasionally drift westward as far as the continental slope off Banquereau Bank and Cape Sable. Otherwise it would be difficult to account for the pool of icy water (−1.7°) then reported off Sable Island—a pool both colder and more saline (32.82 to 33.08 per mille) than the outflow from the Gulf of St. Lawrence, but which reproduced the coldest water of the Newfoundland Banks in its physical character.

These several lines of evidence forbid the possibility that the Labrador Current is directly responsible for the low temperature of the cold water that reaches the Gulf of Maine from the east. Water from the Labrador Current may reach the Gulf of Maine indirectly via the discharge from the Gulf of St. Lawrence, for a certain amount of this Arctic water may enter the latter along the northern side of Cabot Strait. Huntsman's (1925) recent survey of the Straits of Belle Isle points to a greater inflow of Arctic water by this route than Dawson's (1907) earlier survey had suggested; but even so, it is an open question whether this Arctic contribution is sufficient to lower the temperature of the coldest stratum of the Gulf of St. Lawrence (or of its discharge around Cape Breton) below the point to which winter chilling, *per se*, and ice melting *in situ*, would reduce it.

Schott (1897) and Hautreaux (1910 and 1911), abandoning the Labrador Current, saw in the Gulf of St. Lawrence the source of the cold coast water as far west and south as New York. This view is supported by so much evidence that in earlier publications (Bigelow, 1915, 1917, and 1922) I have described the cold Nova Scotian water that flows past Cape Sable into the Gulf of Maine as probably a direct continuation of the current that is known to flow out through Cabot Strait on the Cape Breton side.

Briefly stated, the evidence on which this view was based stood as follows up to 1922, when Canadian experiments with drift bottles threw new light on the subject:

The enormous volume of fresh water poured yearly into the Gulf of St. Lawrence by its tributary rivers, added to a deep current of slope water flowing in through Cabot Strait on the bottom (Huntsman, 1924), apparently, too, with a balance of inflow over outflow in the Straits of Belle Isle, and with the currents on the north side of Cabot Strait usually inward, while the rain that falls on the surface of the Gulf of St. Lawrence almost certainly exceeds the evaporation therefrom, make it certain that the current flowing out via the south side of Cabot Strait discharges a large volume of water. Experimental evidence substantiates this, for current measurements by the tidal survey of Canada (Dawson, 1913) seemed to establish a constant outflow there, at least 30 miles broad abreast of Cape North, with an average velocity of about half a knot per hour at the surface, which Dawson (1913) termed the "Cape Breton current," but was earlier known as the "Cabot current."

Temperatures and salinities taken by the *Grampus* in the eastern side of the Gulf of Maine, near Cape Sable, and as far east along the outer coast of Nova Scotia as Halifax, in 1914 and 1915, pointed to a direct continuation of this "Cape Breton" or "Cabot" current southwestward alongshore, nearly to the Gulf of Maine, during these summers (Bigelow, 1917, p. 234). Futhermore, a dominant surface drift of ⅓ knot per hour toward the southwest was recorded by the Ekman current meter off Shelburne, on July 27 and 28, 1914 (station 10231), only 30 miles east of the entrance to the Gulf of Maine.

Thus the physical character of the water, combined with readings of the current meter, seemed to show a direct surface drift from the northeast along the Nova Scotian coast between Shelburne and Halifax, distinguishable by a considerable difference in temperature and salinity from the salter, warmer water that bounded it on the seaward side. These characteristics and the fact that we found such characteristically Arctic components as *Limacina helicina* and *Mertensia ovum* among its plankton seemed to classify it as actually the southernmost prolongation of the outflow from Cabot Strait (Bigelow, 1917, p. 357).

Observations taken by the Canadian Fisheries Expedition of 1915 (Bjerkan, 1919) and returns from several series of drift-bottle experiments subsequently carried out by the Biological Board of Canada in the years 1922, 1923, and 1924[29] have proven the circulation over the continental shelf along Nova Scotia to be of a nature much

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[29] Huntsman, 1925, and notes kindly contributed by him.

more complex than the simple stream flow from northeast to southwest suggested by the earlier evidence.

The track followed by the ice drifting out of the Gulf of St. Lawrence is especially instructive here in this connection, because this discharge takes place in spring (chiefly in April and May) just when the Nova Scotian current is flooding past Cape Sable into the Gulf of Maine in greatest volume; whereas most of the drift-bottle experiments have been carried out in summer, when this current is usually inactive or at least is carrying so small a volume of water past Cape Sable that it is no longer an important cooling agent for the Gulf of Maine. According to Johnston (1915), the ice that comes out along the Cape Breton side of Cabot Strait does not tend to follow the Nova Scotian coast around to the southwest, as it would if the outflowing current hugged the coastline, but divides. Part drifts out to the southeastward; but the ice that emerges from the gulf nearest the Cape Breton coast moves southward across Banquereau Bank, where it fans out, to the offing of Halifax.

These lines of dispersal correspond very closely with the icy water which Bjerkan's (1919) data for May, 1915, show spreading out from the southern side of Cabot Strait to the region of Misaine and Banquereau Banks (fig. 167), but separated from the still colder (−1°) water on the Newfoundland Banks by a warmer (0°) core in the axis of the Laurentian Channel, and with much higher temperatures off the mouth of the latter. Especially suggestive, from the standpoint of the Gulf of Maine, is the narrow icy tongue (0° to −0.2°) that then extended westward along Nova Scotia past Halifax; a band comparatively uniform, also, in salinity from east to west (31.5 to 32.5 per mille) and considerably less saline than the still colder water on the Newfoundland side of the Laurentian Channel (temperature lower than −1°; salinity 32.7 to 33.2 per mille). This the Ice Patrol cutter had also crossed on her run in to that port about a week earlier (United States Coast Guard stations 26 and 27, May 20, 1915).

Lacking data in the offing of Cape Sable, it is not possible to state whether this cold tongue actually extended to the Gulf of Maine that May, though it may have done so earlier in the season and certainly does so during the spring in some years (p. 681).

A similar concentration of cold water close in to Nova Scotia appears from the temperatures taken by the Ice Patrol along a line from Halifax toward Sable Island in spring in other years. The records for 1919 are especially instructive, showing this band widest at the end of March, when the whole column of water next the land was fractionally colder than zero from the surface to bottom; smaller in volume in April, when it was overlaid by slightly warmer (0° to 1°) water; and shrunken to a narrow tongue on the bottom not more than about 20 miles broad in May.[30]

Drift bottles set out by the United States Coast Guard cutter *Tampa* (Capt. W. J. Wheeler) on April 18, 1924, along a line running 119° (about SE x E½ E.) true from a point about 18 miles southeast of Sable Island (43° 48′ N.; 59° 26′ W.) for 50 miles, likewise show a drift from this region first northward toward the land and then westward toward the Gulf of Maine, three out of the seven returns (all from the inner end of the line) being from Sable Island, one from the Nova Scotian coast not far

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[30] The March profile also cut across the southwestern edge of the icy Cape Breton-Banquereau pool near Sable Island.

from Halifax, and one from Gloucester Harbor, where it was picked up on August 14.[31] Although two of the bottles from this line drifted to Newfoundland, showing a division, this does not detract from the evidence of the Gloucester recovery.

Clearer evidence that the cold tongue that skirts Nova Scotia and flows past Cape Sable into the Gulf in Maine in spring is actually an overflow from the icy pool that develops from Cabot Strait out over Banquereau Bank, when the ice is coming out of the Gulf of St. Lawrence, could hardly be asked than results from the temperatures, salinities, and bottle drifts just discussed.

I believe it now sufficiently demonstrated that while this cold pool (fig. 167) owes its low temperature, to some extent, to the direct outflow of icy water from the Gulf of St Lawrence via the Cape Breton side of Cabot Strait, it more directly mirrors the chilling effect of the field ice from the Gulf of St. Lawrence as this melts in the region between Banquereau Bank and Sable Island. Consequently, cold water that reaches the Gulf of Maine from the east is, in fact, ice-chilled, though this takes place 300 miles or more to the eastward of the eastern portal to the gulf.

It is to this cold band skirting Nova Scotia that the name "Nova Scotian current" is applied in the preceding pages. During the spring a large volume of water enters the eastern side of the Gulf of Maine from this source, producing the effects on salinity and temperature described in the chapters on those physical features; and this is certainly the chief source that contributes cold water of northern origin to the Gulf of Maine—almost certainly the only source making a contribution of this sort sufficient in amount and cold enough to exert any appreciable effect on the temperature of the gulf (p. 682).

This current flows into the gulf in volume during only a few weeks in spring—earlier in some years, later in others. As its fluctuations are referred to repeatedly in the preceding pages a summary will suffice here.

In 1920 (a late season) icy water ($<1°$) from this source had spread westward as far as the offing of Shelburne, Nova Scotia, by the last week in March; but neither the temperature nor the salinity of the eastern side of the Gulf of Maine give any evidence that it had commenced to flood past Cape Sable up to that date, nor do the isohalines for that April suggest any drift of water of low salinity into the gulf from the east. The coastal zone, also, warmed about as rapidly in the one side of the gulf as in the other during that month (p. 553). Conditions seem, then, to have remained comparatively static off Cape Sable through the first two months of the spring of 1920, and if the Nova Scotian current discharged at all into the gulf in that year this did not happen until May or later. In 1919, however, an early season, its western expansion culminated before the last of March, and had slackened, if not ceased, by the end of April (p. 558). In this respect 1915 seems to have been intermediate (so may be taken as a representative spring), with the Nova Scotian current exerting its chief chilling effect on the eastern side of the gulf before the first week in May (p. 560), and slackening from May to June, as indicated by the contraction (to the eastward) of the area inclosed by the surface isohaline for 32 per mille (cf. fig. 120 with fig. 128).

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[31] Information kindly supplied by Dr. A. G. Huntsman.

