

## INTRODUCTION

This memoir is the third and final part of the general report on the oceanographic survey of the Gulf of Maine.<sup>1</sup>

Key charts to the stations will be found in the preceding part of this volume (Bigelow, 1926, figs. 1-9); the dates and positions are tabulated below (p. 976) with the physical data.

The chapter on hydrodynamics has been made possible by Lieut. Commander E. H. Smith's collaboration; R. Parmenter tabulated the physical data for the *Fish Hawk* cruises of 1925, collaborating also in the charts and discussion based thereon.

Records of temperature or salinity have been contributed by R. A. Goffin, Wm. C. Schroeder, Capt. G. W. Carlson, Capt. G. W. Greenleaf, C. G. Corliss, and Dr. C. J. Fish of the Bureau of Fisheries. Capt. John W. MacFarland, from his schooner *Victor*, and Henry Stetson and T. C. Graves, from their yachts, also have taken welcome observations.

I owe a debt of gratitude also to Dr. A. G. Huntsman, who has generously allowed quotation from his report on Canadian drift-bottle experiments in advance of publication, and who contributed other data acknowledged in the appropriate connections; to Dr. J. P. McMurrich, who has offered the use of his unpublished data on temperatures at St. Andrews, New Brunswick; and to the late Dr. A. G. Mayor, who contributed the colorimetric tubes used in the determination of alkalinity on the *Albatross* and *Halcyon* cruises of 1920-21.

## OCEANOGRAPHIC HISTORY

### 1. GULF OF MAINE PROPER

The first Gulf of Maine temperatures, so far as I can learn, were taken in October, 1789, by Benjamin Franklin's nephew, Jonathan Williams, who read the "heat of the air and water at sunrise, noon, and sunset" (1793, p. 83) on a voyage from Boston to Virginia, and found the surface 8.9° C. (18° F.) off the mouth of Massachusetts Bay on October 11, warming to 11.1° (52° F.) off Chatham on Cape Cod, to 15° (59° F.) over the outer part of the continental shelf south of Nantucket, and to 18.3°-19.4° (65° to 67° F.) in the inner edge of the Gulf Stream outside the edge of the continent on the 13th—readings that agree very well with the usual distribution of temperature for that season. On another voyage (from Halifax to New York) during the last week of July, 1790, he again took temperatures on Roseway Bank, Browns Bank, and in the gully between them; also along the southern side of Georges Bank (53° to 64° F.).

Enough readings of the surface temperature of the Gulf of Maine had accumulated during the first half of the nineteenth century to permit Maury (1855 and 1858) to show its coastal belt and the Bay of Fundy as between 50° and 60°, its southern side out to the continental edge as between 60° and 70° in July, and the entire gulf as colder than 50° in March.<sup>2</sup>

<sup>1</sup> The first part was devoted to the fishes (Bigelow and Welsh, 1925); the second to the plankton (Bigelow, 1926).  
<sup>2</sup> Petermann (1870) more correctly interprets the individual readings reproduced on Maury's (1852) thermal chart by showing the inner parts of the Gulf of Maine as 54.5° to 59° and the Georges Bank-Nantucket Shoals region as about 59° to 65.5° in July; about 32° and 32° to 41°, respectively, in January.

The first attempt to measure the temperature of the gulf below the surface was made in the summer of 1870, when Verrill (1871, p. 3) found the water virtually homogeneous, surface to bottom, in Passamaquoddy Bay, though readings with thermometers of the maximum-minimum type established a considerable range of temperatures on the offshore slope of Georges Bank (Verrill, 1873; Sanderson Smith, 1889, p. 887).

Two summers later surface and bottom temperatures were taken at a large number of stations in the neighborhood of Casco Bay from the Fish Commission steamer *Blue Light* (Verrill, 1874, 1874a), and also at various localities in deep water in the western side of the gulf by the Coast Survey steamer *Bache* (Sanderson Smith, 1889, p. 885; Packard, 1876). As a result of this summer's work Verrill was able to bring to scientific attention the contrast between the low bottom temperature and the warm surface of the western side of the gulf.

The survey was continued by the *Bache* in the summer of 1874 at about 40 dredging stations in the western side of the Gulf of Maine, in depths of 27 to 113 fathoms (Sanderson Smith, 1889, p. 886). No observations were taken in the gulf in 1875 or 1876; but in 1877 the Fish Commission, from the *Speedwell*, in connection with a survey of the bottom fauna, took surface and bottom temperatures in the northern part of Massachusetts Bay, with serial observations at several stations on a line crossing the gulf to Cape Sable.

Unfortunately, none of the subsurface temperatures taken in the gulf up to that date were even approximately dependable, according to present-day standards, because the Miller-Casella thermometers employed were not only unreliable (Verrill, 1875, p. 413), but, being of the maximum-minimum type, they would register merely the lowest temperature at each station, which was not necessarily at the level at which the reading was ostensibly taken. Modern oceanographic research in the gulf may therefore be dated from the summer of 1878, when the *Speedwell* took temperatures in Massachusetts Bay and off Cape Ann, including serials at 31 stations (Sanderson Smith, 1889, p. 905; Rathbun, 1889, p. 1005), with reversing thermometers. This type, improved from time to time, has been employed regularly ever since. The *Speedwell* worked again in the gulf in the summer of 1879 (Sanderson Smith, 1889, p. 909; Rathbun, 1889, p. 1006). In June, 1880, the *Blake* took surface and bottom readings at three stations inside the 200-fathom contour on the eastern part of Georges Bank (Rathbun, 1889, p. 972, and A. Agassiz, 1881), while in August the *Fish Hawk* obtained similar data off Chatham, Cape Cod, in 10 to 43 fathoms (Rathbun, 1889, pp. 922-923), but did not visit the more northern parts of the gulf.

The year 1882 is an important one in the annals of North American oceanography, because that spring saw the oft-quoted destruction of the tilefish<sup>3</sup> and of the invertebrate fauna that inhabited the warm band along the edge of the continent, presumably by flooding with very cold water. During the following August the *Fish Hawk* took observations south of Marthas Vineyard and made one trip to the 100-fathom line east of Cape Cod (Rathbun, 1889, p. 925).

Surface and air temperatures were recorded from early spring to late autumn at several lighthouses and lightships along the coast of the gulf from Nantucket Shoals to Petit Manan during the years 1881 to 1885, the 10-day averages of which are

<sup>3</sup> For an account of this event and of the gradual reestablishment of the species see Bigelow and Welsh, 1925.

tabulated by Rathbun (1887). The very large number of temperatures taken on the lightships in the ordinary routine since that time have not been examined critically, however.

The *Albatross* occupied a large number of dredging stations along the offshore slope of Georges Bank during 1883, 1884, 1885, 1886, and 1887, but only five of her serial readings and a few of the bottom records fall within the limits of the Gulf of Maine.<sup>4</sup> An extensive series of temperatures taken by Dr. W. C. Kendall at the surface and at small depths in the western part of the gulf, in connection with mackerel investigations carried out by the *Grampus* in 1897, also deserves mention (p. 594).

A gap follows in the thermal history of the gulf until the summer and autumn of 1904, when the Tidal Survey of Canada took a large number of surface and subsurface temperatures in the Bay of Fundy region and off the west coast of Nova Scotia (Dawson, 1905, 1922). Many of these were repeated in 1907. In July, 1908, a few readings were taken from the *Grampus* in the region of Nantucket Shoals.

The reestablishment of the biological station of the Biological Board of Canada at St. Andrews, at the mouth of the St. Croix River, in 1908 marks an epoch in the oceanographic study of the Bay of Fundy region. The first published survey of the temperature and density (the latter determined by hydrometer) in the neighborhood of St. Andrews was carried out in July, 1910 (Copeland, 1912). Since then the taking of temperatures and of salinity has been a regular part of the station's work, and such of the data as have been published are mentioned below.

Although the preceding summary may seem somewhat formidable, very little was yet known of the subsurface temperatures of the offshore parts of the gulf, even in summer, for only one small area in its western side had been examined with satisfactory instruments. Nor had anything been learned of its winter state or of the salinity of its deep waters at any time of year until 1912. In that year the United States Bureau of Fisheries and the Museum of Comparative Zoology jointly undertook the general oceanographic exploration of the gulf, which, continued to date under my direction, has been the foundation of this report and of those that have preceded it (Bigelow, 1914 to 1926; Bigelow and Welsh, 1925).

The first fruits were the serial records at 46 stations (10001 to 10046) in the northern half of the gulf during that July and August (p. 978; Bigelow, 1913, 1914), including the first determinations of the salinity of the water of the gulf by the titration method (p. 976) that for some years had been in general use on the other side of the Atlantic. This, subsequently, has been a routine part of our station work. Observations were taken bimonthly off Gloucester by the *Blue Wing* during the winter of 1912-1913; north of Cape Cod during the following spring by W. W. Welsh (stations 10047 to 10056; W. W. Welsh stations 1 to 32; and Bigelow, 1914a); also a few temperatures and water samples between Massachusetts Bay and Georges Bank by Thomas Douthart and W. F. Clapp (table, p. 980).