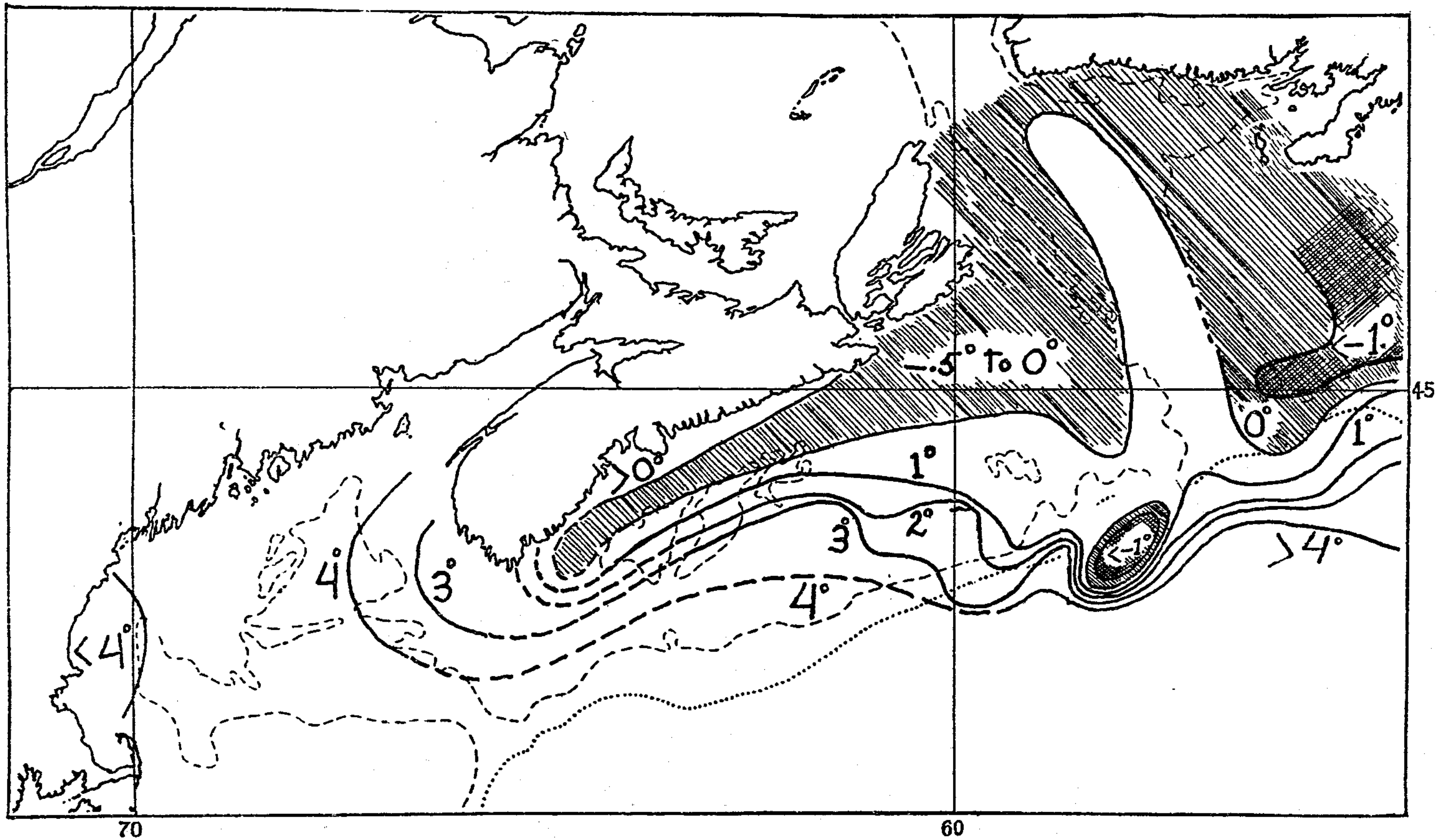

FIG. 167.—Distribution of the coldest water, irrespective of depth, from Newfoundland to the Gulf of Maine, for May, 1915, based on the records of the Canadian Fisheries Expedition (Bjerkan, 1919) and *Grampus* stations 10266 to 10279

The salinities and temperatures of the eastern side of the gulf make it probable that the westerly flow past Cape Sable slackens or ceases by June, at the latest, every year—often a month or more earlier than that. In some years sporadic movements of water undoubtedly take place from east to west past the cape later in the season; but the drift of bottles put out on several lines off Nova Scotia by the Biological Board of Canada during 1922, 1923, and 1924 shows that the circulation over the continental shelf between Browns Bank and the Laurentian Channel becomes exceedingly complex during the late summer, variable from summer to summer, and largely controlled by the contour of the bottom.[32]

During some summers a rather definite current from east to west persists along the Nova Scotian coast right through July and August. This statement is based on the drifts for 1924, when a number of bottles set out on three lines normal to the general trend of the coast between Halifax and the Straits of Canso, during July and August, were picked up in autumn in the Gulf of Maine. Many other bottles from the most easterly lines also traveled westward during that summer but stranded before they reached Cape Sable.[33]

The probable tracks of the bottles that went westward, localized some 12 to 25 miles out from the land, correspond so closely with the tongue of coldest water charted for May, 1915 (fig. 167), that the dominant drift was evidently essentially the same for both. In May, as temperatures show, this east-west movement involved a stratum of considerable thickness; but in the summer of 1924 it was more strictly a surface phenomenon, probably with the underlying water circling offshore along Roseway and La Have Banks in the more usual anticlockwise eddy, because what few temperatures were taken in the gulf that summer (p. 996) suggest no greater transference of cold water (such as a bottom current past Cape Sable would entail) than usual.

The westerly set may again have continued past Cape Sable until September in 1926, when many drifts were recorded from the offing of the cape into the gulf, as summarized on page 909.

The bottle drifts for the other summers of record show, however, that it is unusual for the Nova Scotian current to persist as a definite stream-flow as far west as Cape Sable after June, but that the deep basin between Sable Island Bank on the east and La Have Bank on the west is usually dominated (in summer) by an anticlockwise eddy named by Doctor Huntsman the "Scotian eddy," similar to, though not as extensive as, the eddy that dominates the basin of the Gulf of Maine.

In summers of this type whatever drift takes place intermittently around Cape Sable into the eastern side of the Gulf of Maine draws from what Doctor Huntsman describes as a sort of dead-water region off the cape. True, this, in its turn, receives water of low temperature from the Scotian eddy, but also from the warmer slope water that drifts westward along the edge of the continent, as appears from the recoveries of Canadian drift bottles. Consequently, the surface water that

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[32] Only a preliminary statement of the general results has yet appeared (Huntsman, 1924); but Doctor Huntsman has very kindly allowed quotation from his unpublished notes.

[33] The account of these experiments contributed in advance of publication by Doctor Huntsman also shows complex drifts inshore and to the eastward for many bottles set out off County Harbor and off Beaver Harbor, which need not be discussed here.

enters the eastern side of the Gulf of Maine in summers of this type is not cold, but actually is warmer than the water it meets within the gulf.

This we found to be the case in July and August of 1914, when salinities and temperatures showed that the cold tongue was eddying offshore toward the edge of the continent, and to the left, a short distance east of the longitude of Cape Sable (Bigelow, 1917), although a dominant southwesterly set of about 1 knot per hour was then recorded in the offing of Shelburne (station 10231). The observations taken during the last week of July, 1915, by the Canadian Fisheries Expedition (Bjerkan, 1919), corroborated by our own September stations for that year (10312, 10313, and 10314), again showed the coldest and least saline water as veering southward from the offing of Shelburne toward La Have Bank — not continuing westward to Cape Sable.

The summer of 1922 seems also to have belonged to this category, because, as Doctor Huntsman informs me, not one of the bottles that were put out to the eastward of Shelburne, Nova Scotia, during that summer has been reported from the Gulf of Maine; but a series set out on a line running southwesterly for 125 miles from Brazil Rock, just east of Cape Sable, on the 17th of that July, evidently coincided with the zone of transition between the Scotian and Gulf of Maine eddies, because about as many bottles from the inner end of the line were reported from the Gulf of Maine and Bay of Fundy (p. 908) as from the eastward, while more either drifted inshore or remained stationary.[34]

Four others, set out near the outer edge of the continental shelf, were picked up on the west coast of Nova Scotia, in the Bay of Fundy, and on the coast of Maine. The latter drifts, Doctor Huntsman points out, indicate a westward tendency along the edge of the continent and entrance into the gulf around or across Browns Bank with the slope water discussed below (p. 842). Such of the bottles from this line as finally drifted into the Gulf of Maine eddy traveled with considerable speed (p. 847); but so many of them worked slowly shoreward, and the dispersal was so nearly equal in the two directions, east and west, that the water off Cape Sable is described by Doctor Huntsman as "a relatively dead zone" at the time, so far as any nontidal drift is concerned. Tidal currents, however, run with great velocity in this region, especially close in to land.

A dead zone of this same sort seems again to have developed off Cape Sable during the summer of 1923, when, as Doctor Huntsman writes, some bottles from a line running eastward from Browns Bank toward La Have Bank (i. e., at right angles to the Cape Sable line of the year previous) were finally recovered in the Gulf of Maine after drifts no more rapid than those of the 1922 series, while others were picked up on the other side of the Atlantic (England, Ireland, France, and the Azores) a year later. The only bottle from lines east of La Have Bank, which is known to have reached the Gulf of Maine during that summer, was one set adrift in Cabot Strait on July 18 and picked up near Cape Sable on December 2. This bottle, Doctor Huntsman suggests, may have gone out along the western side of the Laurentian Channel, then westward along the edge of the continent, and so

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[34] Doctor Huntsman kindly allows quotation of these results in advance of publication. They are discussed more fully in another chapter (p.908).

finally northward toward the Gulf of Maine, via Browns Bank and the Cape Sable dead water.

In years such as those just described the region in the offing of Cape Sable, out to Browns Bank, between the two major circulatory eddies (Scotian and Gulf of Maine) but not directly within the sweep of either, is evidently the site of a very active mixing of waters of diverse origins. Under such conditions a very abrupt east-west transition in temperature and salinity develops off the cape, proving that the westerly (inshore) component of the Scotian eddy is not the motive power for such water as does then flood into this side of the Gulf of Maine. This eddy, on the contrary, is clearly outlined by the surface salinity for July and August, 1914 (Bigelow, 1917, fig. 18), and for June, 1915, as swinging offshore toward La Have Bank, which prevents it from flooding westward through the Northern Channel, toward which the rotation of the earth would direct it, did the contour of the bottom allow.

The strong tidal currents off southern Nova Scotia must tend, however, to pump water from the Cape Sable deadwater into the gulf, because the flood, running westward at a mean velocity of 1.4 knots (Dawson, 1908, station R; a journey of something like 8½ miles for any given particle of water), must follow westward and northward around Cape Sable as it is forced to the right against the shore by the effect of the earth's rotation. With the ebb similarly deflected to the right, a clockwise movement around the rounded outline of southwestern Nova Scotia naturally results, such as eddies around any submerged shoal in high northern latitudes.

TROPIC WATER

We may next consider the possibility that overflows of the surface stratum of tropical or "Gulf Stream" water, the inner edge of which always lies within a few miles of the edge of the continent, may enter the Gulf of Maine from time to time; also possible movements of the coast water from west to east past Cape Cod into the gulf, either via Vineyard Sound or around Nantucket Island. Water from either of these sources would reach the gulf as warm currents, contrasting with the cold Nova Scotian current, the former high in salinity, the latter low.

As pointed out above (p. 700), events of the first category undoubtedly do occur on occasion. Small amounts of "Gulf Stream" water have long been known to drift inward, toward the sector of coast line bounded on the east by Marthas Vineyard and on the west by Narragansett Bay, during most summers, bringing with them a typically tropical fauna of fishes, planktonic invertebrates, and Gulf weed (Sargassum).

Were it not for the peculiar distribution of densities off the slopes of Georges and Browns Banks, shortly to be described (p. 843), which produce more or less constant dynamic tendency for the surface stratum to move out, seaward, from the edge of the continent (a tendency altered into a long shore current to the westward by the deflective effect of the earth's rotation; p. 846), tropic water might similarly be expected to drive in over the surface right across the banks under the propulsion of high and prolonged southerly winds. Under most conditions, however, the distribution of density imposes an impassible barrier to surface drifts from the southward into the gulf (p. 939). It is fortunate for the fisheries of New England that such is the case, for were Georges and Browns Banks subject to frequent overflows by the high temperatures of the so-called "Gulf Stream" sufficient in amount to dominate the column from surface to bottom, existence on the Banks would become impossible for cod, haddock, halibut, and, in fact, for the whole category of boreal fishes.

Under exceptional conditions departures from the normal temperatures and salinities along the zone of contact of the banks and tropic waters may allow the latter to reach the Gulf of Maine as a surface drift if driven by southerly winds. An overflow of this sort was, in fact, reported by Capt. E. Kinney of the S. S. *Prince Arthur*, who observed unusually blue water with gulf weed and a temperature of 20° C. (68° F.) in the center of the gulf, latitude 42° 43′ N., longitude 69° 13′ W., on July 14, 1911, preceded for several days by a strong current toward the northwest in its western side (U. S. Hydrographic Office pilot chart for January, 1913). However, no events of this sort have come under our observation, so they must be exceptional, for their effects on the salinity of the gulf and on its plankton would be unmistakable.

It may be definitely asserted, therefore, that tropic water from outside the continental edge seldom affects the temperature or salinity of the gulf except as one of the constituents of the water that flows in through the Eastern Channel.

It is one of the most interesting oceanographic features of the Gulf of Maine that the latter is so little subject to tropic influences, either in the physical character of its waters or in its fauna or flora, when tropic water lies so close at hand.

COASTAL WATER FROM THE WEST

The possibility that the coastal water overflows around Cape Cod from the west in any considerable volume, and so into the Gulf of Maine, seems extremely remote. On the contrary, all the evidence of current-meter measurements, drift-bottle experiments, distribution of temperatures and salinities (see especially p. 974), and geographic distribution of the fauna (bottom as well as planktonic) points to just the reverse movement—i. e., out of the gulf in this side. The evidence that the dominant drift past Cape Cod, and so around or over Nantucket Shoals, is out of the Gulf of Maine, not into the latter, is conclusive.

RIVER WATER

In addition to the superficial ocean currents just discussed, which bring water to the Gulf of Maine, its tributary rivers discharge a volume of fresh water so large that it must be taken into consideration in any study of the salinity or circulation of the gulf.

Unfortunately, the annual combined discharge of the several river systems can not yet be stated, much less the contribution made by the numerous minor streams that empty into the gulf, for most of the flow measurements made by the United States Geological Survey within recent years (see especially Porter, 1899; Pressey, 1902; and Barrows, 1907 and 1907a) have been for localities far upstream. The published data for the Kennebec at Waterville, Me., and for the Merrimac at Lawrence, Mass., are perhaps the most instructive in the present connection. These records for the Kennebec cover a drainage area of 4,410 square miles[35] out of a total 6,330—i. e., about two-thirds of the river basin. The average flow is given by Porter (1899) as 6,400 cubic feet per second for the four years 1893 to 1896; and though a great number of records have been obtained subsequently, this figure may be taken as representative. In other words, if this be two-thirds of the total flow of the river (probably it is no more, because two important tributaries enter below Waterville), the Kennebec River annually pours something like 300,000,000,000 cubic feet of water into the Gulf of Maine, or enough to flood an area of about 8,000 square miles[35] to the depth of 1 foot. The discharge from the Merrimac is about the same in relation to the area of its watershed—i. e., an average of about 6,800 cubic feet per second (8 years, 1890 to 1897) from about 4,553 square miles. Flow measurements of the Androscoggin, taken at Rumford Falls, Me., at which point the river receives the run-off from one-half to two-thirds of its total watershed of 3,700 square miles, give a mean of 3,884 cubic feet per second for the years 1893 to 1901, suggesting about 6,400 for the entire watershed of this river. The discharge from the Penobscot, with its larger drainage area (8,500 square miles), averaged about 23,500 cubic feet per second for the years 1899 to 1901 (Pressey, 1902), at White Horse rips, where it drains 7,240 square miles of its total watershed of 8,500, indicating a total run-off of not less than 28,000 cubic feet per second. By a simple arithmetical calcuation the combined discharge from these four rivers alone is sufficient to raise the whole level of the Gulf of Maine, out to its southern rim, by about 1½ feet per year.

This does not include the St. John, the largest tributary of all, with a watershed more extensive than those of the Merrimac, Androscoggin, and Kennebec combined (p. 521), but for which no definite record of its discharge is available; nor of the discharges from the many lesser streams—the Saco, for example, the Presumpscot, the St. Croix, and many smaller. However, the general physical features and vegetation of northern Maine and of such parts of New Brunswick and Nova Scotia as are tributary to the gulf are comparatively uniform, as is the rainfall. Consequently, it is fair to assume that at least as large a proportion of the rain that falls on the watershed of the St. John and of the other unmeasured streams reaches the sea as from the following watersheds where this run-off has actually been measured. The run-off from the St. John watershed may, indeed, be expected to be greater, the rainfall in the interior of New Brunswick being heavier than it is over most of Maine.

River	Locality	Area of watershed, square miles	Period	Annual run-off, depth in inches, for watershed[a]		
				Maximum	Minimum	Mean
Merrimac	Lawrence, Mass.	4,452	1907–1917	24.14	13.12	17.29
Androscoggin	Rumford Falls, Me.	2,090	1893–1902 1907–1917	28.66	14.28	22.35
Kennebec	Waterville, Me.	4,270	1893–1916	32.45	12.73	23.08
Penobscot	West Enfield, Me.	6,600	1907–1917	32.06	14.01	25.94
St. Croix	Woodland (Spragues Falls), Me.	1,420	1903 1907–1911	30.52	14.96	24.14

[a] The statistics on which this and the following tables are based will be found in Porter (1899), Pressey (1902), Barrows (1907), and in U. S. Geological Survey Water-Supply Papers Nos. 97, 201, 241, 261, 301, 321, 351, 381, 401, 431, 451, and 481.

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[35] Nautical miles.

The run-off from the area tributary to the St. John River may therefore be set at about 24 inches annually. Probably this applies equally to the Nova Scotian streams, while the run-off for the minor rivers along the west and north coasts of the gulf may be estimated at 18 to 22 inches—an average of not less than 18 to 24 inches for the whole watershed of the gulf.

It is not wise to estimate more precisely from data of this sort, because longer terms of observation or a multiplication of recording stations might alter the results; but the ratio that has now been established between the rainfall and the annual run-off at several observing stations confirms this calculation. Thus, Barrows (1907a, p. 110) found the run-off from the Androscoggin basin to range from 22 to 67 per cent of the rainfall over the period 1893 to 1905, averaging 59 per cent. During the same period, the run-off from the Cobbosseecontee, one of the chief tributaries of the Androscoggin, averaged 44 per cent of the rainfall (Pressey, 1902, p. 70). The average for the Presumpscott basin for 1887 to 1901 was 46 per cent of the rainfall (Pressey, 1902, p. 104), and data for the four-year period, 1914 to 1917, showed that 50 per cent of the rain that fell on the Merrimac watershed ran off via that river.

The average amount of fresh water reaching the gulf via the chief rivers tributary to it may therefore be set at about 50 per cent of the annual precipitation over its watershed, which ranges from about 38 to about 50 inches.