The *Grampus* carried out a general survey of the western and northern parts of the gulf in the summer of 1913 (stations 10057 to 10061, 10085 to 10112, p. 982; Bigelow, 1915), as well as of the coastal waters between the longitudes of Marthas Vineyard and Chesapeake Bay. This was followed by a more comprehensive oceanographic examination of the offshore banks, as well as of the inner parts of the gulf and of the coastal

<sup>4</sup> For these *Albatross* data see Townsend (1901, dredging stations 2053, 2054, 2060-2064, 2068, and 2522).

shelf eastward along Nova Scotia to Halifax in the summer of 1914 (stations 10213 to 10264, p. 985; Bigelow, 1914b, 1917). Temperatures and water samples (density of the latter determined by hydrometer) were taken at many localities in the Bay of Fundy region that summer and the following winter from the biological station at St. Andrews (Mavor, Craigie, and Detweiler, 1916; Craigie, 1916, 1916a; McMurrich, 1917; and Doctor McMurrich's unpublished plankton lists). In 1915 the *Grampus* cruised in the gulf from spring to midautumn (stations 10266 to 10339, p. 987; Bigelow, 1917). Craigie (Craigie and Chase, 1918) likewise took serial temperatures in the Bay of Fundy, in Annapolis Basin, and in St. Marys Bay, as well as salinities in the latter (Vachon, 1918).

That same summer is memorable in oceanographic annals for the general survey of eastern Canadian waters carried out by the Canadian Fisheries Expedition (Hjort, 1919; Sandström, 1919; Bjerkan, 1919). This, however did not touch the Gulf of Maine region except for one profile crossing the shelf off Shelburne, Nova Scotia, in July.

It is a fortunate chance that the western and southwestern parts of the gulf, on the one hand (stations 10340 to 10357, 10398 to 10404; Bigelow, 1922<sup>5</sup>), and the Bay of Fundy, on the other (Vachon, 1918), both were studied in 1916, for that summer and autumn followed an almost Arctic winter and a backward spring.

Exploration of the offshore waters of the Gulf of Maine was interrupted by the war, except that serial observations were taken at a station between Grand Manan and Nova Scotia by the St. Andrews station at intervals from 1916 to 1918.

In 1919 work was resumed, when the United States Coast Guard cutter *Androscoogin*, on ice patrol, ran profiles across the gulf in March, April, and May (United States Coast Guard stations 1 to 3, 19 to 22, 35 to 38, p. 997; E. H. Smith, 1924, p. 103), while Mavor (1923) made an oceanographic survey of the Bay of Fundy in August. Study of the surface currents of the Bay of Fundy by drift bottles also was inaugurated by the St. Andrews station during that summer (Mavor, 1920 to 1923), and later was expanded into a joint project to cover northeastern American waters generally.

Prior to 1920 attention had been directed chiefly to the state of the gulf during the warm half of the year. To remedy this seasonal deficiency the *Albatross* carried out a general survey of the entire region from February to May, 1920 (stations 20044 to 20129, p. 998; United States Bureau of Fisheries, 1921), while the *Halcyon* cruised in the northern half of the gulf during the following December, January, and March. The *Halcyon* also occupied a net of oceanographic stations in Massachusetts Bay during August, 1922, and has made scattered observations at various seasons since then (stations 10631 to 10645, p. 995, and unnumbered stations, p. 1012). Finally, the *Fish Hawk* took temperatures and salinities at many stations in Massachusetts and Cape Cod Bays at intervals during the winter and spring of 1924-25 (p. 1004).

The following lines of drift bottles have been set out in the Gulf of Maine since 1919: July, 1922, one line running southeasterly from Cape Elizabeth to the center of the gulf; another from the southern angle of Cape Cod southeasterly out across the edge of the continent; and likewise a line off New York. A line also was set out

<sup>5</sup>The operations of the *Grampus* in 1916 were in the immediate charge of W. W. Welsh.

off Cape Sable that summer by the Biological Board of Canada, besides several other lines farther east (p. 908). During August, 1923, lines of bottles were set out normal to the coast line off Mount Desert, Cape Elizabeth, Cape Ann, and Cape Cod (p. 874); and a much larger number of bottles was put out in more eastern Nova Scotian waters by the Biological Board of Canada, some of which have drifted to the Gulf of Maine, as described below (p. 908). No bottles were put out in the Gulf of Maine proper in 1924, although lines were run across Vineyard and Nantucket Sounds. Some of the many Canadian bottles put out that summer off the outer coast of Nova Scotia have been picked up in the Gulf of Maine. Finally, bottles were put out in Massachusetts and Ipswich Bays in February, April, and May, 1925; in Massachusetts Bay again by Henry Stetson in April, 1926, and off Cape Nedick by T. E. Graves that July, from their yachts (pp. 878, 879).

The measurements of currents, which have been taken in the gulf by the Tidal Survey of Canada and by the United States Coast and Geodetic Survey, are mentioned in a later chapter (p. 857).

## 2. CONTINENTAL SHELF SOUTH OF NANTUCKET AND MARTHAS VINEYARD

The earlier explorations in this area are summarized in a previous report (Bigelow, 1915), hence they may be passed over briefly here.