Assuming a yearly run-off of about 20 inches from the 61,000 square miles of watershed, this is sufficient to form a layer some 31 inches thick over the entire gulf, out to its southern rim, illustrating more concretely the relationship which this vast run-off of river water bears to the area of sea into which it is discharged. If the yearly amount by which rain and snow falling on the gulf exceeds the evaporation from its surface be something over 1 foot (p. 841), the total yearly influx of fresh water is sufficient to raise the level out to Georges Bank by at least 43 inches, or almost ⅔ of a fathom.

The seasonal distribution of this contribution of fresh water has an important bearing on the seasonal fluctuations of the salinity of the gulf (p. 701), hence demands notice here. As every New Englander knows, our rivers are in flood in spring, of which the Kennebec may serve as an illustration, both because records of its daily discharges have been kept for many years (Barrows, 1907) and because its situation and the general topography of its watershed make it typical of the rivers of Maine and New Brunswick. The following table for the 10-year period, 1893 to 1902, is compiled from Barrow's (1907) records.

Mean discharge of Kennebec River at Waterville, Me.

Month	Run-off, cubic feet per second	Run-off, in inches	Month	Run-off, cubic feet per second	Run-off, in inches
January	2,919	0.76	August	3,811	1.03
February	3,357	.82	September	2,893	.75
March	8,454	2.28	October	3,011	.82
April	24,811	6.49	November	4,685	1.23
May	20,032	5.40	December	3,944	1.17
June	10,031	2.62			
July	6,116	1.65	Monthly mean	7,838	2.10

Two-thirds of the total run-off for the year thus falls during the three spring months, and more than half of it during April and May. This does not exactly represent the natural condition, because the Kennebec is more or less controlled by the several dams; but water-power developments have not been sufficient to mask its spring freshets—still less have they on the Penobscot or the St. John Rivers. Hence, the seasonal fluctuations in the flow of the Kennebec may be taken as generally representative of all the considerable streams that empty into the gulf north and east of Cape Elizabeth and of the Saco as well.

Originally the Merrimac, also, came into flood in the spring, at the season when the snow blanket melts and the ice goes out; but it is now so largely harnessed for industrial purposes that its seasonal flow no longer shows as pronounced a freshet in April and May as New England waterways do in their natural state. Its largest run-off still falls in April, however, and its smallest in September, as appears from the following table:

Merrimac River at Lawrence, Mass., for the period 1907 to 1916

Month	Run-off, in inches	Month	Run-off, in inches
January	1.3	August	0.8
February	1.2	September	.6
March	2.7	October	.8
April	3.6	November	1.0
May	2.3	December	1.1
June	1.3		
July	.8	Monthly average	1.4

Automatic tide gauges, which have been in operation at a number of points around the coastline of the gulf between Cape Cod and the Bay of Fundy, have shown the sea 0.1 to 0.2 feet lower than the mean in the latter part of winter, and about this same amount higher than the mean toward the end of the summer.[36] This variation probably reflects the seasonal variation in the inflow of land water.

RAINFALL AND EVAPORATION

Although land drainage is the chief source for fresh water for the gulf, rainfall also adds a considerable increment. No record of the precipitation over the offshore parts of the gulf itself is available, but the monthly and annual averages for four representative coast stations—Boston, Portland, Eastport, and Yarmouth—tabulated below suggest an annual fall of 40 to 45 inches for the gulf as a whole.

Average rainfall, in inches

Month	Boston	Portland	Eastport	Yarmouth	Month	Boston	Portland	Eastport	Yarmouth
January	3.82	3.81	3.84	5.16	August	4.03	3.57	3.26	3.62
February	3.44	3.65	3.62	4.17	September	3.19	3.20	2.97	3.61
March	4.08	3.75	4.28	5.00	October	3.86	3.66	3.85	4.12
April	3.60	3.11	2.94	3.82	November	4.10	3.80	4.08	4.49
May	3.55	3.67	3.80	3.57	December	3.41	3.68	3.97	4.77
June	3.03	3.36	3.24	2.93					
July	3.36	3.25	3.42	3.47	Total	43.40	42.50	43.30	48.73

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[36] Information contributed by U. S. Coast and Geodetic Survey.

Evaporation, of course, partially offsets precipitation. Unfortunately, no data are available on this subject from any localities that might be supposed to approximate conditions as they prevail at sea in the Gulf of Maine; the outer islands, for example, would be such. Nevertheless, there is no reason to suppose that evaporation at sea is greater than on land, especially when the sea is blanketed with thick fog, as the northern and northeastern parts of the gulf and its offshore banks often are during the summer season. The following records of evaporation for Maine, Massachusetts, and Nova Scotia may therefore be taken as the maximum. The average monthly evaporation from a free water surface at three stations in Maine in the basins of the Penobscot, Kennebec, and Androscoggin Rivers is given by Barrows (1907a, p. 114) as follows, in inches:

Month	Average evaporation, in inches	Month	Average evaporation, in inches
March	2. 23	July	5. 28
April	3. 48	August	5. 12
May	1. 90	September	3. 00
June	2. 87	October	2. 33

No data are available for the winter months, when the observations were necessarily made from a frozen surface, but it may be assumed that evaporation takes place no more rapidly from open water from November through February than in October or March—say at the rate of about 2.2 inches monthly. This suggests a total evaporation for the year of about 35 inches of fresh water.[37] According to FitzGerald (1886), the annual evaporation is somewhat larger near Boston (about 39 inches), as might be expected.

Data supplied by the United States Weather Bureau for Yarmouth, Nova Scotia, more closely paralleling conditions over the gulf because of the greater frequence there of onshore winds, show the following monthly averages over a period of 13 years:

Evaporation at Yarmouth, Nova Scotia

Month	Average evaporation, in inches	Month	Average evaporation, in inches
April[1]	1. 08	August	3. 55
May	3. 04	September	3. 57
June	3. 49	October	1. 50
July	3. 94		

[1] 1920 only; ice in the tank on several days.

Assuming an average evaporation of 1.5 to 2 inches monthly, for the period November to March, the annual evaporation of fresh water at Yarmouth would be close to 29 inches from a surface of open (not frozen) water; the average for the Gulf of Maine is probably not more than 30 inches. These measurements are for fresh

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[37] These measurements were taken freely exposed to the sky (Barrows, 1907a, p. 114, pl. 21).

water, however, which evaporates somewhat more rapidly than salt water under equal conditions of temperature, humidity, etc. According to Mazelle (1898), the evaporation of salt water averages about 81 per cent that of fresh at Trieste, while Okada (1903) found it averaging about 95 per cent that of fresh over a 7-year period in Japan. As Okada's measurements were taken open to the sky, Mazelle's under a roof, the former simulate more the conditions at sea.[38]

As a rough approximation, the evaporation of salt water from the surface of the Gulf of Maine may, then, be set at about 27 to 28 inches, or about 71 centimeters, annually.

DEEP STRATUM

SLOPE WATER

The scources so far mentioned contribute chiefly to the superficial stratum of the Gulf of Maine. We must next consider the comparatively warm and highly saline water that drifts intermittently inward along the trough of the Eastern Channel to form the bottom water of the gulf. The high salinity of this makes its offshore origin clear enough. As certainly, however, it is *not* a direct and unmixed indraft from the mid depths of the Atlantic Basin. Two reasons warrant this confident assertion. In the first place, neither the temperature nor the salinity of the bottom water of the Eastern Channel, or of the gulf basin within, is high enough to accord with such an origin. In the second place, profiles enough have now been run by various expeditions to make it certain that a broad band, intermediate in temperature and in salinity between the coastal water, on the one hand, and the tropic Atlantic water, on the other, always separates the latter from the edge of the continent from Georges Bank to the Grand Banks.

The "cold wall" of the earlier oceanographers—the source of this band—has been the subject of much discussion, with upwelling from the ocean abyss and currents from the north most freqently invoked to explain its low temperature as contrasted with the "Gulf Stream" on its seaward side. Recent explorations, however, have made it clear that this "cold wall" is simply the product of the mixture that is constantly taking place between the tropic water, on the one hand, and the coastal water, on the other (or Arctic water in the Grand Banks region), at their zone of contact along the slope of the continent. "Slope water," as defined by Huntsman (1924), is therefore a better name for it than "cold wall," and as such it is referred to repeatedly in the preceding pages.

It is the presence of a continuous zone of this slope water right across the mouth of the gulf at all times of year which effectively bars unadulterated oceanic or tropic water from entering the Eastern Channel. It is because the most saline bottom water of the gulf draws from this source that members of the bathypelagic plankton of the Atlantic Basin occur only as the rarest of stragglers within the gulf (Bigelow, 1926, p. 67).

Explorations by the Canadian Fisheries Expedition (Bjerkan, 1919; Sandström, 1919; and Huntsman, 1924) have similarly proven that the high salinity (34.5 to 34.7 per mille) and comparatively high temperature (4° to 5°) of the deepest stratum

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[38] For further discussion of evaporation see Krümmel, 1907, p. 244.

of the Gulf of St. Lawrence are similarly maintained by an inflowing bottom current of the same slope origin.

The motive power that brings water of this character to the Gulf of Maine as a bottom current through the Eastern Channel (intermittently, it is true, but regularly enough to maintain the comparatively constant salinity and temperature actually recorded) is to be sought in the distribution of density along the edge of the continent. A considerable body of evidence has now been accumulated to the effect that the zone of contact along which coast and ocean waters mix, and where the slope water is manufactured, averages somewhat more dense (heavier) than the water in on the edge of the continent, except right at the surface. All the profiles that have been run out across the continental edge off Nova Scotia in summer, both those by the Canadian Fisheries Expedition (Sandström, 1919, pl. 9, sections 13, 14, 15, 16, and 17) and by the United States Bureau of Fisheries, have shown something of this sort. Thus, on July 25 to 28, 1914, on the first *Grampus* profile out from Shelburne (stations 10231, 10232, and 10233), the stratum between the 20-meter and 150-meter levels was more dense just outside the edge of the shelf than in over the latter, though the surface was less so.