The general range of surface temperature south of Woods Hole is now well known for the summer season, thanks to the early explorations by the vessels of the Bureau of Fisheries, notably in 1880 to 1882 (Tanner, 1884 to 1884b) and in 1889 to 1891 (Libbey, 1891, 1895). Daily records of temperature of air and water also have been recorded for many years at Woods Hole,<sup>6</sup> and observations have been taken on the various collecting trips carried out summer after summer from that station. Dickson (1901) likewise has collected a large number of surface temperatures from the logs of vessels, and the *Grampus* has crossed this part of the continental shelf on several recent cruises.

A large number of subsurface temperatures and determinations of salinity by hydrometer also have been taken from Marthas Vineyard and Nantucket out to the edge of the continent and beyond, beginning with the early dredging trips of the vessels of the Fish Commission (1880 to 1881<sup>7</sup>) and continued by Libbey in 1889, 1890, and 1891. Libbey continued his study in subsequent years, but the results never have been published; nor, except in a few instances, have the bottom temperatures taken subsequently on the various dredging trips sent out to the waters south of Marthas Vineyard from the Woods Hole station of the Bureau of Fisheries.

In 1908 the *Grampus* took temperatures in 31 to 400 fathoms southward from Nantucket Shoals (p. 595; Bigelow, 1909). In July, 1913, she occupied several oceanographic stations in that general region, working southward thence to Chesapeake Bay (Bigelow, 1915; stations 10062 to 10084). During that August she took surface temperatures from Cape Cod to Cape May (Bigelow, 1915, p. 350); in 1914

<sup>6</sup> These are summarized by Sumner, Osburn, and Cole (1913), and by Fish (1925).

<sup>7</sup> For records of temperature during this period, see Sanderson Smith (1889); for the *Albatross* stations, see Tanner (1884a, 1884b) and Townsend (1901).

and 1915 she ran oceanographic profiles across the slope abreast of Marthas Vineyard in August and October, mentioned above (p. 517). In 1916 she again made summer and November cruises from Gloucester to Chesapeake Bay (Bigelow, 1922).

## TOPOGRAPHY

The indentation of the coast between Cape Sable, at the southeast angle of Nova Scotia on the east, and Cape Cod and Nantucket Island, on the west, seems to have gone unnamed until late in the last century, when it was christened "Gulf of Maine." As outlined by the coast, the gulf is roughly rectangular, much wider (about 200 miles) than deep (about 120 miles). It is a far better marked natural province below the surface of the sea than the shallow recession of its shore line would suggest, for its southern boundary is marked by a shallow rim, or "sill," pierced by three narrow passages only. Passing eastward from Nantucket, with its off-lying shoals, these, successively, and the banks that separate them, are: The South Channel (not very well defined and only 40 to 50 fathoms deep), Georges Bank, the Eastern Channel, Browns Bank, the Northern Channel, and finally the Seal Island or coastal bank off Cape Sable. This rim, as Mitchell (1881) long ago pointed out, 259 miles in length from Nantucket to Cape Sable, follows, in its main outlines, the arc of a circle whose radius is about 167 miles. Along this arc the length of Georges Bank, from the deepest trough of the South Channel to the 50-fathom contour on the slope of the Eastern Channel, is about 140 miles, with a greatest breadth of about 80 miles from north to south between the 50-fathom contours. Between these same contours of the Eastern Channel and of the Northern Channel each occupies about 25 miles of the arc. In round figures, the area of Georges Bank is 10,000 square miles; that portion of Browns Bank west of longitude  $65^{\circ} 30'$  W. (taken as the arbitrary boundary of the region under discussion) is about 550 square miles.

The area of the gulf north of the rim is given by Mitchell as about 36,000 square miles. The coast line of the gulf, as it would appear on a small-scale chart, follows a fairly regular curve, but in detail it is extremely complex; for the northern and eastern shores are not only frequently and deeply embayed, but are bordered by a perfect labyrinth of islands, large and small, extending in places 10 to 20 miles seaward from the mainland. Its largest bays (Massachusetts on the southwest and the still larger Bay of Fundy on the northeast) are too well known to need more than passing mention.

The coast of the Gulf of Maine falls into two main types, Cape Elizabeth marking the transition from one to the other. South of this headland the shore line is characterized by a succession of sand beaches alternating with bold headlands, notably Cape Ann, and with rocky stretches, which in Cape Cod Bay give place to the continuous sand strand of the cape. Along this part of the coast there are but few islands, except in Boston Bay, and the fjord type of indentation is notably absent. East of Cape Elizabeth, on the contrary, the shores of the State of Maine are almost continuously rocky, as are the islands of the outlying archipelago already mentioned; and deep bays succeed each other in close succession as far as the mouth of the Bay of Fundy. As a whole, the shores of the gulf are low, seldom rising to more than 100 to 200 feet in the immediate neighborhood of the sea; but the Camden hills