The *Grampus* again found the water heavier over the continental slope (station 10295) than in over the shelf (fig. 168) along this same profile on June 23 and 24, 1915, with a decidedly steep density gradient at the 50 to 100 meter level. Consequently, the whole mass of water on the shelf above 100 meters must have had a hydrostatic tendency to drift seaward, except immediately at the surface.

A March profile along this same general line (stations 20073 to 20077) again shows higher densities at the outermost station, at 100 to 220 meters, than along the edge of the continent (fig. 169)—evidence of this same dynamic tendency for the water of low salinity and temperature to move out across the slope, though at the inshore end of the profile the dynamic tendency in the superficial stratum was the reverse.

The water at 20 to 120 meters' depth was likewise somewhat more dense over the southeastern slope of Georges Bank (station 10220) than in on the neighboring edge of the latter (stations 10221 and 10225) in July, 1914; again in April, 1920 (stations 20109 to 20111), though our corresponding profile for March, 1920, crossed a more complex alternative of heavier and lighter bands there (stations 20065 to 20069).

The cross section of the western end of Georges Bank for July 20 and 21, 1914 (fig. 170), is especially instructive in this connection, being the only one of our profiles that has reached water of oceanic salinity (36 per mille). Here, again, the upper 50 meters of water proved slightly more dense at the outer end (station 10218) than over the neighboring edge of the bank (station 10216), resulting in a comparatively steep south-north gradient of density, though the relationship was just the reverse at a depth of 70 to 140 meters. A slight differential of this same order (density higher at the outermost stations than in on the bank) also prevailed in this same general region in February and again in May of 1920 (stations 20045 and 20046 for February; 20128 and 20129 for May); but in the cold July of 1916 this seems to have applied only at depths greater than

40 meters, with the surface water more dense over the bank (station 10348) than over its seaward slope (stations 10349 and 10352), though some doubt exists as to the salinity (hence as to the density) at the critical station (10349, p. 992).

Thus, densities rule lower along the outer edge of the offshore banks, abreast of the Gulf of Maine and off Nova Scotia to the eastward, than along the continental slope that bounds the banks on the offshore side. The relationship at any given date may be of the reverse order, either close to the surface as in July, 1916, or along the 100-meter contour, as in July, 1914. However, we have never failed to find the surfaces of equal density rising comparatively steeply from the outer part of the shelf through the greater part of the depth zone there included, out across the edge of the continent between the longitudes of Shelburne, Nova Scotia, and of Cape Cod.

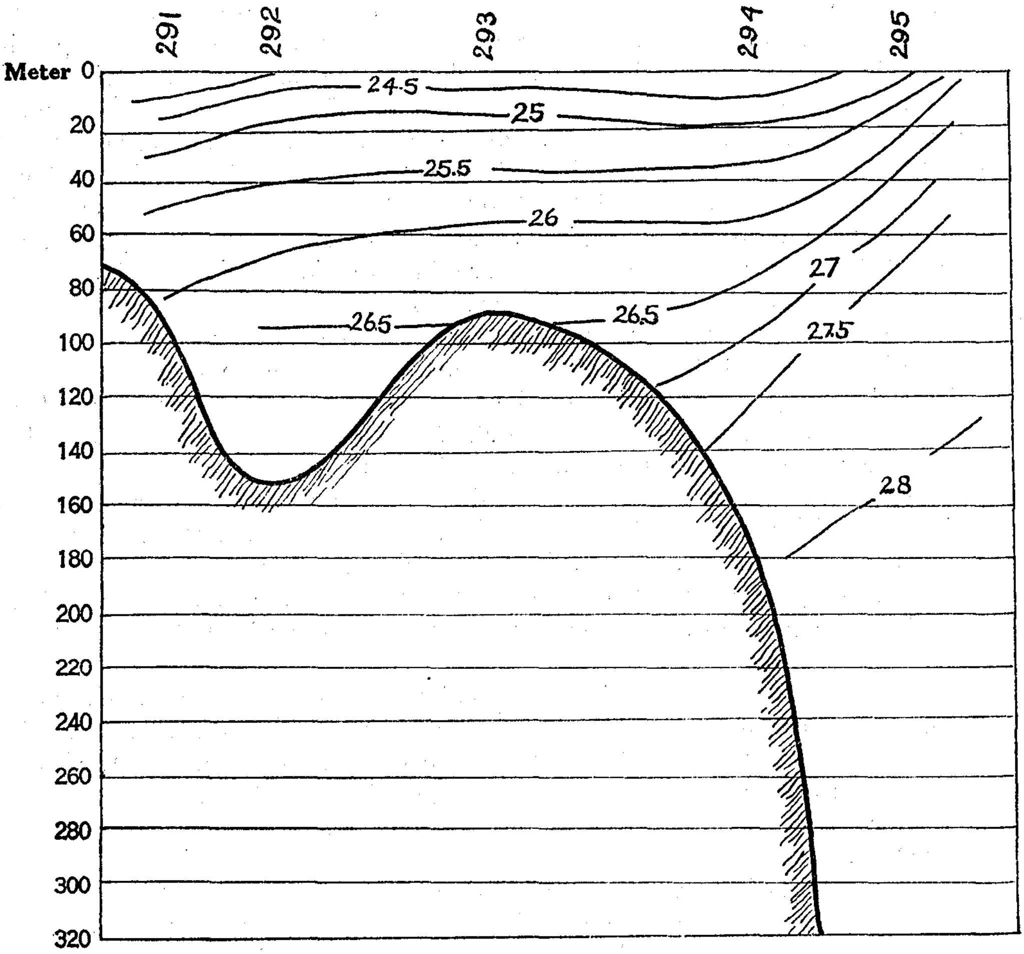

FIG. 168.—Density profile crossing the continental shelf in the offing of Shelburne, Nova Scotia, June 23 to 24, 1915. Corrected for compression

To the east and north of our limits, and especially off the Newfoundland Banks, this zone of mixture is not only heavier than the coast water on its inner side (or

Arctic water, according to locality), but often, if not always, heavier than the tropic water on the outer side as well (Witte, 1910; E. H. Smith, 1924, p. 140, 1925, figs. 10, 12, and 19), causing the dynamic tendency for surface water to move in from both sides toward this heavy zone (or "cabelling"), which seems first to have been emphasized by Witte (1910). Huntsman, too (1924, p. 278), definitely accepts "cabelling" as a governing event in the formation of the slope water; and although more recent hydrodynamic studies (see especially E. H. Smith, 1926) have made it clear that actual sinking is usually prevented there by the effect of the earth's rotation, a potential sinking zone of this sort does nevertheless tend to draw in surface water from both sides toward the zone where the surfaces of equal density depart most from the horizontal, and so to set up a horizontal circulation.

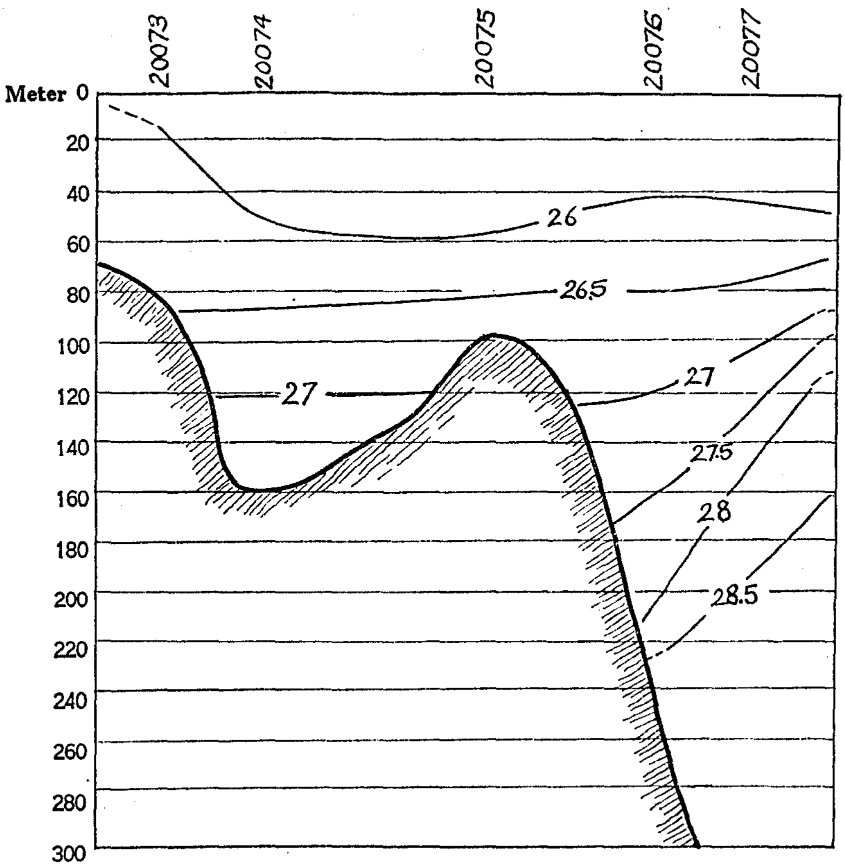

FIG. 169.—Density profile crossing the continental shelf in the offing of Shelburne, Nova Scotia, March 17 to 20, 1920. Corrected for compression

A potential sinking zone of this same sort was revealed by one profile run off La Have Bank by the Canadian Fisheries Expedition in July, 1915, when the upper 100 meters proved more dense just outside the edge of the continent (Bjerkan, 1919, *Acadia* stations 41 to 43) than in on the edge of the shelf, on the one hand (*Acadia* stations 39 and 40), or at the outermost station, on the other (*Acadia* station 44).[39] It is doubtful how regularly profiles abreast of the gulf or off southern New England would show this decrease in density seaward from the continental slope.

In the preceding discussion I have taken pains to speak always of a "dynamic tendency" toward movements of the water, never of such movements as taking place; because in our latitudes the currents that actually follow inequalities of density of this sort are given quite different characters by the deflection resulting from the rotation of the earth, by which the apparent track of any current (or other body moving freely over the earth) in the Northern Hemisphere is deflected to the right.[40]

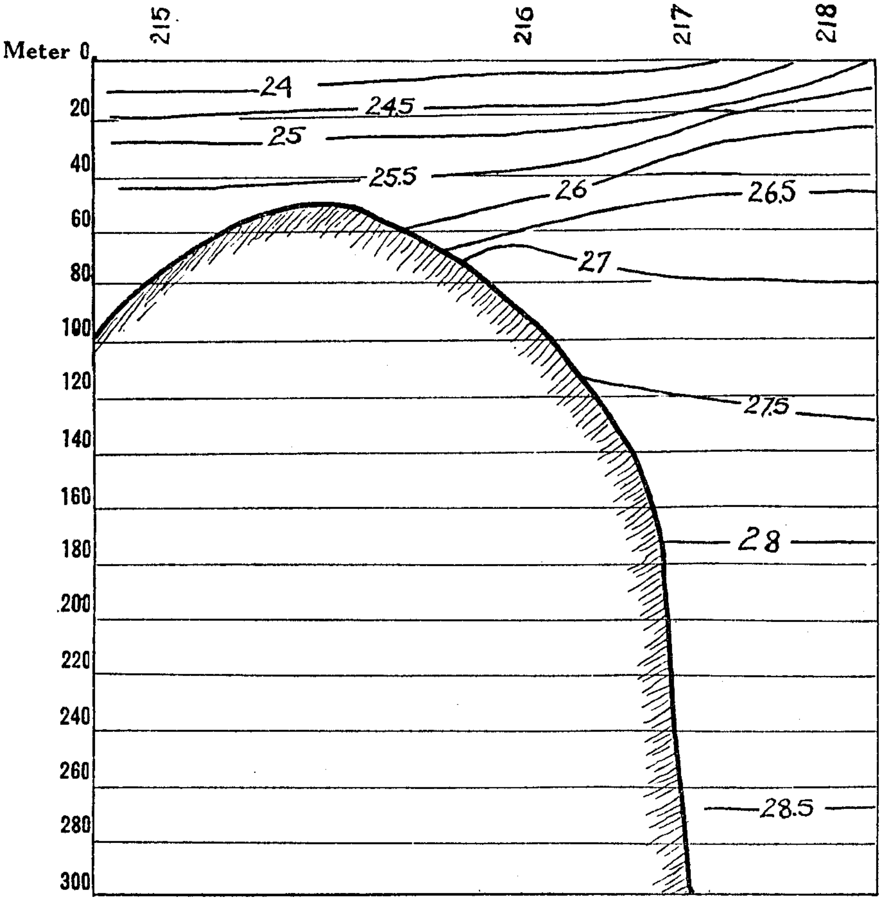

FIG. 170.—Density along a cross profile of the western part of Georges Bank, July 20 and 21, 1914 (stations 10215 to 10218). Corrected for compression

The rôle that this quasi-force plays in directing the ocean currents, however set in motion, is now so generally appreciated that no discussion of it is called for here.

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[39] None of our *Grampus* or *Albatross* profiles have run out far enough to show this relationship, if it existed.

[40] Krümmel (1911, p. 449) and Sandström (1919) have given perhaps the simplest statements of this subject, in its oceanographic bearing, and discussions of the effects of the centrifugal force resulting from the earth's rotation in relation to the ellipsoid form of the earth. See also Ferrell (1911), Davis (1885 and 1904), and Bjerknes (1910 and 1911).

Baldly stated, its practical effect on the slope water which dynamic forces tend to drive out to sea from the continental slope, as described above (p. 843), is to swing this drift to the right (i. e., to the west), thus altering into a longshore current what otherwise would be (and potentially is) an offshore set.[41]

In this way a dominant drift from east to west tends to develop along the upper part of the continental slope of La Have and Browns Banks so long as the distribution of density is of the type actually recorded on the *Acadia*, *Albatross*, and *Grampus* cross profiles of this part of the continental shelf for March, 1920, June and July, 1915, and July, 1914. On each of these occasions the dynamic tendency, acting as the propulsion for such a drift, involved the whole mass of bottom water from the crest of La Have Bank down the slope to a depth of at least 200, if not 250, meters. An east–west drift of the bottom water seems, then, comparatively constant on just this part of the slope.

In July, 1915, this drift involved the whole column of water, surface to bottom; again, in July, 1922, when bottles set out near the edge of the shelf in the offing of Cape Sable drifted into the Gulf of Maine (p. 908). Sandström's (1919) calculation of a surface current of about 5 miles per day[42] toward the southwest, along the outer part of the shelf, on this line (between *Acadia* stations 39 and 41), shows that the surface water may travel with considerable velocity at times when the whole column is involved in this westerly set along the edge of the continent. This is confirmed by the drifts of four bottles set out 48 to 60 miles off Cape Sable in July, 1922, three of which went to the Bay of Fundy at minimum rates of 3 to 4 miles per day, and one to Winter Harbor, near Mount Desert, at a daily rate of at least 2 miles, and probably considerably faster than that (p. 908). However, the obliquity of the surfaces of equal density, which originates this drift, decreased with increasing depth on the *Acadia* section, so that Sandström's (1919, p. 332) table indicates a mean velocity of only about 1 mile per day for the whole column of water, surface to bottom, between the critical stations (from No. 40 out to the 200-meter contour), with the bottom water creeping westward not faster than about one-half mile per day[43] at a depth of 100 to 200 meters.

The outermost bottle (which is known to have gone to the Gulf of Maine from the line put out off Cape Sable by the Biological Board of Canada in 1922) was set adrift over the 200-meter contour[44] 59 miles out from the land, the only returns from bottles set adrift farther out coming from Europe. This limitation of the westerly drift to a narrow belt corroborates the *Acadia* profile of July, 1915, on which it was only about 20 miles wide (and similarly located), giving place farther out to a succession of lighter and heavier bands, indicating a stronger but even narrower countercurrent to the eastward; then, outside of that, a second line of drift to the westward.[45]

Evidently an active mixing of cold and warm waters was taking place at the outer end of this profile at the time, with bands of higher and lower temperature

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[41] See Smith's (1926) exposition of this important concept.

[42] The velocity arrived at by Sandström (1919) from hydrodynamic calculation are only *relative* to the most nearly stationary stratum of water, not absolute. This does not lessen their significance in the present case, for with the whole column moving in the same direction the actual velocities would be somewhat greater than the calculated.

[43] About 1.4 centimeters per second, or 0.025 knot per hour.

[44] Information contributed by Doctor Huntsman.

[45] See Sandström (1919, pl. 15) for the calculated velocities of these two lines of drift.

eddying in the extremely complex fashion that may be expected to characterize the zone of contact between waters that differ widely in their physical character and in their direction of flow.

Similar alternations between colder (and less saline) and warmer (and more saline) bands have been reported on several occasions and at localities widely separated off the eastern seaboard of North America; but in most cases, at any rate, these are transitory and rapidly changing phenomena. The westward drift of water close in to the upper part of the slope, just described, has, on the contrary, proved characteristic of the La Have Bank region; and so long as the dynamic motive for this drift persists, the neighboring oceanic triangle off the mouth of the Eastern Channel is supplied with slope water from the eastward. By this reasoning, the current that flows into the bottom of the gulf via the Eastern Channel draws from the slope water manufactured at about an equal depth on the Nova Scotian slope—chiefly between Browns and La Have Banks—not from shoaler or deeper strata there.

This conclusion is confirmed by the fact that temperature and salinity proved very nearly the same on bottom in the channel (34.7 to 35 per mille and 6° to 7° at 200 to 250 meters) as at equal depths on the slope between these two banks (34.6 to 34.9 per mille and about 7° to 8°) in July, 1914, in June, 1915, and again in the spring of 1920.[46]

Further evidence that the indraft into the channel is supplied from the eastward, not from the westward, is afforded by the fact that considerably lower temperatures and salinities have been recorded around the eastern and southeastern slopes of Georges Bank (p. 714). In fact, there is reason to believe that the western side of the channel is the site of a dominant drift outward from the gulf (p. 974).

The cold band encountered off the southwest slope of Georges Bank by the *Grampus* in July, 1916, and reported there in other summers (pp. 608, 919) may also be credited with an eastern source, because its temperature and its salinity both agree closely with that of the slope water that is manufactured in the offing of Cape Sable in early summer, as exemplified by the observations taken there in June, 1915, and July, 1914 (p. 629; Bigelow, 1922, p. 166). Thus it owes its low temperature indirectly to the Nova Scotian current (and so to ice melting far to the eastward).

Why this southwesterly cold current was so much more in evidence along the bank in 1916 than in 1889, 1913, or 1914 remains an open question, but it seems probable that some westerly movement of slope water takes place along Georges Bank to a greater or less extent every spring as the Nova Scotian current floods to its maximum velocity and volume. In some years (1889, for instance, and 1916) this drift persists into the summer, as seems to have been the state in 1922, also, when so many of the bottles set out at the edge of the continental shelf in July made long drifts to the westward (p. 882). In other years (exemplified by 1914) it seems to be obliterated west of longitude about 68° by July, as the tropic water advances toward the edge of the continent. But although so variable, the existence of this cool band in some summers is extremely instructive as one of the several

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[46] The slope water was somewhat more saline at this locality at the end of July, 1915 (Bjerkan, 1919, *Acadia* station 41), but no observations were taken in the channel at the time.

evidences of the general tendency of the slope water to move westward from the Nova Scotian slope.

The slope water, moving westward, is forced against Browns Bank by the earth's rotation. Consequently, with the Eastern Channel offering an open route for it to the right, it is reasonable to think of a screwing motion as taking place into the latter around the southerly and southwesterly slopes of Browns Bank so long as the propulsive dynamic force resulting from regional inequalities of density persists over the Nova Scotian slope to the eastward.

Additional evidence that the bottom water does actually move inward through the Eastern Channel is afforded by the inequalities of density within the basin of the gulf, where the surfaces of equal density (approximately horizontal in the upper 50 to 60 meters) show a considerable slope from the channel inward at depths greater than 80 to 100 meters.

This density gradient in the deep water may be illustrated most graphically by charting the depth to which it is necessary to sink in order to reach water of a given value, choosing 1.027 as the most illustrative (figs. 171 and 172). The precise upper contour of this mass of heavy bottom water has varied from month to month, as might be expected. Thus, in June, 1915, the slope was steepest near the entrance to the channel, with the surfaces of equal density lying nearly horizontal thence inward along the western arm of the basin. In July and August of 1914 the the most abrupt slope, involving the whole column of water deeper than 50 meters (fig. 171), was situated farther within the basin. A density gradient of the same sort was again recorded in the eastern part of the basin in March, 1920, and a weaker contrast (but one of the same order) between the channel, on the one hand, and the inner parts of the basin, on the other, in April of that year, sufficient to show it a permanent characteristic of the gulf.

The implication of a density gradient of this sort is obvious. Only by the introduction of heavy water into the gulf via the channel could it be maintained against the action of the hydrostatic forces that are constantly tending to make horizontal the surfaces of equal density.

The inflowing bottom current, which maintains the high salinity (34.5 to 35 per mille) of the deeps of the gulf, thus corresponds, both in cause and in effect, to the indraft of offshore water that has been recorded in many an estuary. The gulf, in fact, is nearly as estuarine in this respect as it would be if the offshore banks (Georges and Browns) were above water, and so actually inclosed it except for the deep channels between.

In the preceeding discussion I have spoken as though this inflowing current and the gradients of density that give rise to it were comparatively constant. Actually, however, our observations on temperatures and salinity have revealed considerable fluctuations in the volume of water that enters the gulf via this route at various seasons and in various years.

It goes almost without saying that no sharp distinction can be drawn in salinity between waters of different origins, especially where the water is stirred as actively as it is in the Gulf of Maine; but the isohaline for 34 per mille may be taken as roughly outlining the "slope water" that has recently entered the gulf or that has continued little altered during its sojourn there, if the product of an earlier invasion.

So far as our records go, slope water of this high salinity reaches its widest expansion within the gulf in April (p. 737). The indraft through the channel, however, seems to slacken during that month, for the bottom layer of 34 per mille water was much thinner in May[47] of 1915 than in March or April of 1920 (p. 754), and the area occupied by it was much less extensive. In that year (probably a representative one) but little water can have moved inward through the Eastern Channel during

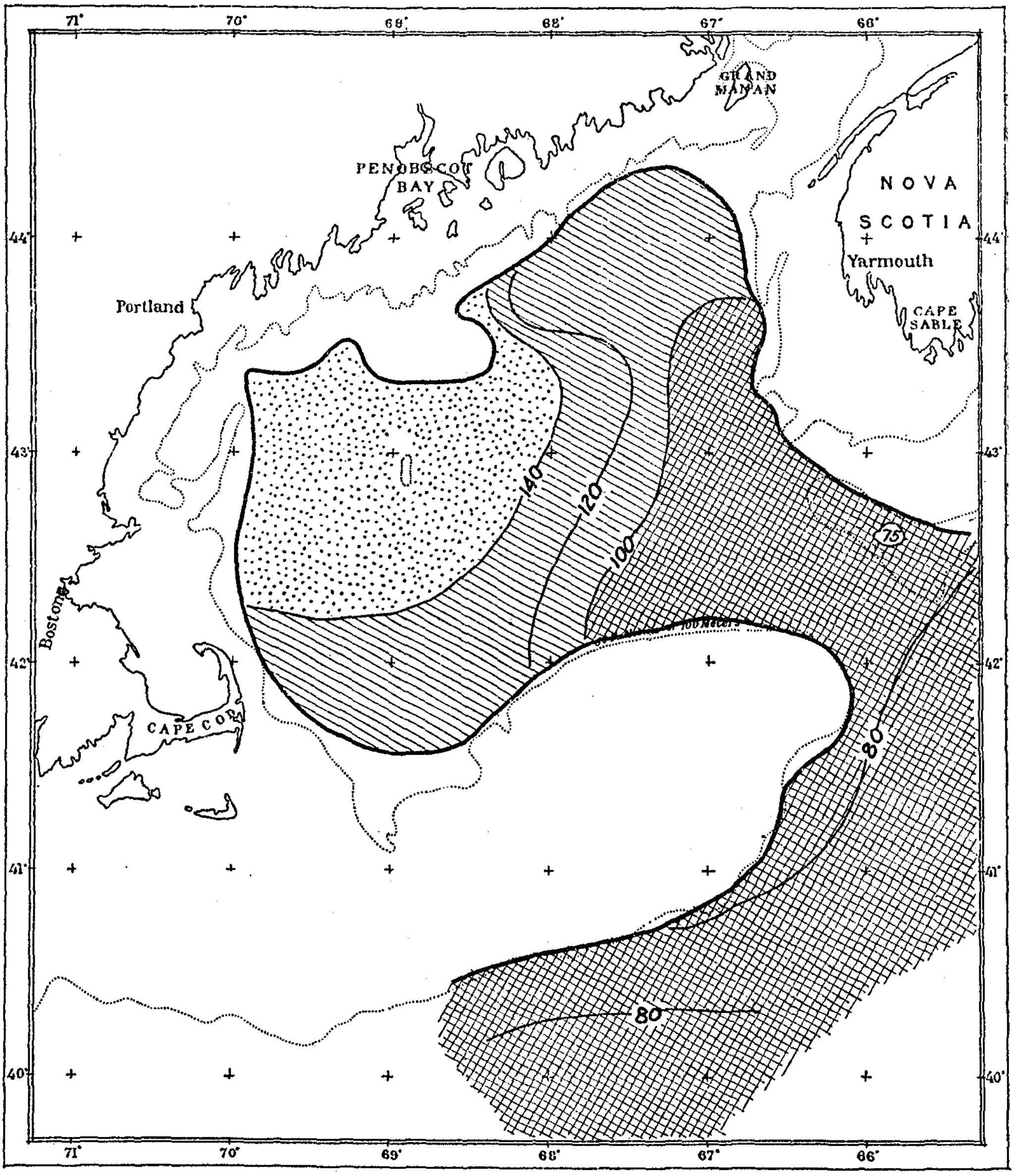

FIG. 171.—Depth of the density surface (isopycnobath) for 1.027; July and August, 1914. Corrected for compression

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[47] In May, 1915, the bottom water of the western arm of the basin was more saline than 34 per mille; that of the eastern less so.

May or the first half of June, for salinities as high as 34.5 to 35 per mille were confined to the channel and to the neighboring part of the basin during the last half of that month, with bottom values of 33.8 to 33.9 per mille in the inner branches of the latter—western as well as eastern. A considerable indraft of slope water certainly took place shortly thereafter, however, spreading inward over both arms of the basin, where the salinity of the bottom water had again risen above 34 per mille by the end of the summer in a layer of considerable thickness (p. 786).

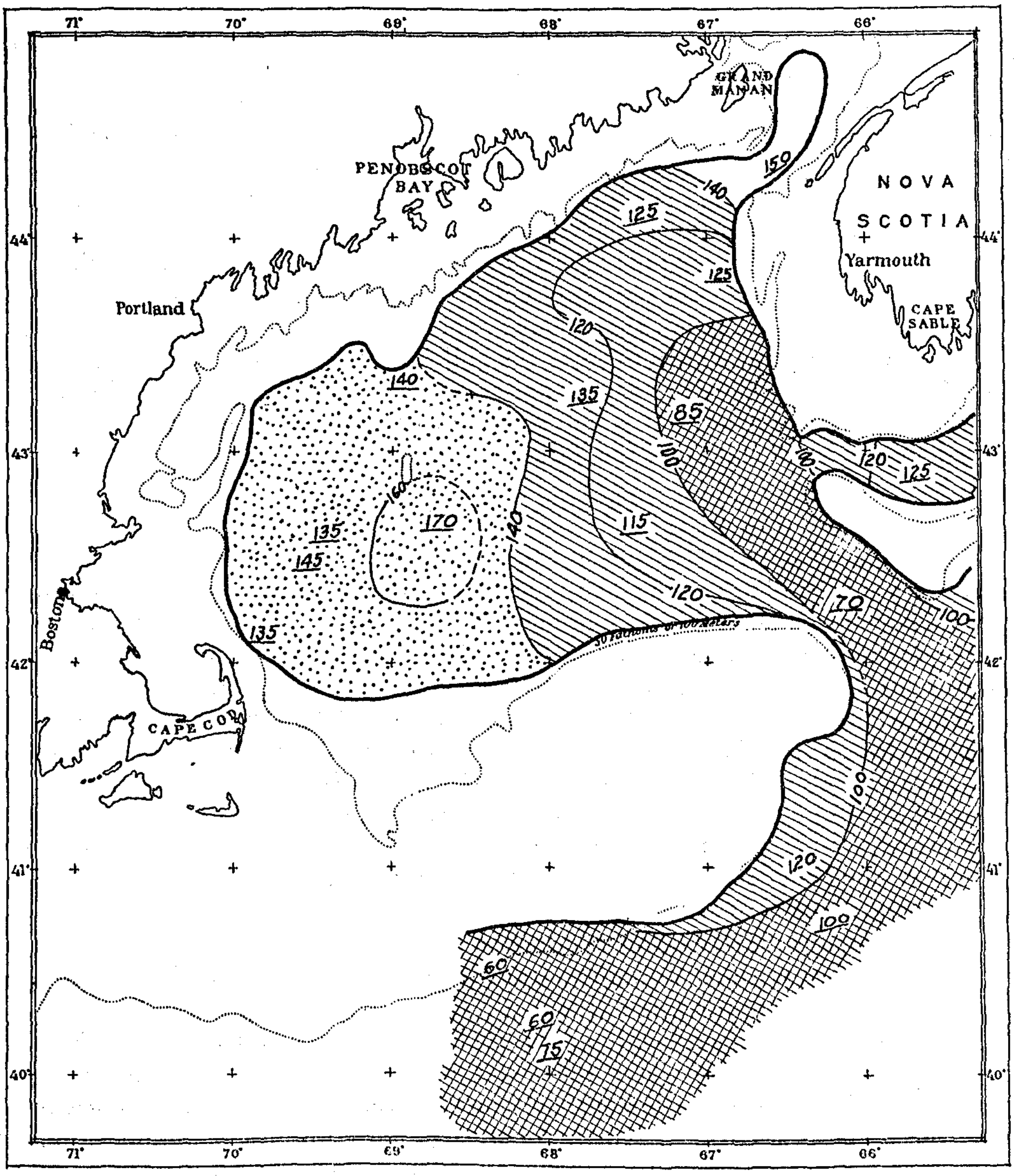

FIG. 172.—Depth of the density surface (isopycnobath) for 1.027; March, 1920. Corrected for compression

With 10 of our 14 August stations as deep as 180 meters (100 fathoms), or deeper, also showing bottom values higher than 34 per mille in 1912, 1913, and 1914, this indraft is evidently characteristic of June or July. No doubt, however, it varies from year to year, both in its seasonal schedule and in its volume and velocity, and the distribution of density (pp. 958, 960) shows that in some summers, at least (as exemplified by 1914), a counterdrift develops through the channel, out of the gulf, in July, though perhaps only for a brief period.

In a summer when this inflowing bottom current is active, slope water may be expected to occupy approximately the area shown in the contour chart for July and August, 1914 (fig. 152), its boundaries, as in March less extensive than in April, 1920 (figs. 100 and 118), including only the two arms of the trough and the region of their junction instead of the whole central part of the gulf basin.

By good fortune our records afford charts of the slope water at its maximum for the respective months[48]—the one representing a period of active inflow, the other the tendency toward equalization that follows such a period.

Slope water is thus shown to enter the gulf from midsummer on through autumn and winter—but certainly in varying pulses—and to slacken or cease during the late spring and early summer. It is not possible to outline its fluctuations in the gulf more definitely than this from the data gathered so far.

ABYSSAL UPWELLINGS

Upwellings from the oceanic abyss, if such occur, would be a second possible source of water of high salinity and moderate temperature for the deeps of the Gulf of Maine. Upwelling of this sort, in fact, has often been invoked to explain the low temperature of the so-called "cold wall" (referred to here as "slope water"), as contrasted with the tropic water on its offshore side (Buchan, 1896).

Thus, Pettersson (1907 and 1907a), for example, definitely classed the cold wall along the North American littoral as an updrift over the continental slope from the cold abyssal water of the Atlantic, having for its motive power the sinking of cold water off Newfoundland. While this view has not found a very favorable reception, both Schott (1912) and Krümmel (1911) have believed that more or less upwelling does occur along our coasts, at least in winter; while A. H. Clark (1914) has argued that the cold water off Nova Scotia must receive something from the abyss to account for the geographical distribution of crinoids.

The criteria by which upwelling from the oceanic abyss would be made recognizable may be stated in a few words.

In temperate zones surface temperature is perhaps the best index of this process in summer, for in regions where the water wells up actively seasonal warming is retarded, causing abnormally low surface temperature. Unless the upwelling extended along the whole east coast of North America (a most improbable supposition) any cold water welling up would be surrounded by a warmer surface to the north and south of it as well as on its offshore side, as is the case off California (McEwen, 1912) and off the northwest coast of Africa (Schott, 1902, pl. 8). At the same time there would be a continuity in salinity between this cold water near the surface and the

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[48] 1920 was a salt March, compared with 1921; 1914 a salt summer, compared with 1913.

deep stratum that served as the source for the updraft, as demonstrated by the distribution of salinity off the coast of Morocco (Schott, 1912, pl. 33). Off the northeastern American seaboard abyssal water would also be betrayed by its precise combination of salinity and temperature, for while only moderately cold (about 4°), the salinity of the Atlantic abyss is much higher (34.9 to 35 per mille) than that of any water on the continental shelf of like temperature.

The observations taken in 1912, on our first cruise, were enough to prove that the inner part of the Gulf of Maine received little if anything from this abyssal source, its salinity being too low and its mean temperature too high.

The rapid warming of the superficial stratum, which takes place all along our seaboard in spring from Nova Scotia to Chesapeake Bay (except in limited areas of active tidal stirring), is, of itself, incompatible with any widespread upwelling of abyssal water, unless this be confined to the deeper strata. So, also, is the wide variation in surface temperature from season to season; for any considerable updraft from the abyss would necessarily check vernal warming and so narrow the seasonal range of temperature. The profiles which the *Grampus*, *Acadia* (Bjerkan, 1919), and *Albatross* have run across the continental shelf between Chesapeake Bay and the Laurentian Channel have produced a large body of evidence to the same general effect; particularly welcome because upwelling had been postulated more on theoretic grounds than from first-hand observation, previous knowledge of subsurface salinity on the continental shelf between Cape Sable and Chesapeake Bay being virtually *nil.* None of these temperature profiles for the summers of 1913, 1914, 1915, and 1916 (Bigelow, 1915 to 1922) yield any evidence that abyssal water ever tends up the slope, much less reaches the continental shelf at that season. To the west of Cape Sable, in fact, the coldest water in on the shelf has been separated from the low temperatures of the water of the deeps by a somewhat warmer zone washing the edge of the continent bottom at intermediate depths in most cases (p. 617). The corresponding salinities have been no more compatible with upwelling either at the time of observation or shortly previous, the coldest water on the shelf being in every case much less saline (below 33.5 per mille) than the level of equally low temperature outside the edge of the continent (34.9 per mille, or higher, at all seasons).

As I have discussed this question in detail in earlier publications (1915, p. 258; 1922, p. 166), I need only add here that none of the observations taken by the *Bache* off Chesapeake Bay in January, 1914 (Bigelow, 1917a), by the *Grampus* between Marthas Vineyard and Chesapeake Bay in November, 1916 (Bigelow, 1922), or by the *Albatross* off the Gulf of Maine in the spring of 1920, show any more evidence of abyssal water reaching the continental shelf than did the earlier observations.

The only route we need consider, then, by which abyssal water might, perhaps, enter the Gulf of Maine, is the Eastern Channel; but the precise combination of temperatures and salinities recorded in its trough for the months of March, April, June, and July (6.07° to 7.2° and 34.6 to 35.03 per mille), combined with the general distribution of salinity and temperature within the gulf, points to quite a different source (the slope water) for the intermittent current that drifts inward over the bottom of the channel, as is discussed above (p. 842).

The distribution of density must, in fact, strongly resist any force, such as offshore winds driving the surface water out to sea, which would tend to draw abyssal water upward over the continental slope abreast the Gulf of Maine; for in every case we have found a decidedly stable state of equilibrium prevailing there. In fact, most of our cross sections of the outer part of the continental shelf abreast the gulf and to the eastward show a general dynamic tendency of quite a different sort—namely, one leading to the development of a drift of the inner slope water toward the west (p. 847), while a counter drift of the outer slope water (or "inner edge of the Gulf Stream") toward the east has often been recorded.

In short, continued observation has not adduced any evidence that water from the ocean deeps ever wells far enough up the continental slope to reach the Eastern Channel, much less to overflow the offshore rim of the gulf.

This conclusion does not imply that upwelling may not take place over the lower part of the continental slope from the Atlantic abyss. On the contrary, much evidence has accumulated to the effect that some such process is of wide occurrence along the lower part of the slope, below, say, the 500 to 1,000 meter level, westward and southward from Georges Bank. Perhaps the clearest evidence of this is afforded by a profile run from Chesapeake Bay to Bermuda by the *Bache* in January and February, 1914, when the uniform abyssal water (about 4° in temperature and 34.9 to 35 per mille in salinity) was banked up against the slope to within 1,100 to 1,200 meters (Bigelow, 1917a, figs. 11 and 12). This also appears on a profile run by the *Dana* from Bermuda to Norfolk, Va., in May, 1922 (Nielsen, 1925, fig. 4). But no direct evidence has yet come to hand that water from this deep source ever reaches the continental shelf of eastern North America in volume sufficient to affect the temperature or salinity of the coast waters.[49]

In denying the occurrence of abyssal upwelling as a cause of low temperature in the Gulf of Maine, I do not refer to upwelling from shallow water along shore—a common event, which often exerts an immediate effect on the temperature and salinity of the surface water in the vicinity in spring and summer, as described in an earlier chapter (p. 550).

RECAPITULATION

The Gulf of Maine incloses a sector of the typical coastwise water of the northwestern Atlantic, receiving its most important accessions periodically from the following sources: Slope water of high salinity (close to 35 per mille) and close to 6°–8° in temperature flows intermittently into the gulf as a bottom current, as it does also into the Gulf of St. Lawrence and into other smaller depressions on the continental shelf. There is strong evidence that the slope water that reaches the Gulf of Maine has its source along the Nova Scotian slope to the eastward. The cold Nova Scotian current brings a large volume of water of low salinity into the gulf from the eastward, past Cape Sable, in spring, as a surface drift; but this current slackens or ceases altogether at other times of year. The gulf also receives a surface drift from the offing of Cape Sable, into the composition of which cold banks water from the east, slope water from the Scotian eddy, and tropic water all enter in proportions that can not yet be stated.

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[49] For further discussion of this subject as it concerns the Gulf of Maine, see Bigelow, 1915, p. 255, and 1917, p. 239.

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

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[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).